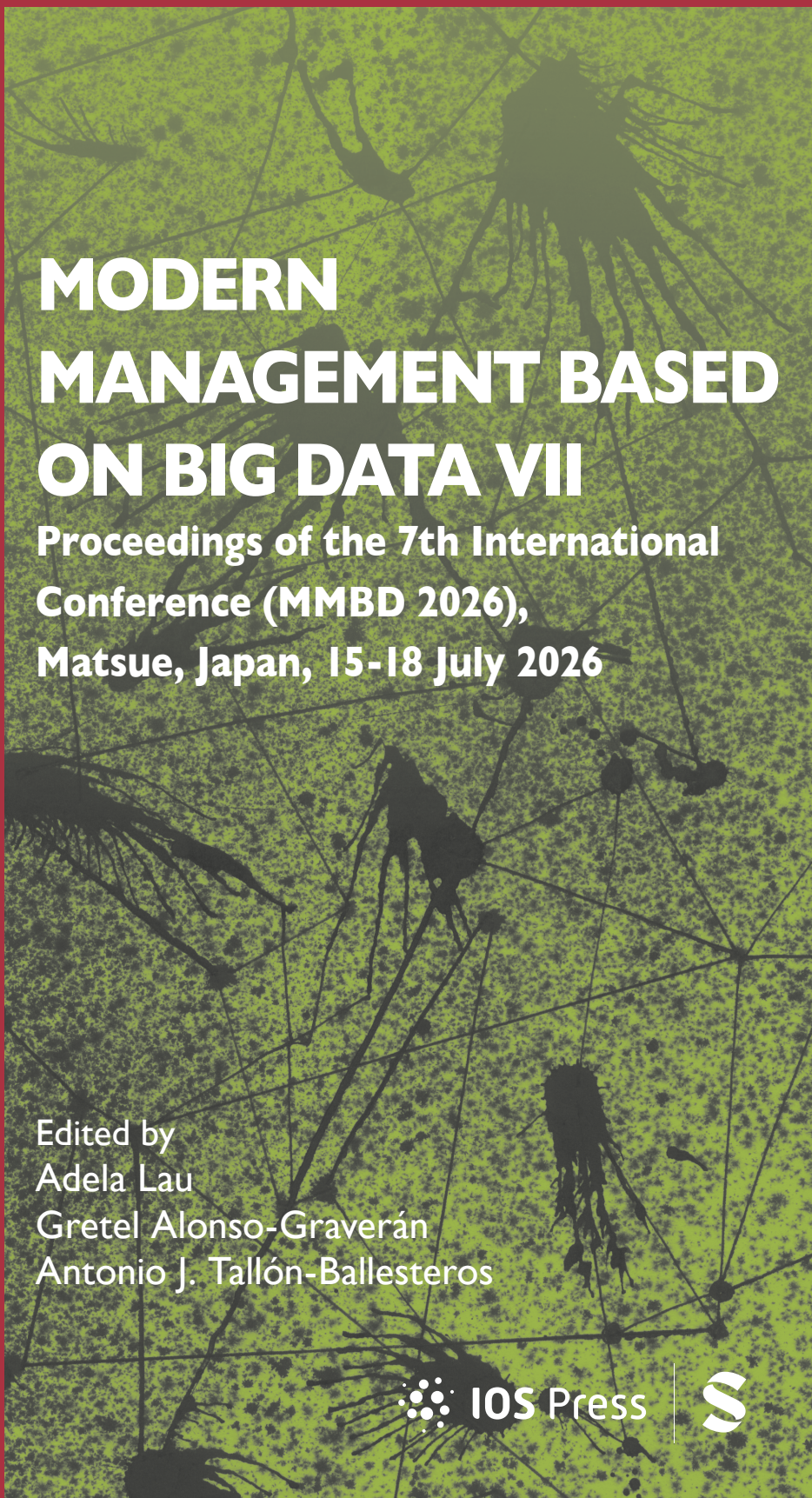
424

Frontiers in Artificial Intelligence and Applications



MODERN MANAGEMENT BASED ON BIG DATA VII

Proceedings of the 7th International Conference (MMBD 2026), Matsue, Japan, 15-18 July 2026

Edited by
Adela Lau
Gretel Alonso-Graverán
Antonio J. Tallón-Ballesteros

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MODERN MANAGEMENT BASED ON BIG DATA VII

Frontiers in Artificial Intelligence and Applications

The proceedings published in the *Frontiers in Artificial Intelligence and Applications* series (*FAIA*) cover a broad spectrum of artificial intelligence research, from theoretical foundations to applied and interdisciplinary applications. Across the series, three recurring areas stand out. First, FAIA presents foundational AI research, including work on machine learning, reasoning, knowledge representation, logic, and intelligent algorithms, which underpins progress across the field. Second, it showcases applied AI and intelligent systems, where AI techniques are developed, tested, and deployed in domains such as robotics, data analytics, software engineering, healthcare, law, and engineering. Third, *FAIA* highlights interdisciplinary and human centred perspectives, exploring how AI interacts with humans, organisations, and society through themes such as explainable and trustworthy AI, human–AI interaction, hybrid intelligence, ethics, and responsible innovation. Drawing on contributions from leading international conferences, the series provides a comprehensive and evolving picture of contemporary artificial intelligence research and practice.

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Gretel Alonso-Graverán

International University of Andalusia, Spain

and

Antonio J. Tallón-Ballesteros

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Preface

Centered on the overarching theme of Big Data and Modern Management, MMBD2026 has attracted extensive global participation from academia (professors, PhD candidates, postgraduate students, technicians), policymakers, and senior executives across several industries and sectors. The conference serves as a pivotal academic platform for the sharing of cutting-edge insights at the intersection of digital technology and management practice.

This volume contains 75 high-quality papers selected from the 243 submissions received. These are organized into five thematic parts. Part I and Part IV lay the theoretical foundation, exploring how big data and AI advance management innovation, organizational optimization, and industrial cluster development. Part II focuses on applied education, data science, Web 6.0, and digital talent cultivation. Part III addresses global sustainability, presenting research on digitalization, carbon governance, green logistics, and resource symbiosis. Part V promotes innovations in lifelong education and university/industry collaboration.

All papers underwent rigorous peer review by the international Technical Program Committee and anonymous reviewers, ensuring strong thematic relevance, analytical rigor, and alignment with the FAIA series standards.

We sincerely thank all the TPC members and anonymous reviewers for their hard work before the conference, and the keynote speakers and authors for their valuable contributions. We would also like to extend our appreciation to the editorial team at IOS Press for publishing this volume as the 7th edition of the MMBD series in FAIA. We believe these proceedings will inspire further research and collaboration in big data and modern management.

May 2026

Adela Lau, The University of Hong Kong, Hong Kong
Gretel Alonso-Graverán, International University of Andalusia, Spain
Antonio J. Tallón-Ballesteros, University of Huelva, Spain

About the Conference

Co-organized by Hannan University and HKU SAAS Data Science Lab (School of Computing and Data Science, The University of Hong Kong), the 7th International Conference on Modern Management based on Big Data (MMBD 2026) was held from 15 to 18 July 2026 in Matsue, Japan. MMBD2026 featured core themes centered on modern management and big data, complemented by cutting-edge research topics and dedicated sessions, including:

- A track on "Applied Education and Applied Research in AI, Data Science, and Web 6.0", the Second Edition, proposed and chaired by Dr. Adela Lau from the HKU SAAS Data Science Lab, School of Computing and Data Science, The University of Hong Kong.
- A special session on "The Potential of Big Data, Digitalization and AI in a Sustainable Economy", proposed and chaired by Prof. Yoshihiro Hamaguchi, Professor of Macroeconomics at Hannan University, Osaka, Japan
- A special session on "New Ecology of Lifelong Education" supported by the Hunan Lifelong Education Research Base (Xiangnan University Base)

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Section 1

Modern Management and Big Data

Modern Management based on Big Data VII
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AI-Driven Recruitment: Efficiency, Ethics, and Human Judgment

Mariza Tsakalerou[1], Aruzhan Balgynbayeva and Yerdaulet Kumisbek
School of Engineering and Digital Sciences, Nazarbayev University, Astana, Kazakhstan
ORCiD ID: Mariza Tsakalerou https://orcid.org/0000-0002-7427-5002

Abstract. The integration of artificial intelligence (AI) is reshaping recruitment by automating resume screening, candidate evaluation, and workforce planning. AI tools reduce costs and manual workload while improving decision-making through predictive analytics and natural language processing. This study compares traditional workflows with AI-enhanced applicant tracking systems (ATS) to show how AI improves hiring accuracy and supports long-term talent strategies. Yet, these benefits raise ethical and operational concerns, including bias, privacy risks, and compliance with the EU AI Act and GDPR. Drawing on empirical evidence, the paper evaluates these challenges and proposes mitigation strategies such as adversarial debiasing, federated learning, and bias audits. Finally, it advances a hybrid model that combines AI efficiency with human oversight, ensuring fairness, transparency, and sound judgment in recruitment.

Keywords. Artificial Intelligence in Recruitment, Talent Acquisition, Algorithmic Bias, AI ethics, Data Privacy, Hybrid Hiring Models, Predictive Hiring analytics, Regulatory Compliance

1. Introduction

The digital transformation of human resource management has reshaped recruitment, with artificial intelligence (AI) emerging as a core component of modern talent acquisition strategies [1]. Traditional methods, which rely on manual screening and assessments, are being increasingly replaced by AI-driven tools [2]. Studies report measurable gains in time-to-hire, cost-per-hire, and recruitment accuracy [3]. Moreover, AI facilitates a more data-driven and proactive approach to identifying skill gaps and optimizing workforce planning [4].

Manual recruitment workflows are often inefficient and difficult to scale. AI-powered applicant tracking systems (ATS) automate core tasks, streamline the candidate selection process, and reduce recruiter workload. This paper contrasts traditional and AI-enhanced recruitment processes (Figures 2 and 3) to demonstrate gains in speed, precision, and scalability.

Despite its advantages, AI-driven recruitment introduces several challenges that must be addressed to ensure ethical and effective implementation. Algorithmic bias

[1] Corresponding Author, Mariza Tsakalerou, School of Engineering and Digital Sciences, Nazarbayev University, Astana, Kazakhstan; Email: mariza.tsakalerou@nu.edu.kz
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remains a critical concern, as AI models trained on historical data may accidentally reinforce existing inequalities and disadvantage certain demographic groups [5]. Additionally, the growing reliance on AI raises questions about data privacy, ethical transparency, and compliance with evolving regulatory frameworks [5, 6]. Beyond fairness and privacy, concerns also exist regarding the candidate experience, as research suggests that applicants often find AI-driven hiring impersonal, especially when automated assessments replace direct interactions with recruiters. Overreliance on automation may leave candidates feeling disconnected, thereby reducing their engagement in the hiring process [7]. To balance efficiency with human interaction, many organizations are adopting hybrid recruitment models, where AI handles initial screenings and assessment tasks, while recruiters oversee interviews and final hiring decisions [8-10]. Studies have shown that hybrid models improve fairness by addressing AI's limitations in recognizing non-traditional career paths and assessing interpersonal skills, ensuring that human oversight remains integral to hiring outcomes [10].

Research on algorithmic hiring predates the current wave of generative AI. Early studies highlighted risks of bias and opacity in automated recruitment systems [11]. Scholars also examined candidate perceptions of AI-driven selection and the ethical implications of automation in HR practices [11, 12]. These foundational works established concerns around fairness, accountability, and transparency, which remain critical as generative AI continues to reshape recruitment.

This paper examines the increasing use of AI in recruitment, assessing both its benefits and the challenges associated with its adoption. The core research problem addressed here is the lack of clarity on how AI can improve recruitment efficiency while avoiding risks of bias, privacy violations, and depersonalized candidate experiences in real-world contexts. Accordingly, this study pursues three objectives: (1) to analyze the role of AI in recruitment processes and its measurable effects on efficiency and scalability; (2) to identify and evaluate the ethical, technical, and regulatory risks—particularly bias and data privacy; and (3) to propose a hybrid hiring model that integrates AI efficiency with essential human oversight to ensure fairness and accountability. By analyzing these issues, this study explores how organizations can integrate AI responsibly to create ethical and effective hiring practices.

2. Methodology

2.1 Data Collection and Instruments

This study employed a mixed-method approach, integrating survey data and semi-structured interviews to analyze the adoption and impact of AI in recruitment. Primary data were collected from October to December 2024, targeting HR professionals from medium and large enterprises across Kazakhstan, Uzbekistan, and Russia.

An online survey was distributed to 50 HR professionals, comprising both Likert-scale and open-ended questions. The Likert-scale items were designed based on insights from the literature review and pilot-tested with a small group of practitioners to refine wording and ensure construct validity. Survey participants represented roles such as recruitment leads, HR generalists, and talent acquisition managers. The sample included professionals from commerce, retail, and IT sectors, with an average of 7 years of recruitment experience. These questions explored key aspects of recruitment such as resume screening burden, interview scheduling delays, candidate engagement, and

perceptions of AI tools. The exclusion of a neutral midpoint in the Likert scale encouraged respondents to take a definitive stance, thereby improving the interpretability of the results. To further strengthen reliability, responses with excessive variance were filtered during analysis, and recurring themes were cross-validated through qualitative feedback in subsequent interview rounds.

To ensure validity, the Likert-scale items were analyzed using mean thresholds and standard deviation filters. Responses with ≥65% agreement (scores of 4–5) or disagreement (scores of 1–2) were considered meaningful trends, while a standard deviation threshold of 1.2 was applied to exclude items with excessive variability. This process refined the survey questions into a stable set of validated measures for subsequent Delphi rounds.

In parallel, 15 semi-structured interviews were conducted via video conferencing with recruiters and HR managers from diverse sectors (Figure 1). Participants were sourced through professional platforms and had between 3 and 15 years of industry experience. Interviews focused on identifying workflow pain points, exploring the use of automation tools, and capturing cultural and operational nuances in recruitment practices.

The interview participants represented a range of industries, with the majority coming from retail, IT, and manufacturing sectors. The detailed industry distribution is shown in Fig. 1.

2.2 Workflow Development and Validation

Findings from the survey and interviews were synthesized to build a stylized AI-enhanced recruitment workflow (Figure 2). Participants consistently reported that AI-led resume screening reduced early-stage hiring time by over 50%, though 68% raised concerns about the loss of candidate nuance and cultural fit. These insights guided the hybrid model structure, ensuring it combined automation with essential human oversight.

Recurring themes such as manual administrative overload, inconsistent communication, and tool fragmentation informed the modular design of the workflow. Candidate engagement challenges — particularly cultural tendencies such as interview no-shows or ghosting — were also incorporated into system recommendations like localized messaging and hybrid scheduling features.

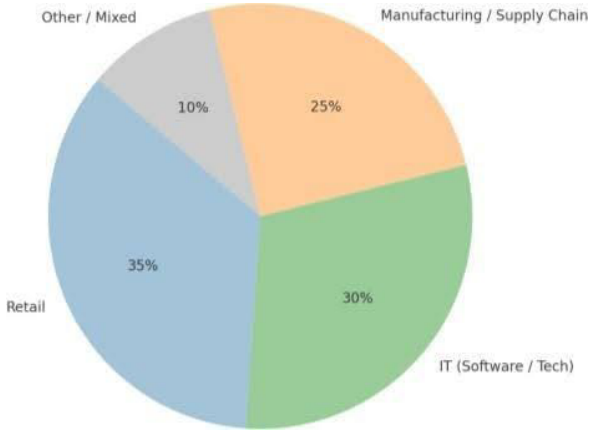


Figure 1. Industry Distribution of Interview Participants (n = 15).

2.3 Limitations

A key limitation of this study is its regional focus on Central Asia (Kazakhstan, Uzbekistan, and Russia). While this provides valuable insights into emerging recruitment practices in transitional economies, the findings may not be directly generalizable to other regions with different cultural, regulatory, and technological contexts. Future research could expand to include comparative studies across Europe, North America, and Asia-Pacific to provide a broader understanding of AI adoption in recruitment.

Another limitation arises from the reliance on self-reported data in both the survey and interviews. As responses reflect participants' perceptions and experiences, they may be subject to biases such as social desirability, selective recall, or overestimation of AI's benefits and risks. While triangulation between survey and interview findings mitigated some of these concerns, the possibility of response bias remains and should be considered when interpreting the results.

Table 1. Key Themes from Survey and Interview Findings

Theme	Survey Insight	Interview Insight
Resume Screening	70% reported manual resume review as the top time-consuming task	AI reduced early screening time by 50%, but nuance and soft skill signals were lost.
Candidate Engagement	62% noted candidates dropping off after initial application	Cultural factors (e.g., ghosting, no-shows) frequently disrupted process flow
Administrative Burden	The majority flagged interview coordination as repetitive and inefficient	Recruiters cited "Excel chaos" and email overload as major workflow pain points
Automation Perception	Mixed feelings on trust in AI decision-making	Recruiters desired more transparency and control over AI scoring

3. AI's Role in Recruitment

Artificial Intelligence is changing the recruitment system in companies, introducing multifunctional tools that automate tasks traditionally performed by recruiters. With the rise of AI-driven systems, organizations started processing large volumes of applications more efficiently, reducing manual processes like screening and decision-making [13, 14]. Machine learning, natural language processing, and predictive analytics allow these systems to evaluate candidates, sort applications, and assist in hiring decisions [9, 13].

One of the most widely used applications of AI in recruitment is automated resume screening. Instead of recruiters manually reviewing hundreds of applications, AI systems analyze resumes to identify relevant skills, experience, and qualifications based on predefined criteria set by the HR manager or recruiter. By scanning and ranking candidates, these systems help organizations shortlist top applicants within minutes, significantly cutting down the time required for initial screenings [13]. Many companies integrate AI-powered applicant tracking systems (ATS) that not only filter resumes but also assess candidates' suitability using behavioral and psychometric data [14].

Beyond resume screening, AI plays a major role in predictive hiring analytics. Machine learning models analyze historical hiring data to predict a candidate's likelihood of success in a role. These models consider previous hiring decisions,

performance reviews, and career trajectories to suggest the best candidates for a position. Companies like Google and Unilever use AI-driven analytics to improve hiring accuracy and forecast workforce needs, allowing HR teams to make informed decisions about recruitment strategies [15].

Another growing area of AI in recruitment is data-driven candidate matching. Traditional hiring relies on keyword-based searches and recruiter intuition, but AI-driven platforms can evaluate candidate profiles against job descriptions with much greater precision. These systems assess work history, skills, and even online professional activity to recommend job matches [14]. Some organizations have integrated AI-powered chatbots that guide candidates through the application process and answer frequently asked questions, improving engagement and reducing delays [9].

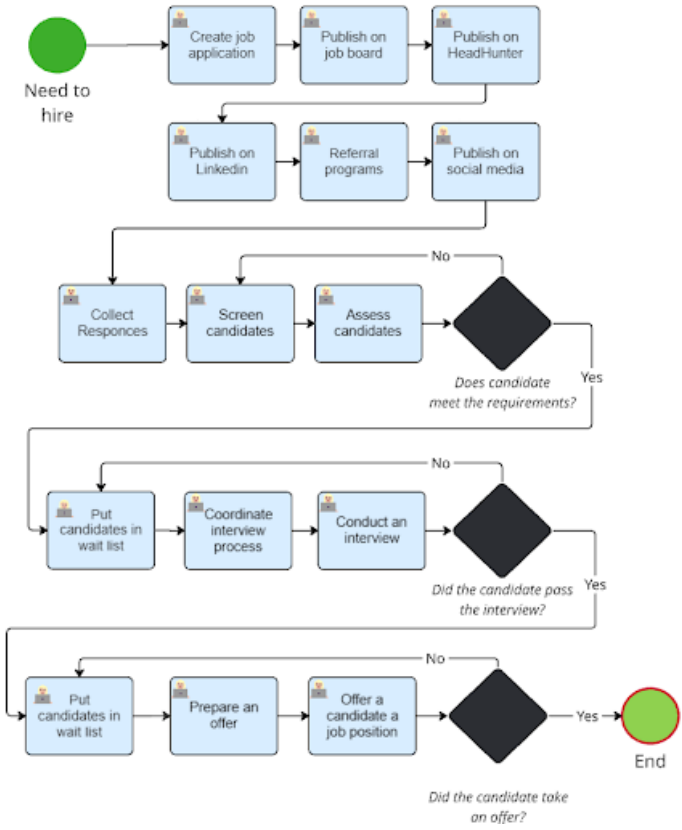


Figure 2. Traditional Recruitment Workflow Without AI and ATS

3.1 Traditional Recruitment Workflow Without AI-Integrated ATS

As illustrated in Figure 2, traditional recruitment workflows involve manual and time-consuming steps, such as resume screening, candidate shortlisting, and interview coordination. Recruiters must review each application manually, which increases time-to-hire, cost-per-hire, and workload for HR teams. These inefficiencies often prolong hiring cycles and make it challenging to manage high volumes of applicants effectively. The process is also susceptible to subjective decision-making, which may introduce bias

into hiring outcomes. This manual approach is often slow, inconsistent, and difficult to scale, particularly in high-volume recruitment settings [16].

3.2 AI-Enhanced Recruitment Workflow with Applicant Tracking System (ATS)

Figure 3 presents a stylized recruitment workflow developed by the authors based on structured consultations with HR professionals and recruitment system specialists from different markets. These insights helped shape the modular AI-ATS architecture illustrated in the diagram.

With the integration of AI-powered ATS, recruitment undergoes a significant transformation. Figure 3 highlights key automation-driven stages, such as AI-driven resume parsing, chatbot-assisted candidate interactions, predictive candidate ranking, and automated application tracking. These advancements eliminate redundant manual tasks, improving screening accuracy and reducing hiring timelines. AI-driven ATS platforms optimize recruitment by automatically ranking applicants, implementing predictive analytics, and reducing recruiter workload.

In particular, AI eliminates manual resume screening, allowing recruiters to focus on higher-value tasks such as engaging with top candidates and enhancing employer branding. As depicted in Figure 3, chatbots automate candidate inquiries, ensuring a smoother candidate experience while reducing administrative burdens for HR teams [14]. However, organizations often implement these AI solutions in modular stages rather than as fully integrated systems, selecting features that best fit their specific recruitment needs.

By comparing Figures 2 and 3, it is evident that AI-driven ATS improves hiring efficiency by reducing processing times, increasing candidate engagement, and enhancing hiring accuracy. These improvements not only optimize operational efficiency but also enable HR professionals to make more data-driven hiring decisions, ensuring a scalable and fair recruitment process.

3.3 ATS Case Study: AI-Driven Recruitment at Unilever and Hilton

Real-world implementations of AI-driven ATS platforms confirm the observed benefits. Johnson & Johnson and L'Oréal reported reduced time-to-hire, better candidate engagement, and higher recruiter efficiency [17, 18].

Table 2 summarizes these outcomes, supporting the relevance of the proposed hybrid model in large-scale recruitment.

Table 2. Ai-driven ATS impact on recruitment efficiency at Johnson & Johnson and L'Oréal

Metric	Johnson & Johnson (Before AI)	Johnson & Johnson (After AI)	L'Oréal (Before AI)	L'Oréal (After AI)
Time-to-Hire	45 days [17]	27 days (↓40%)	50 days	30 days (↓40%)
Candidate Engagement	Moderate	High (80% chatbot interaction)	Moderate	High (AI- driven pre- screening)
Recruiter Workload	High	Reduced (focus on final stages)	High	Reduced (automated assessments)
Bias Mitigation	Manual review	Textio NLP for gender neutrality	Manual review	Adversarial debiasing applied [18]

This paper proposes a hybrid hiring governance model that integrates adversarial debiasing, federated privacy mechanisms, and human oversight. Although the study is conceptual, the proposed structure sets a foundation for empirical validation.

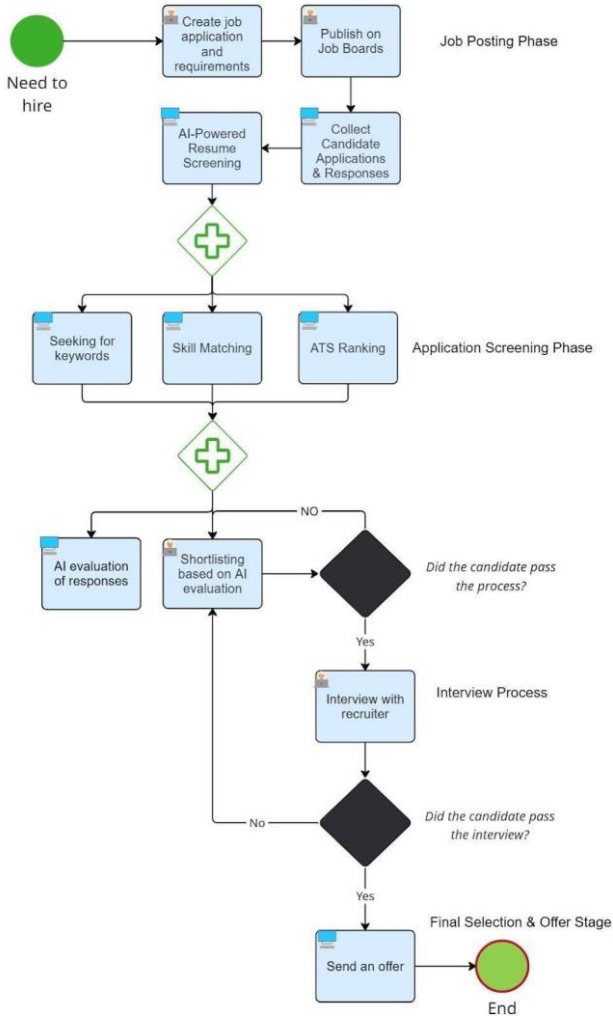


Figure 3. AI-Enhanced Recruitment Workflow with Applicant Tracking System (ATS)

4. Key Challenges in AI-Driven Recruitment

AI-driven recruitment is transforming hiring processes, but its adoption comes with systemic risks related to bias, data privacy, and the role of automation in decision-making. These challenges require careful evaluation to ensure that AI improves hiring efficiency without compromising fairness or accountability. One of the most widely used applications of AI in recruitment is automated resume screening. Instead of recruiters manually reviewing hundreds of applications, AI systems analyze resumes to identify

relevant skills, experience, and qualifications based on predefined criteria set by the HR manager or recruiter. By scanning and ranking candidates, these systems help organizations shortlist top applicants within minutes, significantly cutting down the time required for initial screenings [13]. Many companies integrate AI-powered applicant tracking systems (ATS) that not only filter resumes but also assess candidates' suitability using behavioral and psychometric data [14].

4.1 Algorithmic Bias

One of the most pressing concerns is bias in algorithmic hiring models. AI systems inherit historical biases from patterns in their training data, which can lead to proxy discrimination (e.g., treating gaps in employment as a sign of lower competence) even when protected attributes are removed. Studies have documented cases where AI-based hiring tools reinforced existing inequalities, leading to concerns about fairness and diversity in the workplace [5]. For instance, Amazon's AI hiring model systematically downgraded resumes that included terms associated with women's organizations due to past hiring patterns favoring male candidates [19]. Similarly, research has shown that AI screening tools can infer race, gender, and socioeconomic status through dataset skew (e.g., underrepresentation of non-linear career trajectories), even when explicit demographic data is removed [20]. Some AI tools analyze subjective traits such as communication style or cultural alignment, increasing the risk of biased assessments. Since many AI models function as black boxes – creating a problem of explanatory opacity rather than mere technical complexity – organizations struggle to determine why specific candidates are rejected. These risks are not just technical but also have legal consequences. The U.S. Equal Employment Opportunity Commission (EEOC) has warned that if AI disproportionately eliminates applicants from legally protected groups, it could lead to violations of Title VII of the Civil Rights Act, putting companies at risk of legal action [21]. Employers using AI hiring tools are increasingly urged to audit their systems to ensure compliance with anti-discrimination laws and avoid reinforcing past hiring inequalities [20].

4.2 Data Privacy Risks

Privacy risks are another significant issue, as AI-driven hiring platforms collect vast amounts of personal data, including resumes, online activity, and results from psychometric assessments. The European Parliament has raised concerns about how AI hiring systems profile candidates and whether they provide clear explanations for their decisions, often without giving candidates a fair way to challenge them [22]. The largescale collection and processing of candidate data raise ethical concerns about security, consent, and potential misuse, particularly when AI systems analyze sensitive personal attributes [5, 6]. Regulations like the General Data Protection Regulation (GDPR) require companies to ensure transparency in AI-driven hiring, obtain clear consent for data collection, and implement strict security protocols to prevent unauthorized use of candidate information [22]. However, compliance remains a challenge, especially with AI models that operate as complex and unclear systems, making it difficult for organizations to fully explain how decisions are made. A growing area of concern is AI-powered video assessments, where algorithms evaluate facial expressions and voice patterns to determine a candidate's confidence and communication skills. These tools process biometric data, which falls under the EU AI Act's 'high-risk'

classification, requiring strict safeguards for emotion recognition. Neurodivergent candidates whose nonverbal behaviors may deviate from algorithmic norms are particularly vulnerable to misclassification, raising additional legal and ethical questions about fairness, informed consent, and data storage limitations [9, 19].

4.3 Over-Reliance on Automation

Despite AI's ability to process applications quickly, relying too much on automation can create problems in decision-making and candidate engagement. AI models may reinforce biased feedback loops, such as over-prioritizing elite credentials or linear career paths, which risks excluding qualified applicants from diverse backgrounds. Fully automated interviews can reduce candidate trust and perceived fairness [23]. As a result, many organizations adopt hybrid models that combine AI tools with human oversight. The EEOC emphasizes the legal need for manual review to ensure fairness and accountability in hiring [21].

These challenges highlight the need for carefully regulated AI adoption in recruitment. As organizations integrate AI into hiring, balancing efficiency with fairness and transparency will be critical to ensure ethical hiring practices.

5. Addressing the Challenges

Mitigating the risks associated with AI-driven recruitment requires a structured approach that enhances fairness, protects privacy, and maintains human oversight in hiring decisions. Addressing bias, strengthening data security, and refining hybrid hiring models are essential to ensure the ethical and effective adoption of AI.

5.1 Bias Mitigation Strategies

Proactive auditing and dataset refinement are among the most critical solutions to algorithmic bias. AI hiring tools may inherit hidden biases, leading to indirect discrimination, for example, penalizing employment gaps. Research shows that even when demographic attributes are controlled for, AI models can still infer race, gender, or socioeconomic status through proxy variables such as ZIP codes and university names [19]. To mitigate these risks, organizations are implementing counterfactually augmented datasets (e.g., synthetically generating resumes with non-traditional career paths) and adversarial debiasing techniques, which train models to ignore biased patterns, thereby minimizing bias while preserving predictive accuracy [18]. Algorithmic impact assessments (AIAs) are now a regulatory standard for auditing hiring algorithms [24]. However, concerns persist over the transparency and effectiveness of these audits, with critics arguing that weak enforcement of anti-discrimination laws. More recently, generative AI models such as ChatGPT have introduced conversational capabilities that go beyond traditional algorithmic decision systems. Studies highlight that ChatGPT can admit mistakes, challenge premises, and generate context-sensitive responses, expanding potential applications in business contexts [25]. Although still emergent in recruitment, these interactive features represent a significant shift in the capabilities of AI, with implications for candidate engagement and recruiter support. This highlights the need for independent third-party audits and robust enforcement mechanisms to ensure AI hiring tools align with fairness objectives.

5.2 Strengthening Data Privacy

Addressing privacy risks in AI recruitment requires stronger data governance frameworks. AI hiring platforms process large volumes of sensitive candidate data, including social media activity and psychometric profiles. The European Parliament has raised concerns about candidate rights under opaque decision-making [22, 24]. Regulations such as the GDPR mandate transparency in automated hiring, but critics argue that the GDPR's 'right to explanation' remains inadequate in cases where deep learning models provide little interpretability [24]. Emerging safeguards include differential privacy techniques, which add random data to anonymized datasets to protect individual identities, and federated learning, which allows AI models to train across multiple locations without collecting sensitive candidate data in one place [26]. The EU AI Act (2023 draft) now classifies emotion recognition in hiring as a 'high-risk' application, requiring strict compliance measures. Concerns remain particularly for neurodivergent candidates, whose nonverbal cues may deviate from algorithmic norms rooted in neurotypical benchmarks, leading to biased evaluations in AI-driven video assessments.

5.3 Hybrid Hiring Models

Hybrid hiring models aim to balance AI efficiency with human oversight, helping maintain scalability while preserving candidate trust. Fully automated hiring can erode candidate trust and reduce engagement [7]. To improve fairness, leading companies have shifted toward hybrid models, where AI handles initial screening and human recruiters assess final-stage candidates. The EEOC's 2023 Technical Assistance Guidance also emphasizes the legal requirement for human oversight, recommending that employers establish manual review processes rather than relying solely on algorithmic outputs [21]. Additionally, participatory design approaches (e.g., involving HR professionals and ethicists in AI development) help ensure that hiring tools reflect human-centered values rather than purely algorithmic efficiency.

The ethical implementation of AI in recruitment requires a three-tiered framework: technical debiasing, regulatory alignment, and participatory design. While AI-driven hiring offers significant efficiency gains, its long-term success depends on integrating fairness, privacy safeguards, and human judgment into automated decision-making processes. Organizations that institutionalize bias audits, strengthen privacy protections, and maintain human oversight will be better positioned to adopt AI responsibly while enhancing both hiring efficiency and workforce diversity.

6. Conclusion

The integration of artificial intelligence into human resources is transforming talent acquisition by automating repetitive tasks such as resume screening and video interviews, thereby reducing hiring timelines and costs. These efficiencies allow HR teams to shift attention toward strategic priorities like talent development. Predictive analytics further supports workforce planning by identifying high-potential candidates from diverse backgrounds, helping mitigate the limitations of traditional selection models that often privilege educational credentials over demonstrated skills.

At the same time, the adoption of AI in recruitment introduces significant ethical and operational challenges. Algorithmic bias, privacy risks, and impersonal candidate experiences remain central concerns. Historical data biases may reinforce systemic inequalities, and the opacity of many AI models complicates accountability. Regulatory frameworks such as the EU AI Act and GDPR increasingly mandate safeguards—including bias audits, explainable AI systems, and strict data governance—to ensure fairness and transparency. Hybrid approaches, exemplified by practices at firms like Unilever, demonstrate how combining AI-driven screening with human-led evaluations can balance efficiency with trust and inclusivity.

This study contributes by proposing a conceptual framework that integrates empirical insights with practitioner perspectives. The framework emphasizes AI as an enabler rather than a replacement for human decision-making, aligning technological capabilities with organizational realities and regulatory obligations to support scalable, ethical, and context-aware recruitment systems.

Although grounded in Central Asia, the findings resonate within a wider global discourse. For example, multinational corporations such as Unilever and Hilton have reported significant efficiency gains through the use of AI-driven applicant tracking systems, including reductions in time-to-hire and improved candidate engagement [27]. In the United States, the U.S. Equal Employment Opportunity Commission (EEOC) has issued guidance on the risks of algorithmic discrimination, emphasizing the need for fairness audits and manual review in AI-assisted hiring [28]. Within Europe, the General Data Protection Regulation (GDPR) and the emerging EU AI Act classify AI applications in recruitment as high-risk, requiring explainability, bias audits, and strict safeguards [29]. Meanwhile, studies in China and India underline both the benefits of AI in reducing recruitment costs and the risks of undermining candidate trust and cultural fit [30]. Positioning the Central Asian experience within this international context highlights a broader imperative: organizations worldwide must adopt strategies that embed fairness, safeguard privacy, and preserve human judgment to fully realize the promise of AI-enhanced recruitment.

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Text Mining and Assessment of Policy Quality for Industrial Cluster Initiatives: Empirical Analysis from Xinjiang Utilizing an LDA–PMC Integrated Model

Juanjuan La, Chunyang Chang[1], Yufei Deng, Ainiqar Mamat Aili and Minire Yizibili
School of Politics and Public Administration (National Security College), Xinjiang University, Urumqi, Xinjiang 830046, China

Abstract: As a vital institutional tool for regional economic development, industrial cluster policies exert a direct influence on policy effectiveness and industrial upgrading pathways through their intrinsic structure, thematic orientation, and policy coherence. However, existing research has paid insufficient attention to the systematic quantitative evaluation of regional industrial cluster policies. This study examines 37 industrial cluster policy documents issued by the Xinjiang Uygur Autonomous Region between 2022 and 2024. By constructing a hybrid LDA-PMC framework, it systematically identifies the thematic distribution characteristics of these policies and quantitatively assesses their internal consistency and structural quality. Research findings indicate that while the overall quality of Xinjiang's industrial cluster policies is sound, certain shortcomings persist. These include inadequate support for emerging industries, limited depth in industrial chain extension, insufficient emphasis on sustainable development, and weak industrial coordination mechanisms. Consequently, this paper proposes that the reconstruction of the policy framework should be advanced through four dimensions: policy coordination, system integration, comprehensive support, and supply structure optimization. This approach aims to enhance the effectiveness of policy support for high-quality regional economic development. By constructing an LDA-PMC hybrid framework, this study has effectively established a logical linkage between thematic identification and quantitative evaluation of policy texts, providing a replicable analytical paradigm for regional industrial policy research. It simultaneously reveals the coupling mechanism between the thematic structure of industrial cluster policies and policy quality, thereby expanding the research boundaries for the integrated application of policy text mining and policy evaluation.

Keywords: Industrial cluster policy; LDA topic model; PMC index; policy text analysis; text mining; quantitative evaluation.

Corresponding Author, Chunyang Chang, School of Politics and Public Administration (National Security College), Xinjiang University, China; Email: 16603790172@163.com
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1. Introduction

Industry is the core and cornerstone of economic development[1]. As a golden passage connecting Asia and Europe, a pivotal hub for opening up to the West, a national strategic guarantee base for energy and resources, and a strategic barrier safeguarding national geopolitical security[2], the development quality of industrial clusters in Xinjiang bears not only on the high-quality development of the regional economy and the improvement of people's well-being, but also directly on the construction of the national new development pattern and the implementation of the national geopolitical security strategy. From September 2022 to January 2025, Xinjiang successively put forward eight major, nine major, and ten major industrial clusters, reflecting its all-round consideration in serving the national major strategic layout, adapting to the trend of economic transformation and upgrading, and tapping the potential of regional development[3].

Industrial clusters refer to the spatial agglomeration of interconnected enterprises, suppliers, financial institutions, and other organizations with competitive and cooperative relationships[4], aiming to enhance industrial competitiveness by promoting enterprise agglomeration, optimizing resource allocation, and strengthening synergistic innovation effects. Currently, research on industrial clusters in China has attracted extensive academic attention, and existing studies exhibit three major characteristics. First, at the research perspective level, the focus has shifted from static analysis to dynamic evolution. Scholars such as Zhang Gongwei[5] and Zhao Mengtian[6] have moved beyond the early description of static characteristics including spatial distribution and enterprise quantity, and turned to exploring the dynamic evolutionary process of industrial clusters. Second, at the research methodology level, the paradigm has transformed from qualitative description to quantitative analysis. Diverse quantitative methods have been adopted in industrial cluster research. Some scholars have applied the knowledge mapping method (Li Shuaishuai et al. [7]), the GEMS model (Qin Hong et al. [8]), the grey multi-index evaluation model (Cao Yang et al. [9]), simulation analysis (Jia Weiqiang[10]), and other approaches to analyze the development of industrial clusters in various fields and propose corresponding countermeasures. In addition, the integrated application of LDA and PMC has achieved remarkable progress in multiple policy domains, such as education policy[11], sports policy[12], and data policy[13]. By constructing a multivariate analytical framework, researchers have realized a paradigm shift from fragmented analysis to integrated evaluation[14], which verifies the feasibility of this method and provides a valuable reference for this study. Third, at the research content level, the scope has expanded from pure economic benefits to multi-dimensional evaluation including innovation and resilience. Regarding how local industrial clusters enhance resilience to cope with external shocks, scholars such as Yu Guojun et al. [17], Pan Motao[18], and Shi Lei et al. [19]have revealed the synergistic mechanism of industrial clusters, their driving effects on technological progress and industrial upgrading, and the dynamic mechanism promoting green innovation of enterprises from different perspectives.

In summary, existing research exhibits notable shortcomings in the following areas: Firstly, there is a marked lack of focus on the quantitative evaluation of industrial policy texts, coupled with insufficient consideration of the distinctive characteristics of regional industrial cluster policies. Secondly, although the combined application of LDA and PMC has been employed in related policy domains, it remains largely unexplored within the field of industrial cluster policy research. Thirdly, while existing research has developed multiple integrated analytical frameworks, the theoretical underpinnings for

the combined application of LDA and PMC remain inadequately articulated. Therefore, this study focuses on the development of industrial clusters in Xinjiang, employing a hybrid LDA-PMC model to conduct mixed-method research on 37 industrial cluster policies published in the Xinjiang Uygur Autonomous Region over a three-year period (2022–2024). Ten representative policies were selected for quantitative analysis, with particular emphasis on exploring the following issues: What are the prevailing themes within the industrial cluster policies of Xinjiang? To what extent do these policies demonstrate consistency and comprehensiveness? Which specific dimensions exhibit structural deficiencies within these policies? Through a hybrid approach combining Latent Dirichlet Allocation (LDA) and Policy Mining and Analysis (PMC), this study has successfully established a logical linkage between thematic identification and quantitative evaluation of policy texts, thereby providing a replicable analytical paradigm for regional industrial policy research. Concurrently, it has revealed the coupling mechanism between the thematic structure of industrial cluster policies and policy quality, expanding the research boundaries for the integrated application of policy text mining and policy evaluation.

2. Policy Sample Selection and Text Mining

In this paper, an analytical framework for Xinjiang's industrial cluster policies is constructed based on the LDA-PMC hybrid model (Figure 1). First, relevant policy texts are obtained via web crawling, and subjected to word segmentation and preprocessing using Python, after which the LDA model is employed to identify latent policy topics. Second, the PMC index model is established to quantitatively evaluate policy effectiveness. Finally, targeted policy recommendations are proposed based on the analysis of topic distribution and quantitative results.

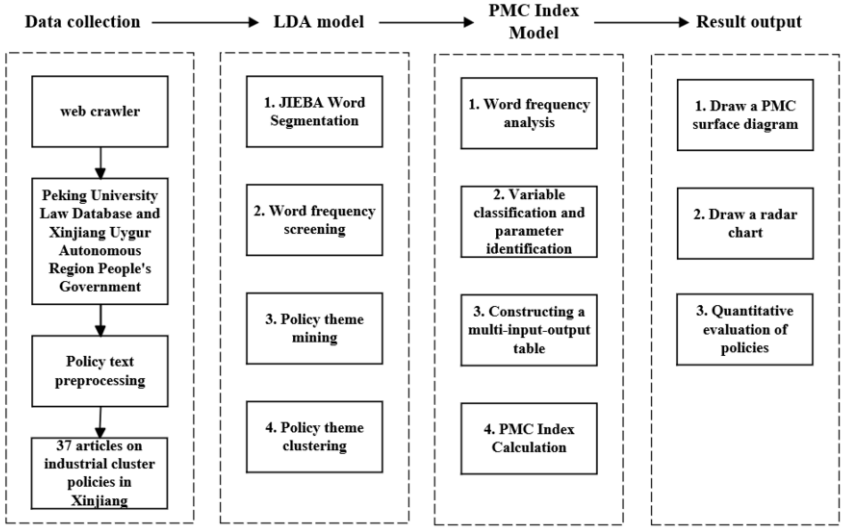


Figure.1. Technical Roadmap

2.1 Selection of policy samples

The selection of policy samples for Xinjiang's industrial clusters adheres to the following criteria: ①Timeframe: Policies issued by Xinjiang's regional-level authorities between 2022—when the region formally proposed its 'Eight Major Industrial Clusters'—and 2024, demonstrating high relevance to industrial cluster development; ②Data sources: Primarily authoritative platforms such as 'Peking University Legal Database' and the 'Official Website of the Xinjiang Uygur Autonomous Region Government', employing web crawling tools for multi-keyword searches; ③Screening criteria: Exclusion of policies that are outdated or have low relevance to Xinjiang's industrial development needs; ④Version control: The latest policy texts published on government websites serve as the definitive version. Ultimately, 37 autonomous regional-level industrial cluster policy texts were retained.

2.2 Policy Text Mining and Topic Analysis

2.2.1 Analysis of industrial cluster policy themes

LDA is a classic topic model proposed by Blei[20],capable of unsupervised identification of latent semantic structures within unstructured text, presenting them as probabilistic distributions. The data preprocessing workflow for the 37 original policy documents is as follows: First, the policy texts underwent data cleansing and structuring. Word segmentation was performed using the Jieba 0.42.1 library under Python 3.9. Subsequently, high-frequency distracting words were filtered using stopword lists from HIT and SCU alongside a custom lexicon to refine segmentation results. Finally, a document-term matrix was constructed as standard input for the LDA model. Table 1 presents the statistics of high-frequency words after preprocessing.

Table.1. List of frequently used terms in Xinjiang's industrial cluster policies

Ranking	Keywords	frequency	Ranking	Keywords	frequency
1	Development	800	19	County-level	253
2	Logistics	757	20	Promotion	249
3	Construction	674	21	Institutions	235
4	Enterprise	630	22	Quality	230
5	Services	527	23	Energy	229
6	Management	496	24	Technology	227
7	Safety	437	25	Supervision	226
8	Organization	383	26	Employment	224
9	Rural Areas	364	27	Enterprises	216
10	Projects	322	28	Legal	210
11	Strengthening	310	29	System	205
12	Facilities	303	30	Promotion	200
13	Society	289	31	Economy	198
14	Food	276	32	Parks	192

15	Resources	272	33	Innovation	189
16	Country	268	34	Guarantee	188
17	Establishment	268	35	Mechanism	188
18	Encouragement	254	36	Region	184

Based on an in-depth analysis of the high-frequency word list, it is found that the policy system for industrial clusters in Xinjiang is not yet mature and still requires further optimization and upgrading.

First, terms such as development, logistics, facilities, rural, and projects rank high, indicating that policy focus is inclined toward infrastructure and basic industries. In contrast, terms related to innovation and technology appear less frequently, implying that the driving force of technology for industrial upgrading may be insufficient. Therefore, risks such as low-level redundant construction should be guarded against.

Second, high-frequency terms including logistics, grain, energy, and resources show that industrial support is concentrated in traditional fields. Emerging sectors such as the digital economy and high-end manufacturing are not sufficiently reflected in the policy themes. It is necessary to formulate industrial planning that integrates traditional and emerging industries, and to provide systematic policy support.

Third, the contrast between high-frequency terms such as employment, security, quality, resources, and energy, and low-frequency terms such as innovation suggests a lack of content related to sustainable development. Meanwhile, statements concerning green and low-carbon transformation are insufficient, requiring greater emphasis on the coordination and integration of ecological protection and economic development.

Fourth, frequent occurrences of terms such as management, strengthen, supervision, law-based, establish, and mechanism indicate that the development of industrial clusters in Xinjiang remains government-led. However, insufficient manifestation of market-oriented forces may inhibit enterprise autonomy. Hence, future efforts should focus on balancing government guidance and market vitality.

2.2.2 Distribution of policy themes and analysis of focus areas

This study uses the LDA model for policy theme mining. Policy keywords can reflect the core content of a policy, and changes in these keywords can reveal shifts in policy focus [21][21]. In terms of model configuration, this study employed Python's Gensim 4.3.0 library for LDA modelling. A combined approach utilizing perplexity and topic consistency metrics determined the optimal number of topics K=4 within the K-value range of 2 to 15. Additional hyperparameters were set as follows: $\alpha = 0.1$, $\beta = 0.01$, with 200 iterations to ensure model convergence. Based on the optimal parameters K=4, the final LDA model was trained, and the most representative feature terms were extracted for each topic. The topic distance visualization (Figure 2) and topic clustering diagram (Figure 3) intuitively demonstrate the distinctiveness and intrinsic connections among the four topics. Each topic was named according to the semantic connotations of its feature terms, as detailed in Table 2.

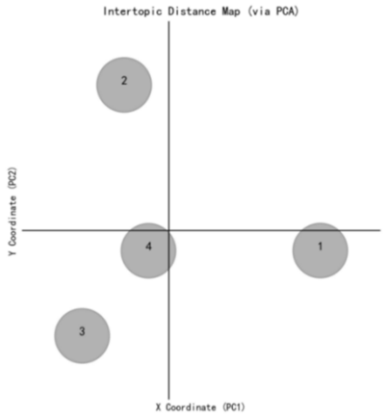


Figure.2. Theme spacing diagram

Table.2. Distribution of "themes and terms" in policy texts

Theme Number	Theme Name	Theme Keywords
Theme 1	Agricultural Development and Rural Economy	Food, new energy, subsidies, financing, standardization, local areas, farmland, automobiles, plastic mulch, village roads, reserves, sales, textiles, clothing, agriculture
Theme 2	Logistics and Supply Chain Management	Logistics, credit, hub, international, assets, emergency response, cold chain, science and technology, center, personnel, transportation
Theme 3	Industrial Agglomeration and Innovative Development	Pilot zone, cluster, park, culture, agriculture, development zone, tourism, outline, informatization, report, national economy, review, talent
Theme 4	Mining Development and Utilization	Survey, quality culture, mineral resources, tourism, demonstration zone, key projects, prospecting rights, address, base, park, minerals, mining rights, naming, geological minerals

In Theme 1:The terms demonstrate that Xinjiang's industrial cluster policies have formed a full-chain support system for agriculture covering "grain production, subsidy policies, rural road construction, and textile employment". Agricultural modernization is promoted through technical specifications such as "standardization" and "plastic film". However, the policies remain insufficient in value chain extension, including intensive processing of agricultural products, brand building, and ecological protection.

In Theme 2:According to terms such as "hub", "cold chain", and "emergency", policies for the logistics system focus on building a modern logistics network centered on "hub layout, cold chain technology, and emergency management", with an emphasis on "internationalization". Nevertheless, insufficient attention is paid to localized

demands such as industrial coordinated development, distribution in remote areas, and multilingual services.

In Theme 3:Policies foster non-resource-based industries through “culture-tourism integration, information construction, and experimental zone innovation”, and establish a “review and evaluation” mechanism. However, problems such as overlapping functions of “parks and development zones” and inadequate supporting measures may weaken the practical implementation effects of the policies.

In Theme 4:Relevant terms show that policies have established a complete management system for mineral resources covering “survey and exploration, mining development, and demonstration bases”, which supports large-scale and intensive development and strengthens the advantages of the resource-based economy. Yet the policies are overly concentrated in the upstream sector, and further improvements are needed in downstream intensive processing, green technologies, and regional coordinated development.

Overall, industrial policies are relatively sound in terms of basic support, but still need to be improved in high-quality development dimensions such as industrial chain extension, sustainable development, and regional coordination.



Figure.3. Policy cluster analysis diagram

3. Construction of the PMC Index Model for Industrial Cluster Policy

3.1 Variable classification and parameter identification

The PMC index model originates from Ruiz Estrada's Omnia Mobilis hypothesis, which posits that all things are in motion and interconnected, with each relevant variable being equally significant and consistent, and thus all should be considered [22]. To overcome selection bias potentially arising from singular literature sources or subjective experience, and to ensure the systematicity, representativeness, and operational feasibility of the indicator system, this study adopted a three-pronged approach combining theoretical underpinnings, text mining, and expert validation when constructing the evaluation framework: First, a systematic review of policy evaluation literature was conducted, drawing upon the Omnia Mobilis hypothesis and variable design methodologies from scholars such as Mao Zijun [23], Fang Siyue [24], and Wang Jinfu [25] to establish a preliminary multidimensional indicator framework. Second, the indicator system

underwent validation and refinement based on policy theme distributions and high-frequency terms identified by the LDA model. Finally, three experts in public policy and industrial economics were invited to assess the indicators' comprehensiveness and rationality. Integrating these processes yielded the PMC Index evaluation system comprising 10 primary variables and 37 secondary variables (see Table 3).

Table.3. Design and Sources of Policy PMC Evaluation Indicator System

Primary variable	Secondary variable	Indicator source
X_1 Policy Content	$X_{1:1}$ Innovation-driven, $X_{1:2}$ Openness, $X_{1:3}$ Infrastructure, $X_{1:4}$ Human Resources, $X_{1:5}$ Industrial Structure Optimization	Based on policy text mining sources
X_2 Incentives	$X_{2:1}$ Institutional Guarantees, $X_{2:2}$ Financial and Tax Support, $X_{2:3}$ Performance Evaluation and Incentives, $X_{2:4}$ Technological Support, $X_{2:5}$ Land Use Guarantees	Based on policy text mining sources
X_3 Policy Objectives	$X_{3:1}$ Politics, $X_{3:2}$ Economy, $X_{3:3}$ Environment, $X_{3:4}$ Culture, $X_{3:5}$ Science and Technology, $X_{3:6}$ Society	Mao Zijun
X_4 Policy Type	$X_{4:1}$ Planning-related (plans, guidelines, regulations, standards, strategies), $X_{4:2}$ Measures-related (measures, policies, regulations, guidelines), $X_{4:3}$ Opinions-related (opinions, decisions)	Fang Siyue et al.
X_5 Policy Evaluation	$X_{5:1}$ Sufficient Basis, $X_{5:2}$ Reasonable Planning, $X_{5:3}$ Clear Objectives, $X_{5:4}$ Scientific Solutions	Wang Jinfu et al.
X_6 Policy Function	$X_{6:1}$ Implementation, $X_{6:2}$ Coordinated Promotion, X6:3 Distinctive Development	Based on policy text mining sources
X_7 Policy Nature	$X_{7:1}$ Forecasting, $X_{7:2}$ Supervision, $X_{7:3}$ Recommendations, $X_{7:4}$ Support	Zhang Yong'an et al.
X_8 Policy Audience	$X_{8:1}$ Enterprises, $X_{8:2}$ Social organizations, $X_{8:3}$ Government, $X_{8:4}$ Research institutions	Wang Si et al.
X_9 Policy Validity Period	$X_{9:1}$ Long-term (involving content spanning more than 5 years), $X_{9:2}$ Medium-term (involving content spanning 3–5 years), $X_{9:3}$ Short-term (involving content spanning 3 years or less)	Estrada
X_{10} Policy Content		

3.2 Assigning values to secondary variable parameters and establishing a multi-input-output table

During the secondary variable assignment phase, a binary scoring method is adopted, whereby variable values are strictly constrained within the interval of [0, 1]. Specifically, a value of 1 is assigned if the policy text fully aligns with the characteristics represented by a given variable; conversely, a value of 0 is assigned if the policy text is irrelevant to or fails to reflect such characteristics. In the stage of constructing the multi-input-output table, the numerical values of each primary and secondary variable are explicitly presented in the table. This approach establishes a more structured framework for the quantitative calculation and evaluation of the strengths and weaknesses of various indicators.

3.3 Calculation of the PMC Index

Building upon the assignment of secondary variables, this study further quantifies the Policy Matching Coefficient (PMC) index for each policy. The specific calculation logic is as follows: Firstly, employing a binary assignment method, all secondary variables undergo standardisation within the 0–1 range based on whether the policy text aligns with the corresponding characteristics, ensuring comparability and consistency between indicators. Secondly, scores for each primary indicator are calculated through weighted aggregation (Formula 1). Let the i-th primary variable comprise n secondary indicators, with its score denoted as X(i):

$$X(i) = \sum_{j=1}^{n} \frac{X(ij)}{N_{X_{ij}}} \qquad (1)$$

Where X_(ij) denotes the assigned value for the jth secondary indicator under the ith primary variable; finally, the scores for the nine primary variables are aggregated to yield the policy's PMC index (Formula 2).

$$PMC = \sum_{i=1}^{9} X(i) \qquad (2)$$

After calculating the PMC index for each policy, the PMC index can be divided into five grades in accordance with the evaluation criteria of the PMC index model proposed by Ruiz Estrada. A higher PMC index indicates a better score, and the detailed grading criteria are presented in Table 4.

Table 4. Policy Level Classification

PMC Index	Evaluation
0~5.99	Poor
6~6.49	Passing
6.5~6.99	Good
7~7.99	Excellent
8~9	Perfect

3.4 Visual output

PMC surface plots and radar charts can objectively present visualized results. ①The PMC surface plot (Equation 3) three-dimensionally displays the 3D evaluation results of each indicator, directly revealing the strengths and weaknesses of policies. ②Radar charts are drawn based on the mean values of all PMC evaluation indicators to clearly show the distribution of indicator means, realizing multi-dimensional visualization measurement and structured evaluation of policies, thus providing a systematic quantitative assessment for policies.

$$PMCcurved\ surface = \begin{bmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{bmatrix} \qquad (3)$$

4. Empirical Research

4.1 Selection of evaluation subjects

Given the large number of policy documents covered in this study, 10 industrial cluster policies and regulations were selected (Table 5) for an objective assessment of policy effectiveness using the PMC model. The selection was conducted based on multiple criteria, including policy level, binding force, and relevance to the core evaluation theme. In terms of policy content, priority was given to policies with the highest legal effect and strong relevance to Xinjiang's Top Ten Industries. Regarding policy structure, core texts explicitly targeting the Top Ten Industry Policies and highly correlated alternative texts were selected. This sampling strategy ensures both the completeness of policy coverage and the representativeness of research objects.

Table.5. Sample Industrial Cluster Policies

Number	Text Name	Date of Publication	Publishing Agency
1	Notice of the General Office of the People's Government of the Xinjiang Uygur Autonomous Region on Issuing the "Fifteen Measures for Promoting High-Quality Development of Industrial Parks (Development Zones)"	2024.12	Autonomous Regional People's Government
2	Notice of the General Office of the People's Government of the Xinjiang Uygur Autonomous Region on Issuing the "Several Measures for Promoting High-Quality Development of the Mining Industry"	2024.9	Autonomous Regional People's Government
3	Notice of the General Office of the People's Government of the Xinjiang Uygur Autonomous Region on Issuing the "Management Measures for Key Projects in the Xinjiang Uygur Autonomous Region"	2024.7	Autonomous Regional People's Government
4	Notice of the Xinjiang Uygur Autonomous Region Industry and Information Technology Department on Issuing the "Xinjiang Uygur Autonomous Region Measures for the Development of Small and Medium-sized Enterprise Specialized Industrial Clusters"	2024.5	Xinjiang Uygur Autonomous Region Industry and Information Technology Department
5	Notice of the Xinjiang Uygur Autonomous Region People's Government Office on Adjusting and Optimizing the Autonomous Region's Cotton and Textile and Apparel Industry Policies and Measures	2024.4	Autonomous Regional People's Government
6	"Several Policy Measures of the Xinjiang Uygur Autonomous Region for Promoting the High-quality Development of the Private Economy"	2023.11	Autonomous Regional Development and Reform Commission
7	Notice of the Xinjiang Uygur Autonomous Region People's Government Office on Issuing the Implementation Plan for Promoting the High-quality Development of Cold Chain Logistics in the Autonomous Region (2023-2025)	2023.10	Xinjiang Uygur Autonomous Region People's Government
8	Notice from the Development and Reform Commission of the Xinjiang Uygur Autonomous Region on the Issuance of the "Several Policy Measures for Supporting the Construction of Hydrogen Energy Industry Demonstration Zones in the Autonomous Region"	2023.8	Autonomous Regional Development and Reform Commission

9	Notice on Accelerating the Coordinated Development of New Energy and Related Industries	2023.5	Autonomous Regional Development and Reform Commission and other three departments
10	Notice on the Issuance of the Action Plan for Further Breaking Through Bottlenecks and Promoting the High-Quality Development of Winter Sports and Winter Tourism in the Autonomous Region (2022–2025)	2022.8	Xinjiang Uygur Autonomous Region People's Government

4.2 Calculation of the PMC Index

Based on the results of the policy text analysis, an input-output table for the ten industrial cluster policies in Xinjiang was first compiled. Subsequently, the PMC indices and their respective means for each policy were calculated using Equations (1) and (2) (Table 6). The findings indicate that the mean PMC index stands at 6.95, with the policies ranked in descending order of effectiveness as follows: P6 > P4 > P1 > P10 > P9 > P7 > P5 > P2 > P8 > P3. The results indicate four "excellent" policies (P1, P4, P6, P10); four "good" policies (P2, P5, P7, P9); and two "passable" policies (P3, P8). While no "perfect" policies were identified, the overall quality is sound. Nevertheless, the policy type (X4) indicator scored only 0.33, reflecting high homogeneity. According to policy portfolio theory, an effective policy system requires balanced allocation of policy instruments. The current singular instrument configuration risks creating a coordination dilemma where 'government enthusiasm is high while enterprise engagement is low,' hindering the mobilisation of social forces. This also indicates that Xinjiang's industrial clusters remain in a phase of strong government dominance, with insufficient tools reserved for transitioning towards multi-stakeholder governance.

Table.6. PMC Index of Xinjiang Industrial Cluster Policy Samples

Variable	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
X1	1.00	0.60	0.60	1.00	0.80	1.00	1.00	1.00	0.60	1.00
X2	0.81	0.81	0.80	0.97	0.97	0.80	0.80	0.81	0.81	0.80
X3	0.83	0.83	1.00	0.83	0.83	1.00	0.83	0.83	0.83	1.00
X4	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
X5	1.00	0.75	0.75	1.00	1.00	1.00	1.00	0.50	1.00	1.00
X6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.67	1.00	1.00
X7	1.00	1.00	0.75	0.75	0.50	1.00	1.00	0.75	1.00	1.00
X8	0.75	0.75	0.50	1.00	1.00	1.00	0.50	1.00	0.75	0.75
X9	0.66	0.66	0.33	0.66	0.33	0.66	0.33	0.33	0.66	0.33
PMC Index	7.38	6.73	6.06	7.55	6.77	7.79	6.80	6.22	6.98	7.22
Depression Index	2.62	3.27	3.94	2.45	3.23	2.21	3.20	3.78	3.02	2.78
Ranking	3	8	10	2	7	1	6	9	5	4
Grade	EX	Good	Pass	EX	Good	EX	Good	Pass	Good	EX

4.3 Drawing PMC surface graphs

The policy PMC surface for Xinjiang's industrial clusters was plotted according to Equation (3), presenting the assessment results through three-dimensional visualisation. The colour gradient across the surface reflects the distribution of PMC scores, with convex regions indicating policy strengths and concave areas corresponding to weaknesses. Comparing the pass-grade policy P3 (Figure 4a) with the excellent policy P6 (Figure 4b) reveals that P6's surface occupies a predominantly upper-middle position within the coordinate system, exhibiting fewer depressions and overall balance. whereas the P3 surface leans towards the lower-middle position with pronounced depressions, revealing weaknesses in dimensions such as timeliness or typology. Across the entire sample, policy surfaces exhibit significant protrusions in traditional areas of strength like energy resource development and agricultural industrialization, while showing widespread depressions in emerging fields such as the digital economy and green low-carbon sectors. This structural characteristic, while linked to Xinjiang's functional positioning as a national energy and resource base, also reflects the policy system's lag in adapting to industrial transformation and upgrading requirements. Overall, the policy effectiveness of Xinjiang's industrial cluster samples meets satisfactory standards, yet structural imbalances persist.

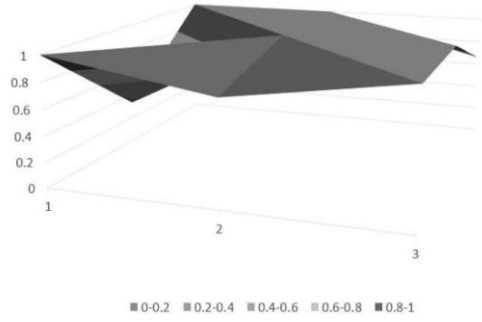


Figure.4a. P3 surface diagram

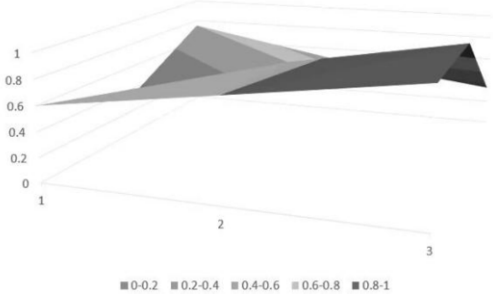


Figure.4b. P6 surface diagram

4.4 Analysis of policy evaluation results

By plotting a radar chart of the mean values of each PMC assessment indicator, it is possible to clearly present the multidimensional characteristics of the overall policy and achieve visual measurement and structured assessment of the policy (Figure 5).

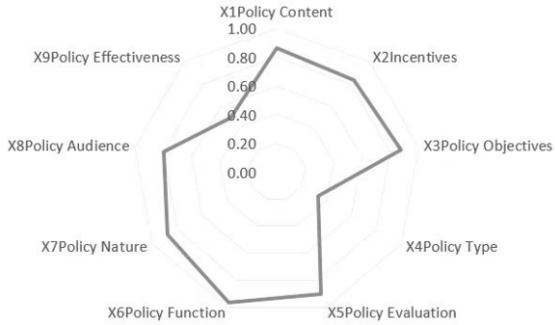


Figure 5. Radar chart showing the average PMC indicators for industrial cluster policies in Xinjiang

The radar chart indicates that Xinjiang's industrial cluster policies score highly across dimensions such as policy content (X1), incentive measures (X2), and policy functionality (X6). This demonstrates that the policy framework has established relatively comprehensive institutional support in traditional areas of strength, including resource development safeguards and industrial agglomeration guidance. This aligns closely with Xinjiang's policy orientation, which leverages its resource endowments to serve national strategic needs. Concurrently, significant disparities exist across policies in the policy audience dimension (X8). This reflects the tension within Xinjiang's industrial cluster policies between government leadership and market-driven approaches. On one hand, as a frontier region, the government must retain a dominant role in resource allocation. On the other, stimulating market vitality and cultivating endogenous growth momentum necessitates policies that are more precisely targeted towards micro-level entities such as enterprises. However, current industrial cluster policies in Xinjiang exhibit structural shortcomings in policy types (X4) and policy timeliness (X9), a situation that may exert systemic impacts on the region's economic development. In summary, while Xinjiang's industrial cluster policies have achieved notable success in safeguarding national strategic resource security and consolidating industrial foundations, they still face structural deficiencies in adapting to industrial transformation and upgrading requirements and cultivating new growth drivers. Future industrial cluster policies in Xinjiang must strike a balance between resource dependency and innovation-led development, government guidance and market-driven forces, as well as short-term effectiveness and long-term strategic planning.

5. Conclusions and Recommendations

5.1 Analysis of the results of research on industrial cluster policies in Xinjiang

From the perspective of policy text mining, Xinjiang’s industrial cluster policies concentrate on four core domains, and diverse policy instruments are adopted to boost cluster development. From the perspective of policy evaluation, the overall assessment of these policies is excellent, reflecting strong scientific rationality and stability. Nevertheless, the comprehensive policy evaluation reveals that there remains considerable room for improvement in Xinjiang’s industrial cluster policies:

Firstly, in terms of the integrity of policy structure, the policies exhibit an obvious structural imbalance characterized by the dominance of traditional industries and inadequate support for emerging industries.

Secondly, regarding the comprehensiveness of policy content, the policies demonstrate a distinct feature of "selective focus". Specifically, excessive preference is given to traditional industries such as energy and agricultural product processing, while insufficient support is provided for culture and tourism, which is designated as the Ninth Major Industrial Cluster.

Thirdly, from the standpoint of policy system coherence, the current industrial cluster policies in Xinjiang suffer from insufficient coverage of sectors, lack of balanced policy supply, and inadequate dynamic flexibility.

Fourthly, in terms of policy effectiveness, Xinjiang's industrial clusters are confronted with dual deficiencies in industrial coordination and industrial chain integration, which hinder the vertical integration of industrial chains and restrain the horizontal synergistic effects among industries.

5.2 Development of industrial cluster policies in Xinjiang and policy recommendations

First, policy coordination and supporting mechanisms should be strengthened to improve industrial linkage and development. Future industrial cluster policies in Xinjiang should focus on building a cluster-based supply chain suitable for the development of small and medium-sized enterprises within clusters, and formulate a complete supporting policy system. This will accelerate industrial correlation and complementarity, enhance inter-industry collaboration, and promote the coordinated and agglomerated development of industries [25].

Second, attention should be paid to the systematic integration of policies to support the coordination of industrial clusters. Targeted improvements should be made in weak areas such as policy coverage, policy types, and policy timeliness to remedy shortcomings as soon as possible. This will help build a more flexible and coordinated industrial ecosystem for Xinjiang's industrial clusters, with a focus on enhancing policy adaptability and long-term effectiveness.

Third, comprehensive policy support should be reinforced to stimulate the diversified value of industries. In future decision-making, the government should gradually increase its focus on policy comprehensiveness and allocate governmental attention more scientifically. Policy support for the culture and tourism industry in Xinjiang's industrial cluster system can be appropriately optimized, and targeted support plans can be formulated according to the current development of the culture and tourism sector.

Fourth, the policy supply structure should be optimized to strengthen the leading role of innovation. Constructing a policy structure that integrates traditional industries and emerging industries is likely to be the key to promoting the sustainable development of Xinjiang's industrial clusters. Based on Xinjiang's actual development conditions and existing industrial foundations, emerging fields such as digitalization and intelligence should be actively incorporated, with supporting policies issued in a timely manner. This will not only follow the trend of scientific and technological innovation but also achieve the in-depth transformation and upgrading of Xinjiang's industries [26].

5.3 Limitations and Outlook

This paper quantifies the assessment of Xinjiang's industrial cluster policies by constructing a hybrid LDA-PMC analytical framework. It expands the boundaries of integrated application between policy text mining and quantitative evaluation, enriches the methodological approaches for quantifying regional industrial cluster policies, and offers insights for more objective understanding and refinement of industrial cluster policy evaluations in future research. Nevertheless, certain limitations remain. For instance, while the policy evaluation indicator system incorporates prior research and text mining outcomes, variable selection retains a degree of subjectivity. Subsequent research may incorporate methods such as the Delphi technique and grounded theory to further enhance the scientific rigour of evaluation indicators. Moreover, while this study primarily focuses on the quantitative evaluation of policy texts themselves, future research could build upon this foundation by integrating policy implementation outcomes to conduct more comprehensive empirical studies on Xinjiang's industrial cluster policies, thereby achieving a synthesis of theory and practice.

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Bridging the Talent Gap: Interdisciplinary Talent Cultivation from the Perspective of Job Market Demand

Xiuli JING[a], Yining SUN[a], Haiyi HUANG[a], Kaihan YOU[a], Yu ZENG[a], Wei Li[b,1] and Luying Chen[b,2]
[a] *Shenzhen Campus, Jinan University, Shenzhen, Guangdong, China. 518053*
[b] *Undergraduate School, Jinan University, Guangzhou, China. 510632*
ORCiD ID: Xiuli JING https://orcid.org/0000-0003-3634-684X

Abstract. The rapid evolution of the fintech sector is intensifying a critical structural mismatch between talent supply and demand. Although the need for fintech professionals is growing exponentially, traditional single-discipline higher education approaches persistently fail to equip students with the interdisciplinary knowledge and applied skills required to address evolving industry needs. To bridge this gap, this study employs a quantitative approach integrating text mining and word frequency analysis to identify competency demands of core fintech positions. Based on these findings, we propose an integrated three-pillar talent cultivation model. This model systematically integrates professional competencies, advanced technologies, and practical application scenarios into a cohesive framework designed to produce industry-ready professionals. Our work extends pathways for interdisciplinary talent cultivation and offers an actionable framework to align fintech education with evolving market demands.

Keywords. Fintech, Interdisciplinary Studies, Talent Cultivation, Job Positions, Integrated Three-Pillar Model

1. Literature Review and Theoretical Exploration

1.1. Structural Mismatch in Talent Supply and Demand and Market Status

By 2025, the development of fintech talent is experiencing rapid growth, yet remains undersupplied. According to the *White Paper on Enterprise Digital Talent Development* released by iResearch and Alibaba Cloud, persistent fintech talent shortages are prompting governments and enterprises to accelerate talent cultivation efforts. The structural mismatch between talent supply and demand has become a key constraint on fintech industry development. This imbalance reflects a disconnect between existing cultivation systems and actual industry needs, manifesting in insufficient talent supply, misaligned cultivation structures, and a gap between educational objectives and practical requirements. Such a mismatch originates from the rapid upgrading of fintech skill requirements while educational offerings fail to advance at the same pace. In the AI era, core technologies such as artificial intelligence, big data, and blockchain are evolving rapidly, creating surging demand for interdisciplinary professionals. However, fintech

[1] Corresponding Author: Wei Li, Email: jnuliwei@126.com.
[2] Corresponding Author: Luying Chen, Email: clyjndx@163.com.

education in higher institutions has not fully integrated or updated training in these core technologies in a timely manner, leading to a noticeable mismatch between students' capabilities and enterprise job requirements[1]. In China's fintech market, a survey of 112 Shanghai-based financial enterprises revealed that most companies face a shortage of interdisciplinary talent[2]. Research further indicates that this structural mismatch may exacerbate labor resource misallocation, resulting in broader structural distortions in the labor market and negatively affecting economic efficiency[3].

1.2. Analysis of Talent Supply-Demand Alignment and Theoretical Exploration

To address the structural mismatch between talent supply and demand, contemporary talent cultivation must prioritize cultivating interdisciplinary professionals whose competencies align with specific job requirements in China's fintech labor market. Existing research conceptualizes fintech competency as a multidimensional construct integrating specialized financial knowledge, technical skills, and scenario application capabilities. These three dimensions of competency emerge from the rapid convergence of financial technologies and the co-evolution of industry practices[4]. Theoretically, the professional competency dimension focuses on the financial knowledge framework and risk management capabilities, enabling individuals to operate efficiently within complex financial environments. Simultaneously, the disconnect between higher education curricula and industry demands is a primary factor contributing to skill shortages in technology-intensive fields like fintech[5]. In fintech talent cultivation, universities play a pivotal role, and the effective achievement of higher education institutions' objectives in fintech talent cultivation will provide a solid foundation and institutional guarantee for talent development[6]. Consequently, fintech talent cultivation must integrate digital and analytical competencies into financial education to ensure graduates possess technological adaptability. Furthermore, application-oriented capabilities emphasize the ability to translate specialized technical knowledge into practical scenarios. Effective talent cultivation requires establishing contextualized learning mechanisms that bridge theoretical instruction with industry applications, thereby enhancing employability and labor market matching efficiency. However, despite this conceptual consensus on multidimensional competencies, there is a scarcity of data-driven evidence identifying which specific competencies are prioritized by employers in China's evolving fintech market. This gap limits the ability of educators to design targeted cultivation programs. Therefore, this study focuses on China's domestic fintech labor market, examining competency requirements reflected in job postings. The study consists of two parts: first, a quantitative analysis of fintech job positions in China to identify core competency requirements; second, the construction of a talent cultivation model grounded in empirical job-market evidence and existing education theory. The proposed model aims to directly translate market insights into an actionable educational framework, thereby helping to align talent cultivation with the specific, evolving requirements of the fintech industry.

2. Text Analysis of Fintech Job Positions in the Chinese Local Context

2.1. Research Design

2.1.1. Research Methods and Logic

This study employs a quantitative approach integrating text mining and word frequency analysis to identify competency demands by analyzing keywords in recruitment texts for core fintech positions. This approach is particularly suited to handling unstructured textual data. Methodologically, it aligns with the paradigm described by Kraussl and Loges[2], thereby ensuring rigor. Substantively, it directly addresses the core research objective of quantifying the competency requirements of fintech positions in China.

2.1.2. Data Source and Sample Selection

Data is retrieved from three primary online recruitment platforms in China (Boss Zhipin, 51job, Liepin). Selected for extensive fintech job coverage, timely updates, and diverse enterprise representation, these platforms ensure robust sample validity. The time frame (January 2022 to December 2024) balances demand stability and trendiness. After excluding duplicates and incomplete entries, 300-500 valid samples were retained: 180-250 for fintech product managers and 120-250 for data analysts. This sample size is adequate for applying unstructured text analysis techniques.

2.1.3. Research Questions

To address the core objective of aligning talent cultivation with market demand, we have formulated two primary research questions:

RQ1: What are the key dimensions into which the core competency requirements for fintech product managers and data analysts in China can be categorized?

RQ2: What are the demand differences between these two positions regarding professional knowledge, technical skills, and scenario application capabilities?

These questions are designed to accomplish two core tasks: identifying competency requirements of fintech positions in China and comparing the specific requirements across key fintech roles. By doing so, they help to resolve the structural talent supply-demand mismatch and provide a precise, evidence-based foundation for developing an effective talent cultivation model.

2.2. Analysis Results of Core Job Demands

Based on word frequency statistics, word cloud analysis (as shown in Figures 1 & 2), and the “competence-technology-scenario” framework, the findings that address the research questions are summarized below.

2.2.1. Demand Results for Fintech Product Manager Positions

The word cloud analysis (Figure 1) reveals the top five high-frequency keywords: “product”, “business”, “ability”, “management”, and “experience”. These keywords collectively point to three core competency dimensions, which directly address RQ1.

Professional competence: This dimension, signified by keywords such as “finance,” “risk,” and “management,” requires solid knowledge of financial markets and risk

management frameworks. It also entails proficiency in product lifecycle management and cross-departmental project coordination.



Figure 1. Keyword Cloud of Fintech Product Manager Position Information



Figure 2. Keyword Cloud of Fintech Data Analyst Position Information

Technology adaptation capability: Keywords including "technology," "data," and "analysis" underpin this dimension. It involves understanding the application boundaries of emerging technologies like AI and blockchain in finance, coupled with practical skills in product prototyping and the use of basic data analytics tools.

Scenario application capability: Evidenced by terms like "business," "customer," and "ecosystem," this dimension focuses on the precise identification of customer pain points within specific scenarios, such as small/micro-enterprise credit and personal wealth management. Furthermore, it necessitates the cross-departmental communication skills required to drive a product from design to implementation.

2.2.2. Demand Results for Fintech Data Analyst Positions

The word cloud for data analyst positions (Figure 2) highlights the top five high-frequency keywords: "data", "analysis", "model", "finance", and "risk". The corresponding competency demands coalesce into three distinct dimensions, addressing RQ1 as follows.

Professional competence: Signified by keywords such as "finance," "management," and "risk," this dimension requires an in-depth understanding of core financial business logic, including credit assessment and risk control. Analysts must be capable of

translating data insights into actionable strategies for risk management and resource allocation.

Technology application capability: Dominated by keywords like "data," "model," and "tool," this dimension emphasizes technical proficiency. Essential skills include mastery of data processing tools (e.g., Python, SQL) and the ability to perform data cleaning, statistical modeling, and in-depth data mining.

Scenario application capability: Reflected in terms such as "business," "industry," and "customer," this dimension focuses on practical application. Analysts are required to tailor their analyses to specific business scenarios, such as credit risk control and market trend forecasting, and effectively translate analytical results into decision support that addresses concrete business needs.

2.2.3. Demand Difference Results Between the Two Types of Positions

To address RQ2, the analysis reveals key differences between the two roles.

Professional competence: Product managers emphasize "product design and project management"; data analysts focus on "business logic and risk strategy formulation".

Technical skills: Product managers require "technology understanding and basic application"; data analysts demand "technical operation and modeling capabilities".

Scenario application: Product managers concentrate on "customer demand mining and product implementation"; data analysts focus on "scenario-based data interpretation and decision output".

2.3. Result Discussion and Connection with Existing Research

This section contextualizes findings with extant literature to enhance depth:

Consistent with prior findings of Kraussl and Loges[2], this study provides evidence from China that the demand for fintech talent centers on professionals who integrate financial knowledge with technical skills. The high-frequency co-occurrence of "finance" and "technology" in our word cloud analysis offers concrete, localized empirical support for this conclusion.

Prior research has highlighted that fintech talent requires an integration of finance, data science, and AI education[1]. Responding to this, our study refines job-specific differences: product managers need finance, management, and scenario skills, whereas data analysts require finance, technology, and data competencies. This refinement fills the gap of insufficient attention to segmented demands in prior research.

Corroborating Zhang and Tan's conclusion on the importance of industry practical experience[6], the high frequency of "experience" in job postings for both positions underscores the necessity of integrating practical training into talent cultivation.

In summary, Chinese fintech core positions exhibit three universal demand dimensions (competence, technology, scenario) with distinct position-specific focuses (responding to RQ1 and RQ2). This empirical evidence directly addresses the structural talent supply-demand mismatch and provides a precise, evidence-based foundation for developing an effective talent cultivation model.

3. An Integrated Talent Cultivation Model Built on Three Interconnected Pillars

Based on the empirical and theoretical foundations established, the following section presents an integrated model for fintech talent cultivation. This model, grounded in the job-market evidence and education theory discussed, is structured around three core pillars: professional competence, advanced technologies, and application scenarios (see Figure 3). Its objective is to translate these insights into viable pathways and future-oriented strategies for developing skilled fintech professionals.

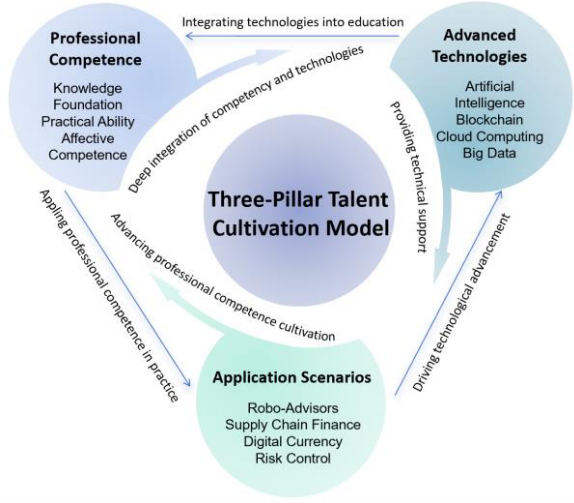


Figure 3. Fintech Talent Cultivation Model

3.1. Professional Competence

Professional competence, which is essential for students to become fully capable in their future roles, forms a fundamental pillar within the fintech talent cultivation model. Universities should establish educational programs centered on the development of professional competence in areas including resource integration, risk management, and financial innovation. These programs, for instance, should enable students to comprehend how financial resources flow among market participants and develop their understanding of resource allocation mechanisms. They should also facilitate the development of competencies in identifying, measuring, and hedging various financial risks, including credit, market, and operational risks, thereby enabling students to operate effectively in volatile financial environments[7]. Furthermore, the programs should encourage and mentor students to design financial products that respond to evolving market needs. This competency-driven approach aims to consolidate students' financial expertise and prepare them to meet the sophisticated requirements of the fintech sector.

An integrated approach to developing professional competence combines three key components: professional curriculum, simulated learning platforms, and project-based learning. The curriculum establishes a theoretical foundation through core courses such as Corporate Finance, Financial Markets, and Financial Risk Management, strengthening students' understanding of financial principles and practices. Simulated platforms, including virtual trading systems and risk modelling laboratories, enable students to

apply this knowledge using real market data for practical tasks like asset allocation and risk assessment. Finally, project-based workshops immerse students in real business challenges, such as portfolio management and financial product design, enhancing their ability to analyze needs and devise innovative solutions.

3.2. Advanced Technologies

Developing technical talent has always been a key focus in fintech education. With technology continuously reshaping financial activities, integrating technical skills into finance education has become indispensable for preparing students to meet industry demands[8]. This is reflected in the growing emphasis on incorporating knowledge from advanced technologies such as AI and big data into education[9] and the increasing focus on cultivating students with interdisciplinary expertise across finance, technology, and data analytics[10].

To effectively embed technical knowledge into finance education, a structured and systematic pedagogical approach is required. A typical learning path commences with foundational tools such as Python and SQL, then progresses to machine learning modeling and blockchain technology. Throughout this process, students develop a comprehensive understanding of how these technologies function within different financial environments. The inclusion of industry-leading technologies within the curriculum provides students with insights into advanced professional practice. This hands-on exposure not only motivates students to actively follow industry trends but also establishes a robust foundation for their long-term career growth, equipping them with the key skills required in the fintech sector.

3.3. Application Scenarios

Real-world scenarios offer students valuable opportunities to integrate professional competence with technical skills. For example, in credit risk management scenarios, students learn to apply financial risk control principles alongside big data modelling techniques to develop effective strategies. This approach helps bridge the gap between theoretical understanding and practical implementation. To further strengthen this connection, financial institutions and universities should develop close partnerships. Through initiatives such as fintech forums, internship programs, and scholarship schemes, these collaborations introduce students to authentic fintech application scenarios. Such industry engagement helps align academic training with actual workplace requirements while creating more direct pathways for talent development[11]. Furthermore, these authentic scenarios facilitate a seamless transition from theoretical knowledge to practical application, effectively preparing students to meet the complex demands of the fintech sector.

3.4. Bidirectional Integration Among Pillars: Building an Interactive Enhancement Loop of "Competence-Technology-Scenario"

The operation of the proposed talent cultivation model entails a synergistic linkage and bidirectional integration among its three core pillars. This interplay establishes a self-reinforcing loop of "theoretical grounding, technological enablement, and scenario internalization," collectively fostering the high-quality cultivation of fintech talent.

Professional competence defines the value orientation and business logic for technology application, while technology provides powerful tools for validating financial theories and simulating complex decision-making. The key to this integration lies in ensuring that the introduction of cutting-edge technology serves and enhances professional judgment. For instance, in highly regulated scenarios like credit risk control, complex machine learning models must address "black box" issues to meet audit requirements. Research demonstrates that by constructing explainable machine learning frameworks, it is entirely possible to achieve transparency comparable to traditional methods while maintaining high predictive performance, thereby deeply integrating technological advantages with professional compliance[12].

The value and efficacy of technology can only be fully validated and iterated within concrete, real-world business scenarios. Therefore, the training process should center on scenario-based, project-driven challenges. Guide students to integrate data analytics, machine learning, or blockchain tools to address real-world problems like "robot-advisor strategy design" or "blockchain solutions for supply chain finance." This problem-driven approach to technology learning has been proven to significantly enhance students' technical comprehension, complex problem-solving abilities, and skill transfer efficiency from classroom to workplace[13].

Dynamic real-world scenarios demand advanced, comprehensive, and adaptive professional competencies, which in turn catalyze the deepening and reconfiguration of theoretical knowledge. In fintech practice, professionals must not only apply financial principles but also holistically consider technological ethics, data compliance, and user experience. For instance, as clients gain increasing information symmetry, the professional role of financial advisors is evolving from mere information providers to educators and planners who enhance clients' financial literacy[14]. This profoundly reveals how evolving application scenarios continuously reshape the core essence and value dimensions of professional competencies.

In summary, the three pillars establish a synergistic ecosystem for cultivating talent. This ecosystem elevates the competencies of interdisciplinary students from knowledge acquisition to innovative application, thereby bridging the gap between theoretical training and the evolving demands of the fintech industry.

4. Conclusion

Based on a quantitative analysis of China's fintech job market and grounded in established education theory, this study has developed an integrated talent cultivation model built on three pillars: professional competence, advanced technologies, and application scenarios. By synergizing these three dimensions, it effectively bridges macro-level labor market demands with micro-level cultivation program design, thereby facilitating collaboration among universities, financial institutions, and industry associations. The study makes two primary contributions. First, it enriches the theoretical framework for cultivating interdisciplinary talent. Second, it offers a transferable analytical framework for cultivating talent in emerging, interdisciplinary fields within economics and management. However, some limitations still exist in this study. The empirical data are drawn primarily from leading public recruitment platforms, which may not capture the full spectrum of talent demand. Besides, the focus on the fintech sector may limit the immediate generalizability of the findings. To address these limitations and advance the field, future research should: (1) diversify data sources by

incorporating a wider range of industries and recruitment channels, and (2) incorporate additional disciplinary perspectives into the proposed three-pillar framework to develop a comprehensive analysis of interdisciplinary talent cultivation pathways.

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Differential Effects of Challenge and Hindrance Stressors on Librarians' Job Burnout in China: The Mediating Role of Stress Appraisal

Jili Chen and Wenming Xing[1]
School of Public Administration, Xiangtan University, China
ORCID ID: Jili Chen https://orcid.org/0000-0002-7103-3075

Abstract. Job burnout among librarians undermines individual well-being, service quality, and the public image of libraries. Building on Cognitive appraisal theory of stress and the challenge-hindrance stressor framework, this study examines whether librarians' cognitive appraisal of stress explains how different stressor types relate to burnout. Survey data were collected from librarians in China (N = 194) using validated measures of challenge stressors, hindrance stressors, stress appraisal (challenge appraisal and hindrance appraisal), and burnout (emotional exhaustion, depersonalization, diminished personal accomplishment). Structural equation modeling (SEM) and bootstrapped mediation tests show that: (1) librarians experience both challenge and hindrance stressors, and stressor type relates differently to burnout dimensions; (2) hindrance stressors exhibit stronger and more consistently adverse associations with burnout than challenge stressors; and (3) stress appraisal significantly mediates the relationship between stressors and burnout, with negative (hindrance) appraisal generally transmitting stressor effects more robustly. These findings indicate that reducing bureaucratic and ambiguous demands (hindrance stressors) and improving appraisal-related resources may be more effective than broadly "reducing workload" alone.

Keywords. job stressors; stress appraisal; job burnout; Cognitive appraisal theory of stress; challenge-hindrance stressors; librarians

1 Introduction

Librarians are often perceived as working in a relatively calm and stable environment. However, empirical evidence suggests that librarians frequently report low occupational well-being and face meaningful work pressure, anxiety, and burnout [1-2]. Burnout typically manifests as emotional exhaustion, disengagement, reduced enthusiasm, and weakened professional efficacy-outcomes that can harm both employees and service recipients.

Prior studies have explored librarian burnout from cultural, organizational, and psychological perspectives (e.g., work environment, management systems, professional

[1] Corresponding Author: Wenming Xing (ORCID:0000-0001-8605-9107), School of Public Administration, Xiangtan University, Xiangtan, Hunan Province, China; Email: xwm789@126.com. Jili

status, emotional labor, technostress) [3-4]. While valuable, much of this literature emphasizes what predicts burnout rather than how stress translates into burnout, and often treats job stress as a single undifferentiated construct.

A key unresolved question is: why do librarians exposed to similar work conditions exhibit different burnout levels? Pressure-Cognitive Interaction Theory argues that stress responses depend not only on external demands but also on individuals' cognitive appraisals of those demands [5]. At the same time, the challenge-hindrance stressor framework suggests that stressors vary in their functional meaning: some are growth-oriented challenges, while others obstruct goals [6].
This study addresses the gap by:

- separating job stressors into challenge and hindrance categories,
- modeling stress appraisal (challenge appraisal vs. hindrance appraisal) as a psychological mechanism, and
- testing these relationships across three burnout dimensions using SEM and bootstrapped mediation.

2 Literature Review and Theoretical Background

2.1 Job stress and burnout

Occupational stress is widely recognized as a risk factor for adverse mental health outcomes, including burnout [7-8]. Burnout is commonly conceptualized as a syndrome resulting from chronic workplace stress that has not been successfully managed [9], and is typically operationalized as emotional exhaustion, depersonalization (cynicism/disengagement), and reduced personal accomplishment [10].

Although stress is generally associated with burnout, research increasingly emphasizes that stressor type and psychological interpretation shape whether stress depletes energy, undermines motivation, or triggers withdrawal behaviors.

2.2 The challenge-hindrance stressor framework

The challenge-hindrance stressor model differentiates job stressors into:

- **Challenge stressors**: demanding but potentially rewarding stressors that may foster learning or achievement (e.g., workload, time urgency, task complexity) [11].
- **Hindrance stressors**: obstacles perceived as constraining goal attainment and growth (e.g., bureaucracy, role ambiguity, conflicting demands, inadequate support) [12].

This distinction is particularly relevant for library work, where professional tasks can include both meaningful challenges (service improvement, skill demands) and obstructive burdens (administrative red tape, unclear responsibilities) [13-14].

2.3 Cognitive appraisal theory of stress

Cognitive appraisal theory of stress proposes that stress is produced through person-environment interaction and depends on cognitive appraisal [15]. The same stressor can elicit different reactions depending on whether it is appraised as:

- **challenge appraisal** (positive, growth-related interpretation), or
- **hindrance appraisal** (negative, obstructive interpretation).

Appraisal or perception of stress is therefore a plausible mechanism explaining heterogeneity in burnout among individuals facing similar stressors.

2.4 Conservation of resources perspective

Conservation of resources theory complements appraisal theory by clarifying why appraisals matter: individuals try to protect limited resources (time, energy, emotional capacity) [16]. Stressors appraised as unrewarding or uncontrollable are more likely to be associated with resource loss spirals and burnout [17-18].

3 Conceptual Model and Hypotheses

Figure 1 presents the conceptual model. Challenge and hindrance stressors are expected to relate to burnout dimensions directly and indirectly through stress appraisal.

H1 (Main effects): Job stressors are associated with librarians' burnout.

- **H1a:** Challenge stressors are significantly associated with burnout dimensions.
- **H1b:** Hindrance stressors are significantly associated with burnout dimensions.
- **H1c:** Hindrance stressors have stronger adverse associations with burnout than challenge stressors.

H2 (Mediation): Stress appraisal mediates the relationship between stressors and burnout.

- **H2a:** Challenge appraisal mediates stressor-burnout relationships.
- **H2b:** Hindrance appraisal mediates stressor-burnout relationships.

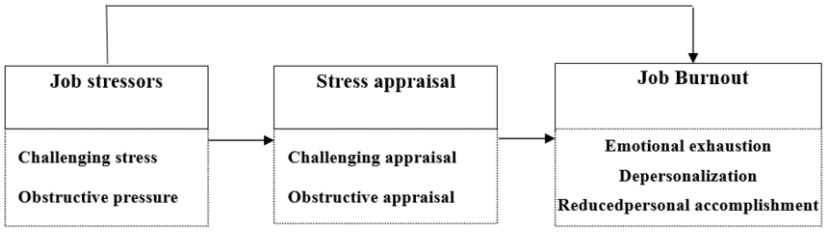


Figure 1. Conceptual model linking job stressors (challenge/hindrance), stress appraisal (challenge/hindrance), and burnout (EE/DE/DPA).

4 Methodology

4.1 Study design and procedure

This study used a two-stage survey design:

- **Pilot survey** (n = 51) to conduct exploratory factor analysis and refine items.
- **Main survey** (N=194 valid responses) administered online to librarians via a large professional QQ group ("Librarians' Hall") to broaden reach beyond a single institution. Participation was voluntary and anonymous.

4.2 Participants and sampling

The target population was practicing librarians. Sampling combined accessibility-based recruitment (pilot) and online recruitment (main survey). After excluding invalid responses (e.g., missing core items), 194 valid questionnaires were retained.
Demographic composition (summary): respondents were predominantly female (74.7%); most were aged 30-50; most held bachelor's degree or above (92.8%); most worked in university libraries (70.1%); tenure was generally long (majority >10 years).

Table 1 basic information of sample objects

Item		Frequency	Percentage
Gender	Male	49	25.3
	Female	145	74.7
Age	under 30	29	14.9
	30-40 years old	77	39.7
	41-50 years old	61	31.4
	Over 51 years old	27	13.9
Education level	junior college or below	14	7.2
	Undergraduate	92	47.4
	Master	84	43.3
	Doctor	4	2.1
Years of service	less than 3 years	34	17.5
	3-10 years	47	24.2
	10-20 years	62	32
	More than 20 years	51	26.3
Do you have any library science education experience?	Yes	112	57.7
	No	82	42.3

Title	Assistant Librarian	47	24.2
	Librarian	87	44.8
	Associate Research Librarian	48	24.7
	Research Librarian	12	6.2
Position	General librarian	109	56.2
	Department deputy director	15	7.7
	Department head	41	21.1
	Assistant curator	2	1.0
	Deputy curator	15	7.7
	Curator	8	4.1
	Others	4	2.1
Unit type	Public Library	39	20.1
	University Library	136	70.1
	Other libraries	16	8.2
	Other units	3	1.5

4.3 Measures

All substantive constructs used a 6-point Likert scale (1 = strongly disagree, 6 = strongly agree).

- **Job stressors (challenge and hindrance stressors):** Items were adapted from established challenge/hindrance stressor measures, contextualized for librarian work. The final stressor scale included two dimensions: challenge stressors and hindrance stressors.
- **Stress appraisal (challenge appraisal and hindrance appraisal):** Appraisal was measured with two subscales: challenge appraisal (positive interpretation) and hindrance appraisal (negative interpretation).
- **Job burnout:** Burnout was assessed using a Chinese-adapted version of the MBI-GS approach, operationalized as three dimensions: emotional exhaustion (EE), depersonalization (DE), and diminished personal accomplishment (DPA).

4.4 Questionnaire language and translation

The survey was administered in Chinese. Several measures have Chinese precedent versions; where items originated from English-only instruments, they were adapted into Chinese and refined through pilot testing for clarity and cultural fit. The survey was conducted anonymously, and no direct identifiers were collected.

4.5 Statistical analysis plan (hypothesis-test mapping)

Analyses were conducted using SPSS and AMOS.

(1) Step 1: Descriptive statistics for all variables.

(2) Step 2: Measurement model assessment using CFA: standardized loadings, CR, AVE, and discriminant validity (Fornell-Larcker). Reliability (Cronbach's α) was reported for each subscale.

(3) Step 3: Structural model tests (SEM) for H1a-H1b: paths from challenge and hindrance stressors to EE, DE, DPA.

(4) Step 4: Strength comparison for H1c: compare standardized effects (hindrance vs. challenge) on each burnout dimension (ideally via constraints/Wald tests; in this paper we interpret relative magnitude using reported standardized coefficients).

(5) Step 5: Mediation tests for H2a-H2b using bootstrapped indirect effects with 95% confidence intervals.

4.6 Hypotheses and corresponding tests

Table 2 Hypotheses and corresponding tests

Hypothesis	Relationship	Statistical test / evidence
H1a	Challenge stressor → EE, DE, DPA	SEM path coefficients (β, p)
H1b	Hindrance stressor → EE, DE, DPA	SEM path coefficients (β, p)
H1c	Hindrance effect > challenge effect	Compare standardized β magnitudes (preferably Wald/constraint tests)
H2a	Mediation via challenge appraisal	Bootstrap indirect effects (CI excludes 0)
H2b	Mediation via hindrance appraisal	Bootstrap indirect effects (CI excludes 0)

5 Results

5.1 Reliability and measurement model (CFA)

Cronbach's α values for the subscales indicated acceptable-to-good internal consistency (most ≥ .78). Because challenge appraisal and hindrance appraisal represent conceptually opposite dimensions rather than a single homogeneous scale, reliability was interpreted at the subscale level rather than for an aggregated "overall appraisal" score.

Table 3 Reliability test results of the scale

Construct and dimension	Cronbach's a Coefficient	Half reliability
Working pressure	0.895	0.663
Challenging pressure	0.859	0.830
Obstructive pressure	0.887	0.844
Work stress cognition	-0.607	-4.836
Challenging stress cognition	0.843	0.822
Obstructive stress cognition	0.835	0.800
Job burnout	0.745	-0.093
Emotional exhaustion	0.903	0.912
Depersonalization	0.882	0.892
Diminished Personal Accomplishment	0.789	0.785

CFA indicated that item loadings were generally ≥ .50, and CR values exceeded .70 for the latent variables. AVE values were mostly around or above .50, supporting convergent validity. Discriminant validity was supported using the Fornell-Larcker criterion: the square root of each construct's AVE exceeded its correlations with other constructs.

5.2 Correlations and descriptive

Challenge and hindrance stressors were positively correlated. Appraisal dimensions were negatively correlated (challenge appraisal vs. hindrance appraisal). Emotional exhaustion and depersonalization were positively correlated, and both were negatively related to diminished personal accomplishment. Challenge appraisal was associated with lower exhaustion and depersonalization and higher accomplishment, while hindrance appraisal showed the opposite pattern.

Table 4 Correlation analysis results of each dimension of construction

	M	SD	CS	HS	CA	HA	EE	DE	DPA
CS	4.032	0.939	**0.686**						
HS	3.631	1.111	0.432**	**0.759**					
CA	4.651	1.029	-0.041	-0.356**	**0.817**				
HA	2.461	0.965	0.186**	0.443**	-0.709**	**0.823**			
EE	2.630	1.026	0.359**	0.491**	-0.382**	0.511**	**0.840**		
DE	2.656	1.114	0.050	0.513**	-0.629**	0.589**	0.566**	**0.811**	
DPA	4.872	0.649	0.155*	-0.088	0.370**	-0.330**	-0.210**	-0.379**	**0.678**

5.3 Hypothesis tests: main effects (H1a-H1c)

SEM model fit was acceptable (χ^2/df = 1.936; RMSEA = 0.070; IFI = 0.901; TLI = 0.888; CFI = 0.900; GFI and NFI slightly below .90, which is common in complex models with multiple indicators).

(1) H1a: Challenge stressor effects on burnout

Table 5 Challenge stressor effects on burnout (H1a)

variable	Standardized estimates	C.R.	P value
Challenge stressor → Emotional exhaustion	0.075	0.902	0.367
Challenge stressor → Depersonalization	-0.349	-3.898	***
Challenge stressor → Diminished personal accomplishment	0.397	3.702	***

Conclusion for H1a: Partially supported. Challenge stressors were significantly associated with depersonalization and diminished personal accomplishment, but not emotional exhaustion.

(2) H1b: Hindrance stressor effects on burnout

Table 6 Hindrance stressor effects on burnout (H1b)

variable	Standardized estimates	C.R.	P value
Hindrance stressor → Emotional exhaustion	0.546	5.859	***
Hindrance stressor → Depersonalization	0.782	7.300	***
Hindrance stressor → Diminished personal accomplishment	-0.317	-3.152	0.002**

Conclusion for H1b: Supported. Hindrance stressors showed consistent adverse associations with burnout dimensions (higher EE and DE; lower accomplishment).

(3) H1c: Hindrance stressors have stronger adverse effects than challenge stressors

Comparing standardized coefficients, hindrance stressors showed substantially larger positive effects on emotional exhaustion (0.546 vs. 0.075) and depersonalization (0.782 vs. -0.349) than challenge stressors, and the direction of effects was also more uniformly adverse across dimensions.

Conclusion for H1c: Supported (based on coefficient magnitude and consistency). Hindrance stressors exhibited stronger and more consistently harmful associations with burnout than challenge stressors.

5.4 Mediation tests: stress appraisal (H2a-H2b)

Bootstrapped mediation analyses examined indirect effects through challenge appraisal (CA) and hindrance appraisal (HA).

(1) H2a: Mediation via challenge appraisal

Based on the reported indirect effects:

- For **challenge stressor → CA → burnout**, indirect effects were generally **not significant** (confidence intervals included zero), indicating limited mediation through challenge appraisal for challenge stressors.
- For **hindrance stressor → CA → burnout**, indirect effects were **significant** for emotional exhaustion, depersonalization, and diminished personal accomplishment (CIs excluding zero), indicating that challenge appraisal transmits part of the hindrance stressor effect.

Conclusion for H2a: Partially supported. Challenge appraisal served as a mediator primarily for hindrance stressors, not for challenge stressors.

(2) H2b: Mediation via hindrance appraisal

Hindrance appraisal showed significant indirect effects linking both challenge and hindrance stressors to burnout in multiple paths (with several indirect-effect CIs excluding zero). Overall, hindrance appraisal functioned as a robust mechanism amplifying burnout across stressor types.

Conclusion for H2b: Supported. Hindrance appraisal significantly mediated stressor-burnout relationships across multiple burnout dimensions.

6 Discussion

6.1 Summary of findings

This study shows that librarians experience both challenge and hindrance stressors, but the two stressor types relate differently to burnout. Hindrance stressors are the most consistent drivers of emotional exhaustion and depersonalization and are negatively related to accomplishment [19-20]. Stress appraisal explains part of these associations: negative appraisal (hindrance appraisal) is a particularly strong pathway through which stressors translate into burnout [21].

6.2 Interpreting the "challenge stressor" pattern

Challenge stressors did not significantly increase emotional exhaustion in this sample, and were negatively associated with depersonalization. This may reflect that challenge demands in librarianship can maintain meaning and engagement even when demanding. At the same time, challenge stressors were positively associated with diminished personal accomplishment, suggesting that heavy demands may undermine perceived efficacy when tasks exceed available resources or training [22].

6.3 Theoretical implications

The findings support Cognitive appraisal theory of stress: appraisal is not a minor "attitude" variable but a mechanism shaping stress outcomes [23-24]. The results also refine challenge-hindrance logic in librarianship: hindrance stressors are especially toxic because they are appraised as obstructive, uncontrollable, and unrewarding, accelerating resource loss and burnout [25-26].

7 Practical Implications

7.1 Reduce hindrance stressors at the management level

Target role ambiguity, conflicting demands, excessive bureaucracy, and insufficient support-these were the strongest drivers of exhaustion and depersonalization.

7.2 Strengthen appraisal-supportive resources

Supervisor communication, feedback clarity, autonomy, and skill development can shift how stressors are appraised, reducing the tendency to interpret demands as obstructive.

7.3 Support efficacy under high challenge demands

Because challenge stressors related to diminished accomplishment, interventions should include training, realistic workload allocation, and tools that improve task mastery.

8 Limitations and Future Research

This study has several limitations. First, participants were recruited mainly through a professional online group, which may overrepresent more engaged librarians and limit generalizability beyond the sampled context. Second, the cross-sectional design restricts causal inference; although the model is theoretically grounded, reciprocal relationships between stress appraisal and burnout cannot be excluded. Longitudinal or multi-wave designs are recommended to validate causal pathways. Third, all measures relied on self-reported data, which may introduce common method bias despite statistical controls. Future research should incorporate multi-source or objective indicators where feasible. Fourth, although the measurement model demonstrated

acceptable reliability and validity, a fully documented forward–back translation process and formal measurement invariance testing were not conducted, limiting cross-cultural generalizability. Finally, this study focused on mediation effects and did not examine potential moderators (e.g., social support, leadership style, or job resources). Extending the model to include boundary conditions and cross-context comparisons would further clarify the mechanisms underlying librarian burnout.

9 Conclusion

By integrating the challenge-hindrance stressor framework with Cognitive appraisal theory of stress, this study clarifies why librarians experiencing similar stressors may exhibit different burnout levels. Hindrance stressors are the most consistently harmful and operate partly through negative appraisal. Effective burnout prevention in libraries should therefore prioritize reducing bureaucratic and ambiguous demands and strengthening appraisal-supportive resources, rather than focusing only on workload reduction.

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Research on the Consumption Psychology and Behavior of Generation Z Towards "Guochao" Products Based on the Howard-Sheth Model

Qiong Li[1]
Wuhan Huaxia Institute of Technology, Wuhan, China

Abstract. Amid the rise of Guochao consumption and Generation Z becoming the primary consumer force, exploring this group's consumption logic of Guochao products is of great value. Drawing on the Howard-Sheth Consumer Behavior Model, this study establishes a framework, collects 782 valid samples via questionnaires, and uses SPSS for reliability/validity tests, correlation analysis, regression analysis, and mediating effect tests. Key findings: Generation Z's Guochao consumption psychology shows no significant differences across gender, age and other individual characteristics, indicating unified market recognition of Guochao; patriotic culture is the core driving factor, with products, social factors and product symbols exerting significant positive effects; consumption psychology plays a partial mediating role between external stimuli and consumption behavior. Based on these, recommendations are put forward: enterprises should deepen cultural connotations and develop product series, while the government should strengthen cultural guidance and foster an aesthetic atmosphere, to promote the sustainable and healthy development of Guochao.

Keywords. Generation Z; Guochao; Consumption Psychology; Consumption Behavior

1 Introduction

As a core cultural and economic symbiosis in China's consumer market, the rise of "Guochao" is closely tied to Generation Z (born 1995-2009) emerging as the primary consumer force. Growing up amid rapid national strength enhancement and full penetration of digital technology, Generation Z has broken free from blind adherence to Western consumption standards and reconstructed consumption logic with strong cultural confidence—their consumption is not merely material satisfaction, but also a

1 Corresponding Author, Wuhan Huaxia Institute of Technology, China; E-mail: liqiong913@163.com
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key carrier for cultural identity expression, self-construction, and circle-based social interaction [1]. Therefore, exploring the psychological and behavioral mechanisms of this group's Guochao product consumption not only offers a crucial perspective for understanding structural changes in the consumer market, but also provides theoretically and practically valuable references for local brand development and youth culture guidance.

2 Related works

Domestic and foreign academia have laid a certain foundation on related topics, yet there remains room for theoretical integration and perspective expansion. Domestic research, closely aligned with market practice, focuses on three core aspects: first, clarifying Generation Z's group characteristics of balancing rational and emotional demands, and pursuing individuality, sociality, and circle identity [2,3]; second, explaining the drivers of Guochao's rise from the dual dimensions of macro cultural confidence, micro brand supply-side reforms, and social media marketing[4]; third, proposing diverse consumption motivations such as identity recognition, nostalgia, and novelty-seeking social interaction, verifying the impact of key variables like brand authenticity and perceived value on purchase intention, with a "seeding-purchasing-sharing" closed-loop behavioral model [5,6].

Though there is no direct research on "Guochao" overseas, relevant global theoretical frameworks offer important references. From the perspective of "Glocalization", Guochao is a typical example of global "cultural counter-convergence", closely aligned with the Korean Wave and the revival of Japanese national brands. It reflects the younger generation's tendency of "cosmopolitan localism" [7] and serves as an active response of local culture to the global tide amid cultural globalization [8]. Based on consumer semiotics, Guochao consumption is essentially "symbolic consumption". Generation Z constructs their identity as "modern Chinese people" through cultural symbols such as traditional patterns and intangible cultural heritage craftsmanship embodied in products [9]. From a post-colonial perspective, Guochao is even a practice of "cultural decolonization" [10], symbolizing the younger generation's efforts to break free from Western aesthetic hegemony and redefine their own modernity . Additionally, Belk's Extended Self Theory and research on symbolic consumption provide crucial theoretical support for analyzing the identity-construction function of Guochao products [11].

In summary, domestic research provides rich empirical cases and market insights for this topic, while foreign research contributes in-depth theoretical interpretation frameworks. However, existing theoretical models lack systematic integration and fail to construct a complete logical chain of "external stimuli-internal psychology-consumption behavior." Meanwhile, most studies focus on the positive effects of Guochao consumption, lacking critical reflection on potential risks such as aesthetic fatigue and resistance to excessive marketing among Generation Z. Furthermore, they fail to propose targeted and operable brand building and cultural guidance strategies combined with the mediating role of consumption psychology, resulting in limited practical transformation value[12]. Therefore, this study aims to integrate and construct a systematic research model, and deeply analyze the psychological and behavioral logic of Generation Z's Guochao consumption through empirical investigation to improve existing relevant theories.

3 Sources of Survey Questionnaire Design

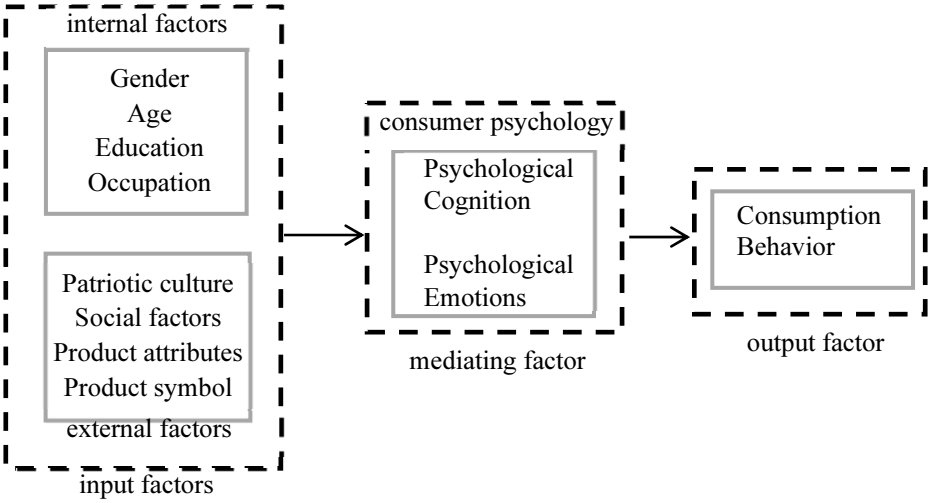


Figure 1 Data Analysis Model Diagram

The theoretical model of this study is designed based on the classic Howard-Sheth Model of Consumer Behavior, with corresponding adjustments made in light of Generation Z's complex consumption behavior toward Guochao products. [13]. It is designed relying on the model's variable system: "input factors" include "internal factors" (demographic variables such as gender, age, occupation, consumption level and education) and "external factors"; the latter focuses on situational external pressures like the macro patriotic cultural atmosphere and consumption scenarios, covering three external information sources-patriotic culture, product attribute stimulation (e.g., quality, price, cultural connotation of Guochao products), product symbol stimulation (e.g., advertising, celebrities, social media promotion) and social stimulation (e.g., influence of family, friends and other relevant groups); "mediating factor" is "consumer psychology", explored in depth from two dimensions: psychological cognition (e.g., judgment on the value and authenticity of Guochao brands) and psychological emotions (e.g., cultural identity, national pride) to reveal the internal processing of external stimuli; "output factor" is consumption behavior.

4 Reliability and Validity Analysis of Formal Survey Data

4.1 Overall Reliability Analysis

Table 1 Overall Reliability Analysis of the Questionnaire

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	Number of Items
0.897	0.912	28

A total of 1,000 questionnaires were distributed, 924 were retrieved. After data cleaning and analysis, excluding non-purchasers, 782 respondents' data remained, with an effective recovery rate of 84.6%. It can be seen from Table 1 that Cronbach's Alpha coefficient of the scale is 0.897 (ranging from 0.7 to 0.9), indicating good overall consistency and reliability of the questionnaire.

4.2 Overall Validity Analysis

Table 2 Overall Validity Analysis

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.969
Bartlett's Test of Sphericity	Approx. Chi-Square	4778.107
	df	406
	Sig.	0.000

As shown in Table 2, the KMO value is 0.969 and the significance level of Bartlett's Test of Sphericity is 0, which indicates that the structural data of the scale meets the required criteria and is suitable for exploratory factor analysis.

5 Data Analysis

5.1 Difference Analysis of Sample Demographics on Psychological Cognition and Affect

5.1.1 Gender Differences in Psychological Cognition and Affect

Table 3 Independent Samples T-test: Gender vs. Psychological Cognition and Emotions

Variable	Gender		Mean	Std. Deviation	Std. Error Mean	T	P
Psychological Cognition	Male	399	4.2167	0.49495	0.03118	0.211	0.466
	Female	383	4.2070	0.53891	0.03362		
Psychological Emotions	Male	399	4.1921	0.50804	0.03200	0.257	0.905
	Female	383	4.2039	0.52899	0.03300		

The results of the independent samples t-test in Table 3 show that the significance p-values of psychological cognition and psychological emotions among different gender groups are both greater than 0.05, indicating that gender has no significant impact on Generation Z's Guochao consumption psychology. Consistent with Generation Z's universal recognition of Guochao culture, this result reflects that "Guochao" as a cultural symbol has transcended gender differences and formed a unified group cognition.

5.1.2 Differences in Psychological Cognition and Affect by Age, Education Level, and Occupation

Table 4 One-Way ANOVA: Age, Education, Occupation vs. Psychological Cognition

Factor	Source	Sum of Squares	Mean Square	F	Significance
Age	Between Groups	0.841	0.280	1.049	0.370
	Within Groups	135.008	0.267		
	Total	135.849			
Education Level	Between Groups	1.057	0.264	0.988	0.414
	Within Groups	134.792	0.267		
	Total	135.849			
Occupation	Between Groups	2.253	0.451	1.697	0.134
	Within Groups	133.596	0.266		
	Total	135.849			

Table 5 One-Way ANOVA: Age, Education, Occupation vs. Psychological Emotions

Factor	Source	Sum of Squares	Mean Square	F	Significance
Age	Between Groups	0.466	0.155	0.577	0.630
	Within Groups	135.972	0.269		
	Total	136.438			
Education Level	Between Groups	0.298	0.075	0.276	0.894
	Within Groups	136.140	0.270		
	Total	136.438			
Occupation	Between Groups	0.861	0.172	0.639	0.670
	Within Groups	135.577	0.270		
	Total	136.438			

As shown in table 4 and table 5, one-way ANOVA results indicate that the significance p-values of psychological cognition and psychological emotions among groups with different ages, educational backgrounds, and occupations are all greater than 0.05, suggesting these demographic characteristics have no significant impact on Generation Z's Guochao consumption psychology. This further verifies that Guochao products have formed a unified market recognition, with their cultural core and fashion expression widely accepted by Generation Z, unaffected by significant individual background differences.

5.2 Analysis of Other Variable Factors

5.2.1 Hypothesis Testing

The following hypotheses are proposed:

Table 6 Hypothesis Test Details

H1: Patriotic culture has a significant positive correlation with psychological cognition.	H2: Patriotic culture has a significant positive correlation with psychological emotions
H3: Social factors have a significant positive correlation with psychological cognition.	H4: Social factors have a significant positive correlation with psychological emotions
H5: Product attributes have a significant positive correlation with psychological cognition.	H6: Product attributes have a significant positive correlation with psychological emotions
H7: Product symbol has a significant positive correlation with psychological cognition.	H8: Product symbol has a significant positive correlation with psychological emotions
H9: Consumer psychology (psychological cognition + psychological emotions) plays a mediating role between external stimuli (patriotic culture, product attributes, product symbols, social factors) and consumption behavior.	

5.2.2 Correlation and Regression Analysis of Influencing Factors

5.2.2.1 Correlation Analysis

Table 7 Correlation Analysis

	Patriotic Culture	Product attributes	Product Symbol	Social Factors	Psychological Cognition	Psychological Emotions	Consumer Psychology	Consumption Behavior
Patriotic Culture	1							
Product attributes	0.672**	1						
Product Symbol	0.619**	0.647**	1					
Social Factors	0.646**	0.666**	0.651**	1				
Psychological Cognition	0.697**	0.701**	0.680**	0.688**	1			
Psychological Emotions	0.684**	0.707**	0.661**	0.687**	0.741**	1		
Consumer Psychology	0.740**	0.754**	0.719**	0.737**	0.933**	0.933**	1	
Consumption Behavior	0.725**	0.765**	0.781**	0.786**	0.862**	0.866**	0.869**	1

Note: ** indicates $p < 0.01$, * indicates $p < 0.05$.**. Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 7, all variables are significantly positively correlated ($p < 0.01$). Among them, the correlation coefficients between consumer psychology and each external stimulus variable range from 0.719 to 0.754, indicating a strong positive association between external stimuli and consumer psychology; the correlation coefficient between consumer psychology and consumption behavior is 0.869, showing a significant positive correlation and laying a foundation for subsequent regression analysis and mediating effect test.

5.2.2.2 Regression Analysis

1) Regression Analysis of Related Factors on Psychological Cognition

Table 8 Regression Analysis of Relevant Factors on Psychological Cognition

	Variable	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	0.445	0.124		3.575	0.000		
	Patriotic Culture	0.253	0.038	0.258	6.596	0.000	0.455	2.197

Product attributes	0.221	0.038	0.237	5.835	0.000	0.423	2.366
Product Symbol	0.225	0.038	0.227	5.889	0.000	0.471	2.123
Social Factors	0.207	0.038	0.216	5.435	0.000	0.440	2.275

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson	F	P
0.806a	0.649	0.646	0.30764	1.958	232.848	0.000b

a. Predictors: (Constant), Social Factors, Product Symbol, Patriotic Culture, Product
b. Dependent Variable: Psychological Cognition

As shown in Table 8, the model fits well overall, indicating that patriotic culture, product attributes, product symbols, and social factors jointly explain 64.9% of the variance in psychological cognition. Specifically, all four factors exert significant positive impacts on psychological cognition (patriotic culture: Beta=0.258, p=0.000<0.05; product attributes: Beta=0.237, p=0.000<0.05; product symbols: Beta=0.227, p=0.000<0.05; social factors: Beta=0.216, p=0.000<0.05), verifying Hypotheses H1, H3, H5, and H7. Among them, patriotic culture has the largest standardized coefficient, proving it is the core factor influencing psychological cognition.

2) Regression Analysis of Related Factors on Psychological Affect

Table 9 Regression Analysis of Relevant Factors on Psychological Emotions

	Variable	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
	(Constant)	0.470	0.127		3.710	0.000		
	Patriotic Culture	0.231	0.039	0.235	5.903	0.000	0.455	2.197
1	Product attributes	0.256	0.039	0.274	6.636	0.000	0.423	2.366
	Product Symbol	0.187	0.039	0.188	4.809	0.000	0.471	2.123
	Social Factors	0.222	0.039	0.231	5.720	0.000	0.440	2.275

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson	F	P
0.798a	0.637	0.635	0.31329	2.032	221.530	0.000b

a. Predictors: (Constant), Social Factors, Product Symbol, Patriotic Culture, Product
b. Dependent Variable: Psychological Emotions

As shown in Table 9, the model fits well overall, indicating that external stimulus variables jointly explain 63.7% of the variance in psychological emotions. Specifically, patriotic culture, product attributes, product symbols, and social factors all exert significant positive impacts on psychological emotions, verifying Hypotheses H2, H4, H6, and H8. Product attributes have the largest standardized coefficient, highlighting their most prominent influence on psychological emotions.

5.2.2.3 Mediation Analysis

Table 10 Regression Analysis Without Mediating Variables

Variable		Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	0.445	0.124		3.575	0.000		
	Patriotic Culture	0.253	0.038	0.258	6.596	0.000	0.465	2.545
	Product attributes	0.221	0.038	0.237	5.835	0.000	0.443	2.512
	Product Symbol	0.225	0.038	0.227	5.889	0.000	0.454	2.518
	Social Factors	0.207	0.038	0.216	5.435	0.000	0.411	2.391

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson	F	P
0.806a	0.649	0.646	0.308	1.958	232.843	0.000b

a. Predictors: (Constant), Social Factors, Product Symbol, Patriotic Culture, Product
b. Dependent Variable: Consumption Behavior

Table 11 Regression Analysis with Mediating Variables

Variable		Unstandardized Coefficients		Standardized Coefficients	T	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	1.169	0.138		8.446	0.141		
	Patriotic Culture	0.165	0.044	0.096	3.750	0.000	0.406	2.464
	Product Attributes	0.132	0.044	0.049	3.000	0.003	0.377	2.652
	Product Symbol	0.162	0.044	0.089	3.682	0.000	0.433	2.312
	Social Factors	0.199	0.044	0.148	4.523	0.000	0.401	2.495
	Consumer psychology	0.736	0.060	0.480	12.267	0.000	0.262	3.823

R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson	F	P
0.887a	0.786	0.784	0.225	1.976	356.232	0.000b

a. Predictors: (Constant), Consumer psychology, Social Factors, Product Symbol, Patriotic Culture, Product Attributes
b. Dependent Variable: Consumption Behavior

As shown in Table 10 and Table 11, after adding the mediating variableer, the model fit significantly improved (R^2increased from0.649 to 0.786). The standardized coefficients of some external stimulus variables decreased but remained significant, indicating that external stimuli can directly influence Generation Z's Guochao consumption behavior and indirectly act on it through affecting their consumer psychology, thus verifying Hypothesis H9.

6 Conclusions

Tests show that Generation Z's consumption psychology toward Guochao products has no significant differences due to gender, age and other individual characteristics, reflecting the unified market recognition of Guochao and the in-depth penetration of cultural confidence among young people. Patriotic culture is the core driving factor for their Guochao consumption. In recent years, with the high popularization of the internet, social events at home and abroad have greatly aroused their patriotic sentiments, thus fueling the Guochao boom, while the enhancement of national strength has further stimulated relevant consumption demand[14,15]. Consumer psychology plays a partial mediating role between external stimuli and Guochao consumption behavior, which verifies the core logic of the Howard-Sheth Model and provides a mechanistic explanation for understanding the consumption behavior of this group.

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A Competency Compass for Improving Homestay Operating Quality: Identifying and Validating the Competency Structure of Homestay Operators

Yilun Deng[a,1] Qiaoyi Zou[a,2],Yidan Zhu [b,3] and Yuqian Liu[b,4]
[a] *Hunan Normal University, Changsha, China*
[b] *Hunan Women's University, Changsha, China*
ORCiD ID: Yilun Deng https://orcid.org/0009-0002-0512-8380
Yidan Zhu https://orcid.org/0009-0006-4583-801X

Abstract. This study develops and validates a competency scale for homestay operators in contexts shaped by digitalisation and platformisation. Following a literature-driven, expert-reviewed, and empirically validated procedure, an initial item pool was generated from evidence in hotel competency research and homestay studies and then contextually refined through expert review and structured interviews. Using purposive sampling, 276 questionnaires were collected, and 248 valid responses were retained after excluding invalid cases. Analyses using SPSS 26.0 and SmartPLS 4 supported a six-dimensional, 42-item structure covering (1) Strategic Innovation and Opportunity Recognition, (2) Digital Competence and Data Analytics, (3) Interpersonal Communication and Teamwork, (4) Professional Image and Operations Management, (5) Human Resource Management and Ethics, and (6) Cultural Diversity and Intercultural Communication. The measurement model demonstrated acceptable reliability, convergent validity, and discriminant validity. The resulting instrument provides a reusable tool for assessing and developing homestay operator competencies and offers empirical evidence on how digitalisation and platformisation reshape competency structures in homestay operations.

Keywords. Homestay operator, Competency, Competency scale, Homestay operating quality improvement

[1] First Author and Corresponding Author: Yilun Deng, Hunan Normal University, Changsha, China; email: dengyilun@hunnu.edu.cn

[2] Second Author: Qiaoyi Zou, email: zoujoey@hunnu.edu.cn

[3] Third Author: Yidan Zhu, email: zhuyidan@hnwu.edu.cn

[4] Fourth Author: Yuqian Liu, email: m19375102120@163.com

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1. Introduction

With tourism demand moving upmarket and tourism expanding, homestays have become a fast-growing segment of the lodging industry, driven by demand for personalised travel and the development of rural tourism [1]. As this sector expands, homestay operators have become increasingly important in accommodation provision. However, unlike formal hotels with professional managers and standardised systems, many homestay operators are individual proprietors or cross-sector entrants who lack systematic hospitality training and operational experience. Under intensified competition and platformised distribution, deficiencies in standardised operations, digital marketing, and crisis response continue to constrain service consistency, customer satisfaction, and business sustainability [2,3]. This indicates that homestay development depends not only on market growth, but also on whether operators possess competencies suited to this context.

Competency generally refers to the integrated knowledge, skills, attitudes, and behavioural attributes required for effective performance [4]. However, existing competency research is rooted largely in hotel settings and focuses mainly on professional managers or frontline employees, making it insufficient to explain the hybrid role of homestay operators, who simultaneously handle guest reception, operational management, business decision-making, and platform operations [5]. Compared with hotel positions characterised by clearer division of labour and standardised procedures, homestay operators perform more integrated, context-dependent, and multitasking work. This raises doubts about the direct applicability of hotel-based competency frameworks to the homestay context. Although prior studies have addressed homestay service and management, the literature still lacks a systematically integrated and empirically validated instrument for measuring homestay operator competency. This gap limits both the standardised assessment of operator competency and the cumulative development of competency theory in homestay research. To address this gap, this study adapts established competency dimensions and indicators from hotel research to the homestay context and develops and validates a multidimensional competency scale for homestay operators, thereby extending competency research to non-standardised accommodation settings.

2. Literature Review

Hospitality competency research has established relatively mature competency frameworks in hotel settings, highlighting core dimensions such as leadership and communication, operations management, human resource management, financial analysis, and technological competence, thereby providing transferable benchmarks for competency measurement [6]. Under turbulent economic conditions and accelerating digital transformation, hotel management competency frameworks further underscore the salience of digital technology and integrated operational capabilities, suggesting that traditional competency structures require contextual extension and refinement [7]. Digital transformation scholarship additionally argues that hospitality management competencies should encompass integrative capabilities related to digital innovation, digital governance, and digital customer experience, shifting the focus from task-based skills to competency system reconfiguration in digitally mediated contexts [8]. Consistently, evidence from ICT-enabled learning environments indicates that digital

competence is trainable and improvable, lending support to incorporating digital capabilities into hospitality competency assessment [9]. Platformisation research further demonstrates that platform business models and market concentration are reshaping tourism distribution and operational logics and prompting regulatory responses, implying that operators increasingly need platform coordination, online operations, and rule-adaptation capabilities to compete in platform-dominated markets [3].

Within homestay research, systematic reviews show rapid growth in the field, yet dominant attention remains on tourist-side behaviours and outcome variables, while operator-side work, particularly on competency structures and validated measurement instruments, remains limited [5]. Reviews of rural homestays and sustainability similarly note that the literature largely foregrounds community-level and sustainability implications but offers less systematic integration of operator capabilities, training, and ICT-related themes, leaving room for competency-focused measurement research [1]. Using online review data, machine-learning evidence identifies multi-dimensional role expectations toward "villager-operators", indicating that the behavioural performances expected of rural homestay operators are structurally definable and measurable as capability constructs [10]. Taken together, hotel-based competency frameworks provide a foundational reference, digital transformation and platformisation literatures specify emergent capability requirements, and the structural gaps in homestay scholarship collectively point to the need for developing and validating a competency scale for homestay operators.

3. Research Design

3.1. Construct Development and Questionnaire Design

The scale was developed using a literature-driven procedure. A review of hospitality competency frameworks was first conducted to define the construct domain and generate an initial pool of dimensions and items, primarily informed by established hotel competency models [6,7]. To enhance contextual fit for homestay operations under digitalisation and platformisation, evidence on digital transformation and digital competence was incorporated to enrich items on digital competence, information handling, and analytics [8,9], and platformisation research was used to inform the contextual refinement of items related to digitally mediated operations, information management, and market-facing adaptation in homestay settings [3].The pool was then refined through expert review and structured interviews with two homestay scholars (professors) and two homestay owners with over ten years of operating experience to improve content validity, clarity, and parsimony. The final instrument comprised 42 items across six dimensions, measured on a five-point Likert scale (1 = strongly inconsistent; 5 = strongly consistent).

3.2. Sample and Data Collection

This study employed purposive sampling to recruit homestay owners and store managers, as they are directly responsible for operational decision-making, service management, and day-to-day coordination, and are therefore well positioned to evaluate the competency requirements of homestay operations. The online questionnaire was administered over a two-week period. Respondents were recruited through two primary

channels. First, homestay operators were identified via business accounts on Xiaohongshu, and invitations containing the survey link were sent through one-to-one direct messages. Second, the questionnaire was disseminated via homestay operator communities, including WeChat and QQ groups, to broaden reach and improve coverage across regions and business types.

To ensure data completeness, all items were set as mandatory and the system prevented submission of incomplete responses. After data collection, responses showing clear signs of low-quality or invalid answering patterns were excluded during data screening. A total of 276 questionnaires were collected, of which 248 were retained as valid, yielding a valid response rate of 89.9%. Participation was voluntary. Informed consent was obtained at the beginning of the questionnaire, and respondents could discontinue at any time without penalty. All responses were anonymised and used solely for academic research.

4. Data Analysis

4.1. Descriptive Statistics

Descriptive statistics were used to characterise the sample and provide a basis for subsequent measurement and model analyses. As shown in Table 1, respondents were drawn from 16 provincial-level regions and represented a range of homestay types and business stages. The largest regional shares were Jiangsu (25.8%) and Zhejiang (23.4%). Most respondents were aged 26-45 (80.7%), and gender distribution was approximately balanced. Overall, the sample exhibits sufficient heterogeneity to support factor-based measurement validation and dimensional structure assessment.

Table 1. Sample profile (N=248)

Variable	Category	Frequency	Percentage (%)
Region	Fujian	22	8.9
	Guangdong	19	7.7
	Jiangsu	64	25.8
	Liaoning	24	9.7
	Zhejiang	58	23.4
	Others (11 provinces)	61	24.5
Age	≤ 20	12	4.8
	21-25	19	7.7
	26-30	56	22.6
	31-35	57	23
	36-40	49	19.8
	41-45	38	15.3
	46-50	11	4.4
	≥ 51	6	2.4
Gender	Female	127	51.2
	Male	121	48.8

4.2. Reliability Analysis

Internal consistency was evaluated for the 42 items. As reported in Table 2, Cronbach's alpha values for all constructs ranged from 0.923 to 0.957, and composite reliability (CR) values ranged from 0.942 to 0.963, exceeding the recommended >0.70 threshold

[11]. Average variance extracted (AVE) values ranged from 0.735 to 0.768, which are well above the ≥0.50 benchmark [12]. These results establish robust internal consistency and convergent validity for the measurement model.

Table 2. Reliability results

Construct	Items	Cronbach's α	CR	AVE
Strategic Innovation and Opportunity Recognition	9	0.957	0.963	0.743
Digital Competence and Data Analytics	8	0.949	0.957	0.736
Interpersonal Communication and Teamwork	7	0.940	0.951	0.735
Professional Image and Operations Management	8	0.955	0.963	0.763
Human Resource Management and Ethics	5	0.925	0.943	0.768
Cultural Diversity and Intercultural Communication	5	0.923	0.942	0.765

4.3. Validity Analysis

Sampling adequacy and sphericity were assessed prior to extraction. As presented in Table 3, the KMO value was 0.982, indicating excellent sampling adequacy [13]. Bartlett's test of sphericity was significant (χ^2=10455.944, df=861, $p < 0.001$), supporting the suitability of the data for factor analysis [14].

Table 3. KMO and Bartlett's test

KMO measure of sampling adequacy		0.982
Bartlett's test of sphericity	Approx. χ^2	10455.944
	df	861
	Sig.	<.001

Additionally, discriminant validity was supported by the Heterotrait-Monotrait (HTMT) results. As shown in Table 4, all HTMT ratios ranged from 0.823 to 0.892 and fell below the 0.90 threshold [15].

Table 4. HTMT results

Construct	SIOR	DCDA	ICT	PIOM	HRME	CDIC
Strategic Innovation and Opportunity Recognition (SIOR)	—					
Digital Competence and Data Analytics (DCDA)	0.844	—				
Interpersonal Communication and Teamwork (ICT)	0.824	0.854	—			
Professional Image and Operations Management (PIOM)	0.877	0.864	0.869	—		
Human Resource Management and Ethics (HRME)	0.868	0.832	0.842	0.879	—	
Cultural Diversity and Intercultural Communication (CDIC)	0.823	0.883	0.877	0.892	0.888	—

As reported in Table 5, the rotated component matrix further supports a six-factor solution: all items loaded strongly on their intended factor ($|\text{loading}| \geq 0.50$) with no substantive cross-loadings, indicating acceptable item-level convergence and discrimination [16].

Table 5. Rotated Component Matrix

Item	F1	F2	F3	F4	F5	F6
A1. Coach staff & monitor quality	0.648					
A2. Adjust to market changes	0.678					
A3. Design differentiated services	0.696					
A4. Identify market opportunities	0.621					
A5. Balance standard & personal rules	0.647					
A6. Motivate staff performance	0.747					

Item	F1	F2	F3	F4	F5	F6
A7.Effectively manages to deal with incidents	0.666					
A8. Schedule concurrent tasks	0.702					
A9. Track industry developments	0.695					
B1. Demonstrate foresight in development trends		0.680				
B2. Apply digital information collection and financial analysis methods		0.679				
B3. Analyze profitability drivers		0.693				
B4. Forecast revenue & expenditure		0.582				
B5. Use financial information to support decisions		0.622				
B6. Use digital front-office systems		0.683				
B7. Interpret online media information		0.664				
B8. Produce online media content		0.629				
C1. Internal staff communication			0.643			
C2. Online and offline guest communication			0.647			
C3. Manage guest issues flexibly			0.636			
C4. Maintain guest relationships			0.675			
C5. Written & oral skills			0.64			
C6. Team collaboration			0.594			
C7. Anticipate guest expectations			0.725			
D1. Professional appearance				0.570		
D2. Product & service knowledge				0.538		
D3. Define operational problems				0.625		
D4. Hygiene & safety compliance				0.685		
D5. Professional & ethical norms				0.621		
D6. Understand operational challenges				0.575		
D7. Master sector-specific terms				0.669		
D8. Manage information channels				0.512		
E1. Act on ethical norms					0.644	
E2. Communicate quality standards					0.606	
E3. Making decisions under pressure or in crisis					0.635	
E4. Staff selection & allocation					0.585	
E5. Performance evaluation					0.594	
F1. Define guest-relation problems						0.649
F2. Resolve guest issues						0.575
F3. Strengthen team cohesion						0.603
F4. Cross-cultural interaction						0.523
F5. Respect cultural diversity						0.552

5. Discussion and Conclusion

5.1. Discussion

This study developed and validated a six-dimensional competency scale for homestay operators, addressing the relative lack of operator-side constructs and measurement instruments in homestay research [5]. The findings indicate that homestay operator competency is not a straightforward transfer of hotel role requirements, but a composite capability structure shaped by small-scale owner-managed operations and digitally mediated market conditions.

Viewed through the lens of digitalisation and platformisation, several dimensions remain foundational to homestay operations. Interpersonal communication and teamwork, professional image and operations management, and human resource management and ethics constitute core competency modules, consistent with key competency domains repeatedly identified in hotel settings and with the emphasis on integrated operational capabilities under transformation pressures [6,7]. Meanwhile,

digital competence and data analytics emerged as a distinct dimension, suggesting that competency requirements extend beyond conventional service and operational skills to information handling and data-informed operational judgement. This aligns with digital transformation research that conceptualises hospitality competencies as integrative digital capabilities and is supported by evidence that digital competence is trainable and measurable [8,9]. The scale also indirectly reflects the growing relevance of platform-mediated operations, particularly through items related to digital competence, media information handling, content production. This is broadly consistent with research suggesting that platform governance and market concentration are reshaping distribution and operational conditions in tourism and accommodation settings [3]. The cultural diversity and intercultural communication dimension is also theoretically coherent, as guests hold relatively structured role expectations toward rural homestay operators and evaluate host behaviour against shared normative standards, providing a stable basis for measuring such competencies [10].

Overall, the dimensional configuration portrays a competency profile that combines general hospitality operations and service-management capabilities with digitally and platform-situated capabilities, particularly those oriented toward data and platform engagement. Given that respondents were recruited primarily through online platforms and operator communities, the sample may over-represent digitally active operators. Future research should therefore examine the structural stability and boundary conditions of the scale across regions, operator types, and platform ecosystems [5].

5.2. Conclusion

This study developed and validated a six-dimensional competency scale for homestay operators in an environment characterised by digitalisation and platformisation. The findings suggest that homestay operator competency is best understood as a composite capability structure rather than a direct transfer of hotel-role requirements. The validated dimensions indicate that foundational hospitality competencies remain central to homestay operations, including interpersonal communication and teamwork, professional image and operations management, and human resource management and ethics. At the same time, the scale captures capabilities that are increasingly salient in digitally mediated markets. Digital competence and data analytics emerged as an independent domain, highlighting that effective homestay operation requires more than service delivery; it also depends on information handling and data-informed operational judgement. In addition, platform-facing competencies are embedded in the overall competency configuration, reflecting the need for platform coordination and rule adaptation under platform governance and concentrated distribution channels. The inclusion of cultural diversity and intercultural communication further indicates that homestay operators are evaluated against relatively stable role expectations, making intercultural competence a measurable and operationally relevant capability. Collectively, these results provide a validated measurement instrument for future operator-side research and offer a structured basis for assessing competency gaps and designing competency-oriented development initiatives for homestay operators.

5.3. Managerial Implications

The validated scale offers a practical tool for competency diagnostics and targeted capacity building among homestay operators. For homestay owners and managers, the

dimensional structure can guide self-assessment and prioritisation of improvement areas, particularly where service consistency, operational discipline, and staff/partner coordination are required. For industry associations and destination management organisations, the results support the design of modular training programmes aligned with the competency profile of contemporary homestay operations. Training should not be limited to conventional hospitality skills; it should also incorporate digital competence and data analytics, such as information handling, basic performance monitoring, and data-informed decision-making. Given the increasing dominance of platform-based distribution, capacity-building initiatives should further include platform-facing skills, including platform coordination, rule adaptation, and compliant operations under platform governance. For education providers and continuing professional development programmes, the scale can serve as a reference for curriculum design and learning outcomes, helping translate competency requirements into measurable training targets. More broadly, the instrument can inform talent evaluation and certification schemes by providing a standardised competency benchmark that is sensitive to the realities of small-scale, owner-managed, and platform-dependent accommodation businesses.

5.4. Limitations and Future Research

Several limitations should be acknowledged. First, the sample was recruited primarily through online platforms and operator communities, which may over-represent digitally active operators and constrain generalisability to less platform-engaged groups. Future studies should employ multi-source sampling and broader regional coverage to test robustness. Second, the present work focused on scale development and validation; predictive validity was not directly examined. Future research should link the competency dimensions to objective and subjective performance indicators, such as occupancy, ratings, repeat business, and compliance outcomes, and test whether competencies mediate the effects of digitalisation and platformisation on business performance. Third, as platform governance and digital tools evolve, longitudinal studies are needed to assess the stability of the competency structure over time and across different platform ecosystems. Finally, cross-context validation, including measurement invariance tests across destination types and cultural markets, would strengthen the scale's applicability in comparative research.

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Does Corporate Data Asset Disclosure Promote University–Industry Collaboration? A Big Data–Driven Management Perspective

Xin XIONG [a] and Ximeng JIA [b,1]
[a] *General Administration Division Liaison Office, Sichuan University, Chengdu, China*
[b] *Business School, Sichuan University, Chengdu, China*

Abstract. This study investigates how corporate data asset disclosure promotes university–industry collaboration (UIC) from a big data–driven management perspective. Using a sample of Chinese A-share listed companies from 2010 to 2023, firm-year level disclosure measures are constructed through a Text CNN-based analysis of annual reports. Empirical findings show that data asset disclosure significantly promotes UIC, and the results remain robust after addressing endogeneity using instrumental variable and propensity score matching methods. Mechanism tests reveal that disclosure enhances the reliability of financial reporting and curbs executives' short-term behaviors, thereby supporting collaboration. Heterogeneity analyses indicate stronger effects in tech-finance pilot cities and data IP pilot cities, highlighting the amplifying role of policy support and intellectual property protection. These findings suggest that firms should integrate data asset disclosure into digital governance and innovation strategies to build external trust and foster collaboration. This research contributes to the literature on corporate information disclosure and the drivers of UIC in the era of big data, while providing practical guidance for corporate digital governance and policy formulation.

Keywords. Data Asset Disclosure, University–Industry Collaboration, Big Data–Driven Management, Innovation Management, Information Governance

1. Introduction

With the rapid development of digital technologies, firms continuously accumulate and utilize various data resources in their production and operations, and data assets have gradually become a crucial source of value creation and competitive advantage for enterprises [1]. Data assets are characterized by high specificity, strong spillover effects, and difficulties in fully confirming property rights, and their value realization depends heavily on corporate data governance and application capabilities. Existing studies suggest that data asset disclosure helps enhance corporate information transparency and improves the capital market's understanding of firms' digital capabilities and future growth potential [2], thereby facilitating better financing conditions and access to resources [3]. Particularly, when the value of data as a production factor cannot be fully reflected through traditional financial indicators, the quality and depth of disclosed information increasingly serve as critical references for external stakeholders to identify long-term corporate value, evaluate sustained innovation capacity, and assess competitive advantage [4].

[1] Corresponding Author: Ximeng Jia, jiaxm@scu.edu.cn.

In the digital age, innovation activities are increasingly complex, diverse, and cross-disciplinary, making it difficult for a single entity to independently complete the process from knowledge creation to technological application. University-industry collaboration (UIC), as an essential organizational form linking firms, universities, and research institutions [5], plays a key role in promoting technological innovation, facilitating knowledge transfer, and enhancing national innovation capability [6]. However, UIC is highly uncertain and information-asymmetric [7]. Firms' technological capabilities, digital foundation, and data resource conditions are often difficult for external innovation partners to accurately identify, which constrains the establishment and deepening of collaborative relationships [8]. In particular, UIC in China is embedded in an institutional environment characterized by a "government guidance + market operation" model [9]. Such an environment is constrained by policy objectives while also needing to meet market return requirements, increasing decision-making uncertainty and coordination costs. Enterprises and universities differ institutionally in areas such as property rights and outcomes allocation, making information disclosure standards and evaluation systems difficult to unify [10]. Moreover, regional development imbalances and variations in policy implementation further amplify the difficulty of accurately identifying relevant information. Therefore, studying the impact of data asset disclosure on UIC is particularly important in the Chinese context.

Compared with traditional financial information, data asset disclosure can more directly reflect firms' capabilities in data governance, data utilization, and digital innovation, carrying significant signaling value [2]. Big data-driven management emphasizes improving decision-making quality, innovation capability, and operational efficiency through data collection, integration, analysis, and application [11]. In essence, firms' disclosure of data assets is a process of transforming internal data resources into information signals for external stakeholders, representing an application of information management practices [3]. Despite the growing attention to corporate information disclosure, little is known about whether and how corporate data asset disclosure promotes UIC. Within China's policy-driven innovation system, this research gap is particularly pronounced. UIC in China relies heavily on policy support, and data asset disclosure not only provides key information for external stakeholders but also serves as an important link aligning firms' data needs with the technological resources of universities and research institutions. From a big data–driven management perspective, this study investigates, within the Chinese context, whether corporate data asset disclosure facilitates UIC, the mechanisms through which such effects occur, and the potential heterogeneity of these effects across regions.

The contributions of this study are threefold. First, it extends the research framework of UIC determinants from the perspective of data assets. Specifically, this study incorporates corporate data asset disclosure into the analysis, systematically examines its mechanisms, and empirically tests the mediating roles of financial information quality and managerial short-termism. Second, from the perspective of big data-driven management, it enriches the research on the impact of information disclosure on innovation activities. Prior studies have largely focused on information asymmetry and principal-agent theory, whereas under the big data-driven management framework, data asset disclosure can accumulate digital reputation, enhance information supply, and mitigate innovation risks, thereby more effectively explaining the formation and deepening of UIC in the digital era. Third, this study provides empirical evidence and managerial implications for corporate digital governance and the practice of UIC within policy-driven innovation systems. In the Chinese context, UIC is embedded within a government-led innovation support framework. The findings indicate that data asset disclosure serves as an effective tool to enhance the effectiveness of policy-driven UIC, offering guidance for fostering a more efficient and integrated innovation ecosystem and informing related policy development.

2. Theoretical Analysis and Hypothesis Development

UIC plays a critical role in integrating diverse innovation resources, facilitating the commercialization of technological outcomes, and enhancing both firm-level and regional innovation capabilities. However, in the early stages of collaboration, limited information and

uncertainty about a firm's true innovation capacity often hinder the formation and deepening of UIC. From the perspective of big data–driven management, this study argues that corporate data asset disclosure can systematically enhance a firm's attractiveness to universities and research institutions through three pathways: accumulating digital reputation, improving information supply, and reducing innovation risk, thereby promoting the formation and deepening of UIC.

First, data asset disclosure shapes an identifiable digital reputation, significantly reducing uncertainty in UIC and fostering long-term collaboration willingness. When selecting partners, universities and research institutions increasingly focus on a firm's data resource capabilities and the feasibility of its technological innovation pathways [7]. By proactively disclosing information regarding data governance, security, application, and technology, firms can accumulate trust-based "digital reputation" [12], effectively signaling the systematization and execution strength of their digital strategies to potential partners. Within a big data–driven management framework, firms can continuously optimize innovation decisions through data analytics and externalize this capability via consistent and standardized disclosure, providing a more robust trust foundation for UIC.

Second, data asset disclosure improves the matching efficiency and decision accuracy of UIC by providing high-quality information. In collaborations, external partners not only consider current firm performance but also attach importance to the potential for technological commercialization and long-term development prospects [6]. Through systematic management and analysis of data assets, firms can disclose forward-looking information regarding the scale of data resources, utilization efficiency, and coverage of application scenarios [4]. Such information provides essential guidance for partners in evaluating technical feasibility, commercialization potential, and market prospects. At the same time, big data technologies enable the integration and interpretation of previously dispersed or unstructured information, reducing information-processing costs for partners and thereby facilitating more effective UIC.

Finally, data asset disclosure reduces innovation risk, providing a more controllable environment for UIC. UIC typically involves long investment cycles and high trial-and-error costs, making external partners particularly sensitive to the controllability of firm-level innovation risk. From a big data–driven management perspective, firms can continuously monitor technological evolution paths and application outcomes using data analytics tools, and convey their risk identification and governance capabilities to external stakeholders through disclosure [4]. This reduces information asymmetry regarding innovation direction and expected outcomes, lowering the risk of misjudgment due to insufficient information. By compressing the "information black box" of the innovation process, data asset disclosure significantly reduces uncertainty regarding a firm's technological capabilities, innovation potential, and resource endowments, thereby facilitating the establishment of UIC.

Based on the above analysis, the study proposes the following hypothesis:

H1: Corporate data assets disclosure positively influences the extent of UIC.

3. Empirical Design

3.1. Sample Selection and Data Sources

This study initially selects all A-share listed companies from 2010 to 2023 as the sample and applies the following screening criteria: first, financial and insurance companies are excluded; second, firms that were ever designated as ST, *ST, or delisted during the sample period are removed; finally, observations with missing key variables are discarded. All continuous variables are Winsorized at the 1% and 99%. After these procedures, a final sample of 42,203 firm-year observations is obtained. Regarding data sources, corporate data asset disclosure information is obtained from the processing and extraction of annual report texts; corporate patent records are sourced from the China National Intellectual Property Administration; financial and corporate governance variables are obtained from the CNRDS and CSMAR databases.

3.2. Variable Measurement

To examine the impact of corporate data asset disclosure on UIC, this study constructs the following baseline regression model, based on existing research:

$$UIC_{i,t+1} = \alpha_0 + \alpha_1 DAD_{i,t} + \lambda Controls_{i,t} + \sum Year + \sum Industry + \varepsilon_{i,t} \quad (1).$$

Where the dependent variable $UIC_{i,t+1}$ represents the level of UIC for firm i in year $t+1$, the independent variable $DAD_{i,t}$ indicates the level of corporate data asset disclosure in year t, and $Controls_{i,t}$ denotes the set of control variables. $\sum Year$ and $\sum Industry$ represent time and industry fixed effects, respectively, while $\varepsilon_{i,t}$ is the random error term.

UIC is measured from the perspective of joint patent applications. Based on the names of listed firms, patent application data over the years were collected from the website of the China National Intellectual Property Administration. In this study, patents jointly applied for by firms and universities or research institutes, including invention patents and utility model patents, are defined as outcomes of UIC. Within China's policy-driven innovation system, joint patents serve as a tangible and institutionally relevant proxy for formalized collaboration. They not only reflect the technological outputs of such cooperation but also capture the influence of government-guided collaborative initiatives. Joint patent applications are an appropriate proxy due to their availability, measurability, and reflection of core technological collaboration. To account for zero values, the number of joint patents is incremented by one and then transformed using the natural logarithm.

Corporate data asset disclosure comprises two dimensions: disclosure intensity (*DAD1*) and relative importance of disclosure (*DAD2*). This study innovatively employs a Text CNN model on corporate annual report texts to automatically identify and quantify data asset-related disclosure content, constructing firm-year level DAD indicators. A keyword library is developed around the core processes of data acquisition, storage, management, and application, from which relevant sentences are extracted from the annual reports. The keyword system is based on the *Data Asset Management Practice White Paper (5.0)* and expanded using Word2vec to improve coverage and generalizability. Approximately 10% of the extracted sentences are randomly sampled for manual labeling to determine whether they reflect the ownership or application of data assets. A combination of GPT-assisted and manual labeling is employed to ensure annotation accuracy. The TextCNN model demonstrates strong performance on the validation set, achieving Precision = 0.91, Recall = 0.88, and F1-score = 0.895, indicating that it can efficiently and reliably identify data asset-related text in corporate annual reports. After model training, disclosure intensity (*DAD1*) is measured as the frequency of sentences related to data asset ownership or application/management in the annual report (log-transformed), and relative importance of disclosure (*DAD2*) is measured as the proportion of these sentences relative to the total report text.

Following prior research, this study includes a set of control variables to account for firm characteristics that may independently influence UIC, ensuring a more precise estimation of the impact of data asset disclosure. Specifically, the controls include firm size (*Size)*, leverage (*Lev*), listing age (*Age*), return on equity (*ROE*), revenue growth rate (*Growth*), operating cash flow (*Cflow*), ownership concentration (*Share1*), loss status (*Loss*), and audit opinion (*AuditOp*).

4. Empirical Results and Analysis

4.1. Descriptive Statistics

Table 1 presents the descriptive statistics of the variables. The mean of *UIC* is 0.184, with a standard deviation of 0.563, a minimum value of 0, and a maximum value of 3.045. This indicates that most firms have limited involvement in UIC, although some firms are more actively engaged in this area. The mean of *DAD1* is 0.455, with a standard deviation of 0.746, ranging from 0 to 3.178. The mean of *DAD2* is 0.003, with a standard deviation of 0.007, ranging from 0 to 0.046. These results suggest that while most firms place relatively low importance on data asset disclosure, a portion of firms show a higher level of disclosure emphasis in this area. The statistics for other control variables are omitted for brevity.

Table 1. Descriptive Statistics.

	N	Mean	P50	SD	Min	Max
UIC	42203	0.184	0	0.563	0	3.045
DAD1	42203	0.455	0	0.746	0	3.178
DAD2	42203	0.003	0	0.007	0	0.046
Size	42203	22.25	22.02	1.372	19.72	26.53
Lev	42203	0.428	0.419	0.212	0.056	0.905
Age	42203	10.15	9	7.983	0	28
ROE	42203	0.052	0.068	0.144	-0.787	0.342
Growth	42203	0.347	0.109	1.047	-0.746	7.666
Cflow	42203	0.046	0.046	0.071	-0.180	0.246
Share1	42203	34.56	32.24	15.02	8.740	74.98
Loss	42203	0.121	0	0.326	0	1
AuditOp	42203	0.914	1	0.280	0	1

4.2. Regression Analysis

Table 2 presents the baseline regression results on the impact of corporate data asset disclosure on UIC. Columns (1) and (2) report the regression results with only control variables included, while columns (3) and (4) further incorporate year and industry fixed effects. Columns (1) and (3) show that *DAD1* has a positive and significant effect on *UIC*, with coefficients of 0.033 and 0.036, respectively. Similarly, columns (2) and (4) demonstrate that *DAD2* also positively influences *UIC*, with coefficients of 2.413 and 2.472. These results suggest that both the intensity and relative importance of data asset disclosure significantly enhance collaboration between firms and academic institutions, providing strong support for Hypothesis 1.

Table 2. Regression Results.

VARIABLES	(1)	(2)	(3)	(4)
DAD1	0.033***		0.036***	
	(9.159)		(9.339)	
DAD2		2.413***		2.472***
		(6.172)		(6.185)
Size	0.104***	0.107***	0.116***	0.118***
	(42.130)	(43.531)	(44.740)	(45.596)
Lev	-0.159***	-0.162***	-0.088***	-0.087***
	(-10.050)	(-10.255)	(-5.430)	(-5.389)
Age	-0.003***	-0.003***	-0.001**	-0.001***
	(-8.370)	(-8.632)	(-2.332)	(-2.644)
ROE	0.034	0.033	0.029	0.030
	(1.262)	(1.232)	(1.098)	(1.123)
Growth	-0.007***	-0.007***	0.005**	0.006**
	(-2.578)	(-2.622)	(2.019)	(2.084)
Cflow	0.193***	0.196***	0.033	0.031
	(4.836)	(4.904)	(0.816)	(0.775)
Share1	0.000	0.000	0.001***	0.001***
	(1.398)	(1.155)	(3.000)	(2.913)
Loss	0.011	0.012	-0.011	-0.011
	(0.994)	(1.063)	(-0.983)	(-1.000)
AuditOp	-0.007	-0.011	0.037***	0.036***
	(-0.712)	(-1.088)	(3.177)	(3.163)
Year	NO	NO	YES	YES
Industry	NO	NO	YES	YES

VARIABLES	(1)	(2)	(3)	(4)
Constant	-2.064***	-2.103***	-2.328***	-2.366***
	(-40.803)	(-41.781)	(-40.154)	(-40.956)
Observations	42,203	42,203	42,203	42,203
Adjust R^2	0.056	0.055	0.100	0.099

Note：*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Values in parentheses represent t-statistics. The same notation applies below.

4.3. Robustness Tests

To address potential endogeneity between corporate data asset disclosure and UIC, this study uses regional digital economy development as an instrumental variable (*IV*) and estimates the model with two-stage least squares (2SLS). Regional digital economy development is measured by indicators such as broadband users, telecom business per capita, and mobile phone users, aggregated using principal component analysis. In regions with more advanced digital infrastructure, companies are more likely to disclose data assets effectively. The first-stage regression results in Columns (1) and (3) of Table 3 show a significant positive impact of the *IV* on data asset disclosure, with an F-statistic well above 10. In the second-stage regression, also presented in Columns (2) and (4) of Table 3, after controlling for endogeneity, the effect of data asset disclosure on UIC remains significant at the 1% level, consistent with the baseline regression results. These findings confirm the robustness of the causal inference.

To address potential unobservable factors, this study employs the Propensity Score Matching (PSM) method for endogeneity testing. Specifically, firms disclosing data asset information are classified as the treatment group, while those not disclosing such information are treated as the control group. Since the variables *DAD1* and *DAD2* are identical after generating the 0-1 variable, only one variable is utilized. The propensity scores are estimated using a Logit model based on the control variables from the baseline regression, followed by one-to-one nearest-neighbor matching. After matching, the distribution of covariates between the treatment and control groups becomes more balanced, mitigating endogeneity issues. The regression results in Column (5) of Table 3 show that the estimates from the matched sample are consistent with the baseline regression, reinforcing the robustness of the conclusions.

Table 3. Regression Results of Robustness Tests.

	(1)	(2)	(3)	(4)	(5)
VARIABLES	*DAD1*	*UIC*	*DAD2*	*UIC*	*UIC*
IV	0.0146***		0.0001***		
	(8.461)		(9.653)		
DAD1		0.263***			
		(2.655)			
DAD2				2.417***	
				(2.701)	
DAD_PSM					2.311***
					(4.516)
Controls	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES
Observations	38,380	38,380	38,380	38,380	20,258
Adjust R^2	0.157	0.100	0.087	0.109	0.1051

4.4. Mechanism Analysis

First, parties involved in UIC rely on corporate financial disclosures to assess a firm's stability and capabilities, and low-quality financial information may exacerbate information asymmetry,

increasing moral hazard and adverse selection [8]. As a crucial component of corporate disclosure, data asset information disclosure enables firms to enhance the authenticity and reliability of financial information by systematically disclosing the formation, application, and economic value of data assets [3]. In this study, earnings aggressiveness (*EA*) and earnings smoothness (*ES*) are used as indicators to measure the extent of earnings manipulation. *EA* reflects the aggressiveness of a firm's accounting recognition, while *ES* measures the extent to which firms smooth profits through accrual items [13]. The regression results in Columns (1) and (2) of Table 4 show that data asset disclosure significantly reduces earnings aggressiveness; the results in Columns (3) and (4) indicate that data asset disclosure also reduces earnings smoothness. These findings suggest that corporate data asset disclosure effectively curbs excessive earnings recognition and profit smoothing practices through accounting manipulation, thereby enhancing the authenticity and reliability of financial reporting, which in turn facilitates UIC.

Second, UIC is characterized by long investment cycles, high uncertainty, and limited short-term financial returns. If corporate management exhibits a short-term orientation, focusing excessively on immediate performance and returns, this can undermine the willingness and sustainability of UIC participation [7]. The disclosure of digital asset information improves the transparency of a firm's operations and strategies, strengthening external oversight and limiting executives' ability to focus on short-term gains at the expense of long-term value [1]. Managerial short-termism (*Myopia*) is measured from the MD&A sections of annual reports as the proportion of words reflecting short-term focus, with higher values indicating stronger short-term orientation. The regression results in Columns (5) and (6) of Table 4 demonstrate that digital asset disclosure significantly mitigates management's short-term orientation (*Myopia*). This suggests that data asset disclosure helps alleviate management's short-term focus, encouraging firms to prioritize long-term strategies and effectively fostering the development of UIC.

Table 4: The Mediating Effect Test of Mechanisms.

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	*EA*	*EA*	*ES*	*ES*	*Myopia*	*Myopia*
DAD1	-0.001***		-0.138***		-0.006***	
	(-3.732)		(-3.094)		(-10.703)	
DAD2		-0.076***		-9.871**		-0.650***
		(-2.793)		(-2.142)		(-10.703)
Controls	YES	YES	YES	YES	YES	YES
Year	YES	YES	YES	YES	YES	YES
Industry	YES	YES	YES	YES	YES	YES
Constant	0.021***	0.022***	5.408***	5.549***	-0.052***	-0.047***
	(5.033)	(5.285)	(7.766)	(7.999)	(-5.848)	(-5.333)
Observations	35,732	35,732	26,383	26,383	42,203	42,203
Adjust R^2	0.806	0.806	0.144	0.144	0.094	0.094

4.5. Heterogeneity Analysis

First, a mature tech-finance system provides more support for innovative firms, making it easier for companies to gain trust and recognition when disclosing data asset information, thereby attracting more collaborative opportunities. In these regions, the financial service system is closely integrated with the technology innovation ecosystem, enabling firms not only to obtain capital support but also to share more data and technical resources with research institutions. From a theoretical perspective, the tech-fin pilot city policy is treated as an "amplifying condition" rather than a direct external influence: it does not independently alter the core relationship between data asset disclosure and UIC, but by providing administrative coordination and resource support (e.g., government-led financial integration and innovation platform construction), it strengthens the positive association between the two. Based on this, the study conducts a heterogeneity analysis using the tech-fin pilot cities initiated by the Ministry of Science and Technology and the People's

Bank of China since 2011 as the grouping criterion. The first batch of 16 regions began the pilot in 2011, and an additional 9 cities were added in 2016. Empirical results in Table 5 show that the impact of digital asset disclosure on UIC is significantly higher in the tech-fin pilot cities compared to non-pilot cities, confirming the amplifying effect of supportive policies.

Table 5. Heterogeneity Analysis Regression Results: Tech-Fin Pilot Cities.

	(1)	(2)	(3)	(4)
VARIABLES	TF Pilot Cities	TF Pilot Cities	TF non-Pilot Cities	TF non-Pilot Cities
DAD1	0.040***		0.028***	
	(7.916)		(4.547)	
DAD2		2.821***		1.565**
		(5.532)		(2.311)
Controls	YES	YES	YES	YES
Year	YES	YES	YES	YES
Industry	YES	YES	YES	YES
Constant	-2.425***	-2.469***	-2.086***	-2.112***
	(-25.479)	(-26.006)	(-27.381)	(-27.823)
Observations	20,765	20,765	21,438	21,438
Adjust R^2	0.118	0.117	0.085	0.084

Second, intellectual property protection directly influences firms' trust in, protection of, and willingness to share technological innovation outcomes. In environments where intellectual property is effectively protected, firms can innovate and disclose data assets with greater confidence, thus reducing the risks of misuse or theft of intellectual property. In November 2022, the China National Intellectual Property Administration launched the first batch of local data intellectual property pilot projects, with the pilot period running from November 2022 to December 2023. Consistent with the tech-fin pilot policy, data IP pilot policies are also classified as "amplifying conditions": by improving the institutional environment for IP protection through administrative coordination, they indirectly enhance the signaling effect of data asset disclosure without directly intervening in collaboration decisions. Empirical results from Table 6 show that the positive effect of data asset disclosure on UIC is significantly stronger in the pilot cities compared to non-pilot cities. This suggests that in these regions, the improvement in intellectual property protection mechanisms effectively enhances the trustworthiness of data asset disclosure, thereby promoting the depth and breadth of UIC.

Table 6. Heterogeneity Analysis Regression Results: data IP Pilot Cities.

	(1)	(2)	(3)	(4)
VARIABLES	IP Pilot Cities	IP Pilot Cities	IP non-Pilot Cities	IP non-Pilot Cities
DAD1	0.056***		0.032***	
	(7.745)		(5.171)	
DAD2		3.889***		2.258***
		(5.344)		(3.174)
Controls	YES	YES	YES	YES
Year	YES	YES	YES	YES
Industry	YES	YES	YES	YES
Constant	-2.753***	-2.836***	-2.264***	-2.296***
	(-13.079)	(-13.507)	(-37.258)	(-37.921)
Observations	5,076	5,076	37,127	37,127
Adjust R^2	0.120	0.117	0.099	0.098

5. Conclusion

Grounded in a big data–driven management perspective, this study investigates the impact of corporate data asset disclosure on UIC within China's policy-driven innovation system. Empirical evidence demonstrates that data asset disclosure exerts a significant positive effect on UIC. The results remain robust after addressing endogeneity concerns using IV and PSM approaches. The primary mechanisms through which data asset disclosure promotes UIC are twofold: it enhances the accuracy and reliability of financial reporting, and it mitigates executives' short-term oriented behaviors. Heterogeneity analyses further reveal that the effect of data asset disclosure is particularly pronounced in tech-finance pilot cities and data intellectual property pilot cities, highlighting that policy support and intellectual property protection act as amplifying conditions.

The findings carry important implications for both corporate practice and policymaking. First, within the context of a policy-driven innovation system, firms should prioritize data asset disclosure as a core component of digital governance and innovation strategy. By systematically disclosing the formation, application, and value of data assets, firms can improve the transparency and reliability of financial reporting, constrain managerial short-termism, and strengthen trust with external partners, thereby facilitating deeper collaboration with universities and research institutions. Second, in response to the institutional development needs of a policy-driven innovation system, policymakers should establish institutional support through well-developed tech-finance systems and robust data intellectual property protection mechanisms. Empirical results indicate that in pilot cities with advanced tech-finance initiatives and local data IP protection, the positive impact of data asset disclosure on UIC is significantly enhanced. This underscores that policy support and intellectual property protection can magnify the effectiveness of corporate disclosure, contributing to the development of a more efficient and collaborative university–industry innovation ecosystem.

Although this study systematically analyzes the relationship between data asset disclosure and UIC in a policy-driven innovation system, some limitations remain. First, the findings are mainly applicable to policy-driven systems and may have limited relevance for market-oriented systems in some Western countries. Second, joint patents are used as a proxy for UIC, providing observable evidence of formal collaboration with institutional relevance, but they may not fully capture non-patent forms such as contract R&D, technology transfer, consulting, or talent mobility. Future research could expand collaboration indicators, include diverse forms of collaboration, and conduct cross-country comparisons to test the applicability and generalizability of data asset disclosure effects on UIC.

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Construction of an Informative Management Framework for Sugarcane Plantation Based on Algorithms and Digital Technologies

Jinghuan ZHU and Shilong WANG[1]
Institute of Modern Sugar Industry Development Research, Guangxi Science & Technology Normal University, Laibin, China

Abstract. To promote the transformation and upgrading of the sugarcane industry toward greater precision and intelligence, this paper systematically explores the deep integration pathways and application paradigms of algorithms and digital technologies in the information-based management of sugarcane cultivation. The study constructs a comprehensive technical framework with the logical main line of "perception-transmission-decision-execution", analyzes the application of perception technologies such as the Internet of Things, remote sensing, and unmanned aerial vehicles in field data collection, and elaborates on the key roles of machine learning, optimization algorithms, and knowledge graphs in intelligent decision-making. Through the prototyping of an integrated management platform and validation through a typical 50-mu sugarcane base, the proposed system achieves approximately 30% water savings, 20% fertilizer savings, and a 20% increase in average net income per mu, thereby providing technical support for the sustainable development of precision sugarcane agriculture.

Keywords. Sugarcane cultivation, Information management, Digital technology, machine learning Internet of Things

1. Introduction

Sugarcane is a crucial sugar and economic crop in China, and the stable development of its industry holds significant importance for regional economies [1]. However, China's sugarcane cultivation has long relied on traditional management methods based on experience accumulation, facing challenges such as low production efficiency, excessive resource consumption, delayed pest control, and increasingly scarce labor. Leveraging modern technological means to drive the transformation and upgrading of sugarcane planting toward informatization and intelligentization has become an urgent

[1] Corresponding Author: Shilong WANG, Guangxi Science & Technology Normal University, Laibin, China; Email: wangshilong@gxstnu.edu.cn
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need for cost reduction, efficiency improvement, and sustainable development in the industry. With the deep integration of technologies like the Internet of Things, big data, and artificial intelligence into agriculture, the synergy between "algorithms" and "digital technologies" is emerging as the core driving force to advance precision agriculture from theory to practice [2-3].

Although certain progress has been made in the informatization of sugarcane cultivation, existing research still exhibits notable shortcomings. Most achievements focus on the independent application of single technologies, lacking top-level design for the organic integration of algorithms and digital technologies at the systemic level. Technical solutions generally lack quantitative evaluation metrics, and their reference to cutting-edge international precision agriculture achievements remains relatively limited. Therefore, this paper aims to establish a fusion application system for algorithms and digital technologies. By designing a four-tier framework of "perception-transmission-decision-making-execution," clarifying input features and cross-validation methods for integrated learning yield prediction models, and conducting quantitative effect evaluations based on a 50-acre demonstration base, it seeks to provide systematic technical support for the informatized management of sugarcane cultivation.

2. Build a Framework for the Integration of Algorithms and Digital Technology

This study constructed a four-layer technology fusion framework that includes perception layer, transport layer, decision layer, and application layer, achieving closed-loop management from data perception to intelligent decision-making and precise execution. The perception layer comprehensively utilizes three perception methods: ground-based, airborne, and space-based. Among them, ground-based sensing is based on IoT sensors, airborne sensing relies on unmanned aerial vehicle multispectral cameras, and space-based sensing utilizes satellite remote sensing technology. The transport layer uses LoRa for data aggregation and uploads it to the cloud service platform through 4G or 5G networks. The decision-making layer is the intelligent hub of the entire system, with machine learning models used for prediction and recognition, optimization algorithms used for resource allocation, and knowledge graphs used for knowledge inference. The application layer converts decision outputs into specific service functions for users [4-5]. Compared with the existing smart agriculture architecture, this framework has been specifically optimized for the specific needs of sugarcane cultivation, including management of perennial sugarcane and scheduling of harvest during the pressing season. Data interface standards have been designed between different levels, effectively solving the problem of interconnection and interoperability between heterogeneous systems. As shown in Table 1.

Table 1: Integrated Framework for Information Management of Sugarcane Planting.

Architecture Layer	Core Functionality	Key Technologies	Main Outputs
Perception Layer	Environmental and crop data acquisition	IoT sensors, UAV remote sensing, satellite observation	Soil parameters, environmental indicators, multi-source image data
Transmission Layer	Data transmission and exchange	LoRa, 4G/5G, NB-IoT	Reliable data streams, real-time transmission channels
Decision Layer	Intelligent analysis and decision-making	Cloud computing, machine learning, knowledge graphs	Prediction models, diagnostic reports, decision solutions
Application Layer	Service execution and feedback	Web/mobile applications, smart agricultural machinery	Visualization reports, control commands, operational plans

3. Key Technology and Algorithm Integration Path

3.1 Field Data Collection Based on Multi-Source Perception

A comprehensive data collection system is the foundation for achieving precision agriculture. In modern sugarcane cultivation, an integrated three-dimensional monitoring network of heaven, earth, and space is established to obtain real-time field data from multiple dimensions [6-7]. Ground sensing uses IoT sensors to monitor soil temperature, humidity, EC values, and meteorological elements; Airborne sensing relies on unmanned aerial vehicle multispectral cameras to obtain centimeter level canopy images, once every two weeks; Space based sensing utilizes Sentinel-2 and Landsat-8 satellites to obtain 10 meter resolution multi temporal images every 5 days, tracking sugarcane growth dynamics through NDVI, EVI and other indicators. As shown in Table 2.

Table 2: Technical parameters of multi-source perception monitoring system for sugarcane fields

Perception Level	Monitoring Indicators	Technical Means	Spatial Resolution	Temporal Resolution
Ground-based Perception	Soil temperature-humidity, EC values	IoT Sensors	Point scale	Real-time monitoring
Airborne Perception	Canopy spectrum, plant morphology	UAV Remote Sensing	Centimeter level	Regular monitoring
Space-based Perception	Vegetation index, biomass	Satellite Remote Sensing	Meter level	Periodic monitoring

3.2 Decision making Core Algorithm Model and Application

The decision-making layer is the intelligent hub of the entire framework, and its core task is to deeply mine and intelligently analyze the multi-source data gathered by the perception layer. This layer integrates three core technologies: machine learning models, optimization algorithms, and knowledge graphs and expert systems, which respectively undertake the functions of predictive recognition, resource allocation, and knowledge reasoning.

3.2.1 Machine Learning Models and Applications

Machine learning algorithms provide the core driving force for precision management of sugarcane cultivation. In terms of yield prediction, a prediction model based on ensemble learning can be constructed, integrating multidimensional features such as remote sensing vegetation index, meteorological data, and soil parameters, and screening key influencing factors through feature importance analysis. In terms of disease and pest identification, deep learning object detection algorithms can be used to improve the model's generalization ability through multi-scale training and data augmentation techniques, achieving real-time analysis and early warning of field images. In terms of growth monitoring, time-series analysis models can be used to integrate multispectral vegetation indices and sensor data, effectively tracking the growth trajectory of sugarcane and providing decision-making basis for precision fertilization and irrigation [8-9]. The specific application directions of the above model are shown in Table 3.

Table 3: Main application directions of machine learning models in sugarcane cultivation

Application Scenario	Main Input Data	Typical Algorithm	Expected Output
Yield Prediction	Remote sensing data, meteorological data, soil data	Ensemble Learning	Yield grade estimation, harvesting plan recommendations
Pest and Disease Identification	UAV or field images	Deep Learning Object Detection	Pest/disease type, occurrence location, early warning information
Growth Monitoring	Multispectral images, environmental sensor data	Time Series Analysis Model	Growth status assessment, nutrient condition diagnosis

3.2.2 Optimization Algorithm and Application

Optimization algorithms have significant value in resource allocation and job planning for sugarcane cultivation. In terms of water and fertilizer management, a multi-objective optimization model based on genetic algorithm can be established, which comprehensively considers constraints such as soil moisture, nutrient status, and weather forecast, with the goal of maximizing water use efficiency and fertilizer partial productivity, to generate the optimal water and fertilizer ratio scheme. In terms of harvest scheduling, a mixed integer programming model can be constructed and solved using ant colony algorithm, taking into account constraints such as sugarcane freshness, equipment capacity, and transportation capacity, to minimize harvest costs and maximize freshness [10]. The specific application directions are shown in Table 4.

Table 4: Main application directions of optimization algorithms in sugarcane cultivation

Application Area	Typical Algorithm	Main Decision Variables	Optimization Objective
Water and Fertilizer Management	Genetic Algorithm	Irrigation amount, fertilizer amount	Water saving and efficiency improvement
Harvest Scheduling	Ant Colony Algorithm	Operation sequence, equipment allocation	Cost reduction and efficiency improvement

3.2.3 Knowledge Graph and Expert System

Knowledge graph technology has constructed a structured knowledge system for sugarcane cultivation. The system constructs an ontology model that covers core concepts such as crop physiology, cultivation management, and pest control, forming a domain knowledge network that supports fast querying and multi hop reasoning of complex knowledge relationships. When the user inputs a composite query, the system analyzes the relationships between entities to generate a solution that includes diagnostic results, prevention and control recommendations, and operational guidance, transforming expert experience into reusable knowledge assets. The specific architecture is shown in Table 5.

Table 5: Architecture of the knowledge graph system for sugarcane cultivation

Function Module	Technical Implementation	Core Function
Knowledge Storage	Graph Database	Support complex relationship query and traversal
Knowledge Inference	Path Ranking Algorithm	Enable multi-hop reasoning and complex query
Knowledge Application	Intelligent Q&A	Provide diagnosis results and control recommendations

4. System Implementation and Typical Case Analysis

4.1 Prototype Design of Comprehensive Management Platform

Based on the above technical framework, this study designed a prototype of sugarcane planting information comprehensive management platform. The platform adopts a layered architecture, including data layer, support layer, service layer, and application layer. Each layer works together through standardized interfaces and can be deeply integrated with external systems such as intelligent irrigation, agricultural machinery management, and meteorological services. The specific architecture is shown in Table 6.

Table 6: Architecture and functions of the integrated management platform

Architecture Layer	Technical Components	Core Functions	Application Value
Data Layer	Distributed database, real-time data stream	Multi-source data integration, storage and management	Achieve unified data governance and value mining
Support Layer	Machine learning models, knowledge graph	Intelligent algorithm services, knowledge reasoning	Provide decision support and problem diagnosis
Service Layer	Microservice architecture, API gateway	Business logic encapsulation, interface services	Ensure system stability and fast response
Application Layer	Visual interface, mobile application	User interaction, business function implementation	Enhance user experience and operational convenience

4.2 Typical Case Analysis

To verify the application effect of the integration framework of algorithms and digital technology in sugarcane cultivation, this paper selects a 50-acre sugarcane base as a

demonstration site to carry out intelligent water and fertilizer integrated management practice for the production cycle of one season of sugarcane. During the system deployment phase, soil moisture sensors and small weather stations will be installed, the irrigation system will be upgraded, and intelligent control valves and variable fertilization equipment will be equipped. The data collection frequency is once per hour, and during the critical growth period, it is increased to once every 30 minutes. The decision model is based on historical data to train a water and fertilizer demand prediction model, which can predict the water and fertilizer demand for the next few days and generate accurate water and fertilizer scheduling plans using optimization algorithms. The implementation effect shows that the intelligent water and fertilizer management system has achieved significant improvements in water conservation, fertilizer conservation, and economic benefits. The specific comparison is shown in Table 7.

Table 7: Indicators before and after intelligent water and fertilizer management

Indicator	Before	After	Change
Total irrigation volume (m^3/mu)	Approx. 500	Approx. 350	-30%
Fertilizer application (kg/mu)	Approx. 200	Approx. 160	-20%
Of which, nitrogen fertilizer (kg/mu)	Approx. 60	Approx. 45	-25%
Average net income per mu (yuan)	Approx. 500	Approx. 600	+20%

5. Summary

This article constructs a four-layer technical framework of "perception transmission decision execution" and systematically explores the integration path of algorithms and digital technology in sugarcane planting information management. At the perceptual level, a multi-source data collection system integrating heaven, earth, and space has been established to achieve comprehensive monitoring of sugarcane growth environment and crop status. At the decision-making level, the application of machine learning in yield prediction and pest identification, the value of optimization algorithms in resource allocation, and the role of knowledge graphs in agricultural knowledge management were explored. Through typical case verification, the intelligent water and fertilizer management system has achieved significant results, validating the effectiveness of the fusion framework [11-12]. The main contribution of this study is the construction of an algorithm and digital technology integration framework for sugarcane cultivation, clarifying the hierarchical interfaces and collaborative mechanisms of the four-layer architecture, and verifying the actual effectiveness of the technical system through real cases. There are still certain limitations to the research, such as limited case size, technical requirements for infrastructure, and further testing of the long-term stability of the model. In the future, we will carry out larger scale demonstrations and promotions, explore lightweight technology solutions, and continuously optimize algorithm performance.

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Modeling Cultural Narrative Mechanisms of Xiang Cuisine on Social Media: A Multi-Modal Deep Learning Approach

Jiaxin Deng[a,1] , Yidan Zhu[b,2],Yao Lu[b,3] and Kun Zhou[c,4]
[a]*Heilongjiang Bayi Agricultural University, China*
[b]*Hunan Women's University, China*
[c]*Zhejiang Business Technology Institute, China*
ORCiD ID: Jiaxin Deng https://orcid.org/0009-0000-3302-9844
Yidan Zhu https://orcid.org/0009-0006-4583-801X
Kun Zhou https://orcid.org/0000-0003-0623-2825

Abstract. Digital platforms have reshaped how local culinary culture is produced and interpreted through user-generated content (UGC), yet tourism research largely treats UGC as an informational stimulus rather than a structured meaning system. Adopting a cultural narrative perspective, this study examines Xiang cuisine short-video UGC on TikTok and Twitter and develops a multidimensional framework encompassing symbolic representation, identity embedding, socio-cultural value framing, processual narration, sensory-affective expression, and platformed engagement. A multimodal multilabel deep learning model is employed to identify narrative elements across visual, auditory, and textual data, combined with time-series segmentation and a Cultural Narrative Intensity index to quantify structural expression. Findings indicate that Xiang cuisine cultural narrative operates as a cross-level system in which symbolic encoding, cognitive-affective processing, and platform mechanisms jointly shape cultural meaning production. By conceptualizing UGC as a structured narrative system rather than a discrete stimulus variable, this study offers a structure-oriented framework for understanding digital cultural meaning generation in tourism contexts.

Keywords. Cultural narrative, Xiang cuisine, Multimodal analysis, Deep learning

[1]First Author: Jiaxin Deng, Undergraduate majoring in Food Science and Engineering, Heilongjiang Bayi Agricultural University, China, Email: 3182015141@qq.com

[2] Corresponding Author: Yidan Zhu, Lecturer, Ph.D., research interests in Hotel and Homestay Digital Intelligent Operation, Email: zhuyidan@hnwu.edu.cn

[3]Third Author: Yao Lu, Lecturer, research interests in Tourisms Digital Intelligent, Hunan Women's University, China, Email: luyao@hnwu.edu.cn

[4] Fourth Author: Kun Zhou, Lecturer, Ph.D., research interests in Artificial Intelligence Technology; Email: zhoukuniyc@gmail.com

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1. Introduction

In the context of digital platforms deeply reshaping communication structures, the production and dissemination of cultural meaning increasingly rely on user-centered media practices [1]. Compared to institutionalized, one-way cultural export, culinary culture, due to its everyday, experiential, and emotionally embedded characteristics, has gradually become an important vehicle for understanding foreign cultures and constructing cultural cognition [2]. As Chinese regional cuisines continue to enter overseas digital platforms, the "going global of Chinese cuisine" has evolved from merely a phenomenon of commercial expansion to a process of cultural meaning construction occurring within platform contexts.

As one of China's eight major cuisines, Xiang cuisine is frequently presented on overseas social media platforms due to its distinct taste features and regional symbols [3]. On short video platforms such as Tiktok, Xiang cuisine content is primarily disseminated in the form of user-generated content (UGC). These videos not only showcase the dishes themselves but also embed local history, lifestyle, and cultural values into the narrative through elements such as ingredient and utensil symbols, local spatial scenes, character identities, and linguistic expressions, transforming food from a material consumption object into a text carrying cultural meaning.

Cultural narrative is not a simple presentation of information, but rather an organized process of meaning generation through symbolic representation, situated narrative context, and emotional expression. Existing research has explored the influence mechanisms of UGC from the perspectives of image formation[4][5], risk perception[6][7], and experiential evaluation[8], it often treats UGC as an external informational cue or stimulus variable, emphasizing its impact on attitudes and behaviors, while paying less attention to how the internal narrative structure of content contributes to the generation of cultural meaning. As a result, existing studies, while addressing whether UGC is "effective," still struggle to answer how UGC "exerts cultural influence through narrative structure." This limitation is particularly pronounced in cross cultural communication contexts dominated by short videos. Cultural meaning in short videos is highly dependent on the narrative structure itself, the configuration of symbols, the development of processes, and the mobilization of emotion directly influence the perceptibility and interpretability of cultural content. However, existing research lacks operational definitions and dimensional breakdowns of the cultural narrative structure in short videos, with analyses typically limited to descriptive phenomena or single-element attribution. Moreover, methodologically, studies still predominantly rely on manual coding and small sample analysis, which are insufficient to address the multimodal characteristics and high heterogeneity of short videos across visual, auditory, and textual dimensions [9].

Based on this, this study adopts a cultural narrative perspective to systematically explore the process of cultural meaning construction in Xiang cuisine short video UGC, with a focus on answering how Xiang cuisine culture is organized into structured narrative texts within the short video context, what its core dimensions and measurable indicators are, and how different narrative dimensions collectively promote the generation and diffusion of cultural meaning through specific mechanism pathways. By integrating cultural narrative theory with multimodal multilabel deep learning methods, this study redefines UGC from an "external informational stimulus" to a "structured cultural narrative system"; it also transforms cultural narrative into identifiable, measurable, and modelable structural dimensions using deep learning methods. This

approach reveals the synergistic mechanisms of cognitive and emotional pathways in short video cultural narratives and provides a structured explanatory framework for understanding the cross-cultural dissemination of culinary culture on digital platforms.

2. Literature Review on Cultural Narrative

Existing research widely recognizes that cultural narrative is the core mechanism through which cultural meaning is generated, organized, and disseminated. Its essence is not a simple reproduction of cultural elements but rather the integration of cultural components into a meaningful structure with inherent logic through symbolic representation, situated narrative context, and emotional engagement [10]. In digital media environments, this process is increasingly shaped by platformization, visualization, and user-driven content production, resulting in a cultural narrative that is highly everyday and decentralized in nature [1].

From a research perspective, cultural narrative has been widely applied in studies of local culture, tourism destinations, and cultural consumption [11]. Existing research demonstrates that cultural narrative plays a critical role in constructing local identity, shaping spatial recognition, and evoking cultural memory by transforming abstract cultural values into perceptible and experiential meanings, thereby strengthening emotional connection and identification among audiences [12][13]. In digital destination branding and strategic communication, cultural narrative is further conceptualized as a key intermediary linking local resources with audience cognition, whose effectiveness depends more on narrative structure and emotional intensity than on information volume itself [14].

In the context of user-generated content (UGC) and short videos, a substantial body of research has confirmed that UGC influences image cognition, emotional responses, and value judgments, subsequently shaping behavioral intentions such as recommendation, visitation, or purchase [4-8]. However, comparatively little attention has been paid to the internal organization of content, particularly how narrative elements are structured, combined, and translated into cultural meaning, indicating that while UGC has been shown to be effective, the narrative mechanisms through which it functions remain insufficiently explored [9].

From a narrative theory perspective, structural approaches emphasize that narratives consist of identifiable units that combine into stable meaning patterns. Although short video studies have applied this perspective to demonstrate that clear narrative cues and emotional trajectories enhance audience responses [15-16], existing research has largely relied on perceptual scales or manual coding, limiting its capacity to address the scalability and multimodal complexity of short-form video content.

On the methodological front, computational approaches and deep learning have enabled narratives to be identified, quantified, in food culture and short-form video research, existing applications of deep learning have focused primarily on sentiment or thematic recognition, while systematic dimensional extraction and indicator construction of cultural narrative structures remain underdeveloped. Accordingly, although previous studies have clarified the theoretical importance of narrative in meaning construction and examined its cognitive and behavioral effects, digital short-video contexts still lack a computable and structurally grounded representation of cultural narrative itself. To address this gap, the present study integrates cultural narrative theory, UGC research, and deep learning methods to model the dimensions, structural features, and generative

mechanisms of cultural narratives in the global dissemination of Xiang cuisine short videos, thereby extending existing literature from narrative effects to narrative structure and mechanism.

3. Methodology

3.1. Research Design

This study takes short video user-generated content (UGC) related to Xiang cuisine on TikTok and Twitter as the research object and conducts systematic encoding and analysis. Building on existing approaches, a multilabel cultural narrative recognition model is developed by integrating deep learning methods based on transformer architectures and incorporating techniques in video representation, audio modeling, and multimodal fusion [16-18]. Given that cultural narratives in short videos typically involve multiple coexisting and interwoven elements, a multilabel learning strategy is adopted to enable each video to simultaneously activate multiple narrative dimensions, thereby providing a more effective representation of the multidimensional structure of short video narratives.

As shown in Figure 1, the proposed framework consists of three stages: multimodal input and feature extraction, cross-modal integration in a shared latent space, and narrative representation through dimension aggregation and mechanism construction. Visual features are extracted from sampled video frames using a CNN-based encoder, audio signals are represented through MFCC and spectral features, and textual information is modeled using a transformer-based language model based on subtitles and captions. These modality-specific representations are projected into a shared latent space and integrated through a late-fusion strategy for multilabel classification.

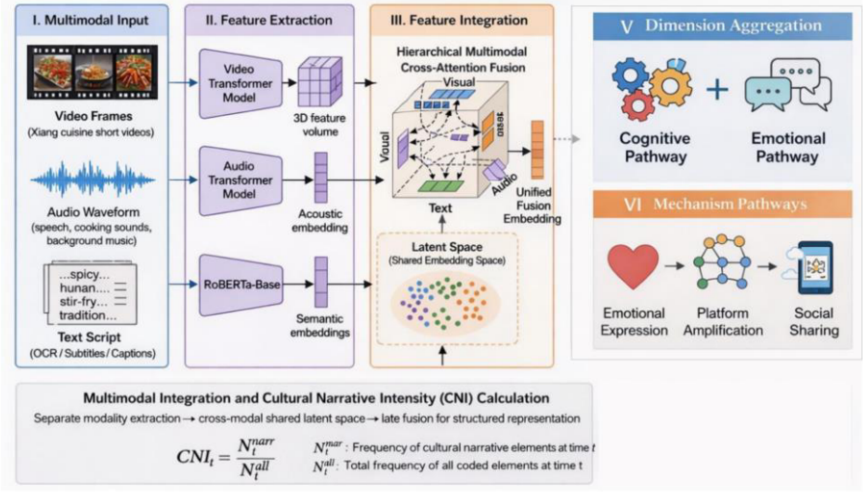


Figure 1. Multimodal Framework for Xiang Cuisine Cultural Narrative Identification and Mechanism Construction

To capture the processual structure of short-video narratives, the study applies time-series segmentation, dividing videos into three narrative phases: Hook, Climax, and Call

to Action (CTA). A Cultural Narrative Intensity (CNI) index is further constructed by integrating multilabel recognition results with narrative phase distribution. Given the relatively modest dataset size, the model is used as an analytical tool for structured narrative identification rather than as an autonomous predictive system.

3.2. Data Sources and Sample Selection

This study uses short video user generated content (UGC) related to Xiang cuisine (Hunan cuisine) as the primary data source. Relevant content was retrieved through the use of keywords related to Xiang cuisine's culinary culture (such as "Xiang cuisine," "Xiang flavor," "Hunan taste", and "traditional Xiang cuisine") on TikTok and Twitter, with rolling collection methods employed, followed by manual screening to ensure the relevance and analytical validity of the sample.

During the data cleaning phase, the study excluded three types of videos: (1) videos where Xiang cuisine was not the core narrative subject; (2) pure advertisements or videos lacking substantial narrative content; (3) videos with incomplete audiovisual information that made semantic recognition difficult. The final dataset consists of 238 valid short videos, covering home cooking, restaurant showcases, heritage or time-honored brand narratives, food exploration videos, tutorial demonstrations, and creator-audience interaction formats (See in Table 1). This sample composition provides a relatively comprehensive representation of Xiang cuisine cultural narratives on short-video platforms.

For model training, an annotated subset of the dataset was manually coded according to the cultural narrative framework developed in this study. Two trained researchers independently labeled the narrative elements using the predefined coding scheme, and disagreements were resolved through discussion. Inter-coder agreement reached a Cohen's kappa value of 0.84, indicating strong coding reliability. Although the dataset size is limited for broad statistical generalization, it is sufficient for exploratory multimodal coding and structured narrative identification.

Table 1. Data Sources and Basic Characteristics of the Short Video Sample

Item	Description
Number of videos	238
Platform sources	TikTok, Twitter
Video duration	10 to 60 seconds, primarily short form videos
Content types	Home cooking; restaurant showcase; tutorial; food vlog; interactive content
Narrative focus	Xiang cuisine as the core subject
Language	English
Audiovisual integrity	100 percent analyzable

3.3. Analytical Tools and Deep Learning Process

Following Figure 1, the analytical process is operationalized through three tasks. Task 1 (T1) performs multilabel identification of cultural narrative elements across multimodal inputs. Task 2 (T2) captures temporal narrative structure through time-series segmentation, dividing each video into Hook, Climax, and CTA phases. Task 3 (T3) integrates these outputs to construct the Cultural Narrative Intensity (CNI) index.

The CNI index is designed to reflect the distribution of culturally meaningful narrative expressions within each video and is calculated as follows [18]:

$$\mathrm{CNI}_t = \frac{N_t^{narr}}{N_t^{all}} \quad (1)$$

N_t^{narr} denotes the number of Xiang cuisine short videos classified as exhibiting cultural narrative characteristics within time window *t*. And N_t^{all} represents the total number of Xiang cuisine short videos within the same time window. In this study, *t* refers to the segmented analytical unit derived from narrative phase division.

The annotated dataset was divided into training (70%), validation (15%), and test (15%) subsets. The model was trained using binary cross-entropy loss with the Adam optimizer. Performance was evaluated using precision, recall, and F1-score. The final model achieved an average F1-score of 0.82 across narrative categories, and outputs were further cross-checked through manual inspection of randomly sampled videos (see Table 2).

Table 2. Multimodal Analytical Pipeline and Core Variables

Analytical Stage	Input Data	Method	Key Output Variables	Variable Type
Data preprocessing	Video, audio, text	Audiovisual feature extraction	Duration, acoustic energy, visual features	Numerical
Narrative segmentation	Audiovisual stream	Time-series segmentation	Hook, Climax, Call to Action	Categorical
Narrative element identification	Video, audio, text	Multilabel learning	Cultural narrative codes (A–F)	Probabilistic / binary
Narrative intensity measurement	Narrative outputs	Composite index construction	Cultural Narrative Intensity (CNI)	Continuous

4. Results

4.1. Multimodal Text Analysis and Narrative Structure Segmentation

Multimodal text analysis reveals that Xiang cuisine short videos exhibit a highly standardized narrative structure, with distinct functional configurations across different narrative stages. The analysis shows that visual, auditory, and textual cues are systematically differentiated along the temporal progression of the video.

Specifically, visual appetite cues and immediate sensory stimulation are predominantly activated in the Hook phase, technical and cultural content concentrates in the Climax phase, and emotional expression together with interaction-oriented cues intensifies in the Call to Action (CTA) phase. These results indicate a clear alignment between narrative stages and multimodal functional roles in Xiang cuisine short videos (see Table 3).

Table 3. Narrative Stages and Multimodal Characteristics

Narrative Stage	Main Visual Cues	Main Audio/Text Cues	Narrative Function
Hook	Glaze, close-ups, slow motion	Cooking sounds, brief subtitles	Attention capture
Climax	Cooking process, heat display	Explanatory language, step prompts	Cultural meaning construction
CTA	Finished dish display, character appearance	Emotional expression, interactional language	Engagement and identity mobilization

4.2. Construction of Xiang Cuisine Cultural Narrative Coding System

Building upon the multimodal multilabel recognition model, this study develops an operable and replicable coding system for cultural narrative elements in Xiang cuisine

short-video UGC (see Table 4). Table 4 reports the model-identifiable narrative cues, their operational definitions, multimodal evidence cues, and average activation probabilities, providing the basis for subsequent structural analysis and index construction.

Table 4. Multi-label Cultural Narrative Coding Scheme and Probability Estimates

code	Items	Operational definition	Evidence cues	Overall mean p
A1	Ingredient symbols	Chili/chopped chili/dried chili/millet chili/fermented black beans/cured meat, etc.	Ingredient close-ups/ingredient tray close-ups/voice-over subtitles	0.33421862
A2	Dish symbols	Classic Hunan dishes and finished dishes	Finished dish close-ups/menu shots/topic tags	0.33421862
A3	Tools& cookware	Iron wok/sand pot/earthenware pot/wood-fired stove/ladle, etc.	Utensil close-ups/sound of fire on the stove	0.5056816
A4	Dining space	Big stalls/night markets/time-honored brands/home kitchens	Storefront shots/street scenes/crowd shots	0.37504816
A5	Raw material origin	Raw material origin stories (production areas, farmers' markets, mountain goods, local direct procurement)	Market footage/production area narration	0.39958417
B1	Prep&cutting	Chopping/cutting/marinating/seasoning, etc.	Knife work shots/sound of chopping/cutting	0.17242493
B2	Aromatics& stir-fry	Stir-frying (scallion, ginger, fermented black beans)/large fire stir-frying	Stir-frying (scallion, ginger, fermented black beans)/large fire stir-frying	0.64086735
B3	Seasoning logic	Stir-frying close-ups/flame shots/quick cuts	Stir-frying close-ups/flame shots/quick cuts	0.33392933
B4	Heat control	Fire control (oil temperature/ time/temperature control, etc.) as "artistic narrative"	Wok interior changes/timed prompts	0.49089396
B5	Plating& serving	Out of the pan/drizzling oil/ sprinkling seasoning/serving on the table	Serving shots/slow-motion action	0.3142186
B6	Recipe tutorial	Tutorial narratives (step-by-step editing, key tips, failure-correction)	Step 1/side-by-side comparison shots	0.6478587
C1	Spiciness rhetoric	Stir-fry/head rush/sweating/overcooking	Emotional reactions/vocabulary enhancement	0.20796773
C2	Aroma& wok hei	Fragrant/spicy/aromatic/appetizing/down with rice	Sensory-motor actions/sound intensification	0.34760407
C3	Texture rhetoric	Crispy/tender/glutinous/savory /umami	Close-ups of cross-sections/chewing shots	0.2882744
C4	Soundscape ASMR	Sizzling/slicing/crunching/ASMR	Audio enhancement/contrast between quiet and loud sounds	0.50719845
C5	Visual appetite cues	Visual appetite cues (grease, drawing silk, juice, slow-motion close-ups)	Close-ups/slow-motion shots	0.6721951
D1	Toponyms	Hunan/Changsha/Western Hunan/old alley landmarks	Location stickers/road sign cards	0.26088148
D2	Human roles	Chef/boss lady/ transmitter/ family chef	Character appearances/self-narratives	0.17446457
D3	Dialect& speech style	Tone/way of speaking/air	Tone/subtitle word choices	0.4615485

D4	Night economy scene	Late-night snacks/ night markets / queuing hotspots	Night scenes/crowd sounds	0.4008896
D5	Brand/heritage shop	Brands and time-honored brands	Storefronts/awards/old photos	0.5737726
E1	Everyday ethics	Home cooking/warmth/down with rice	Family/friends dining together	0.24077429
E2	Nostalgia	Hunan hometown flavors/ childhood memories/ mom's cooking	Nostalgic narratives/ accompanying music	0.22169685
E3	Craftsmanship & inheritance	intangible cultural heritage/ decades of craftsmanship	Inheritance narratives/ master-apprentice stories	0.30566737
E4	Hospitality& sociality	Inviting guests/gatherings/late-night cultural events	Multiple people dining together	0.24077429
E5	Identity pride	Regional pride (self-proclaimed identity and "Xiang flavor" self-expression)	Declarations/commentary leads	0.49089396
E6	Health/ comfort framing	Healing comfort food (relieving stress, relieving pressure and other emotional values)	Slow-paced shots/emotional cues	0.4452391
F1	CTA conversion	Address/price/queuing/favorites list	Closing screen voice-over	0.340596
F2	Hashtags& trends	Platform topics/challenges/ same-style videos	Label stickers/title cards	0.5340357
F3	KOL/UGC style	Ratings/rankings/comparisons/ top picks	Leaderboards/comparison shots	0.27827445
F4	Comment engagement	Comment interaction narratives (reply comments, compilations, secondary creations)	Comment overlays/pinned comments	0.3268262

4.3. Structural Integration and Mechanism Analysis of Cultural Narrative Dimensions

Based on the coding results, the identified narrative elements were aggregated into six relatively distinct and functionally differentiated dimensions (see Table 5). Their distribution indicates a multi-level narrative structure in which processual and sensory elements show stronger salience, while place- and value-related dimensions function as supportive layers within platform interaction mechanisms. This structural configuration provides an empirical basis for subsequent narrative intensity measurement and mechanism analysis.

Table 5. Structural Dimensions of Cultural Narratives and Measurement Indicators

Dimension	Definition	Items
Culinary Semiotic Symbolism	refers to the structured deployment of culinary symbols, such as ingredients, tools, spatial settings, and raw material origins, to construct culturally recognizable meanings of regional food identity.	A1:Ingredient symbols A2:Dish symbols A3:Tools & cookware A4:Dining space A5:Raw material origin
Culinary Processual Narrativity	denotes the narrative representation of cooking procedures through sequenced actions, technical logic, and instructional framing, facilitating cognitive understanding of culinary practices.	B1:Prep & cutting B2:Aromatics & stir-fry B3:Seasoning logic B4:Heat control B5:Plating & serving B6:Recipe tutorial
Sensory-Affective Rhetoric	refers to the narrative use of multimodal sensory cues and affective expressions as rhetorical devices to evoke embodied imagination and emotional engagement.	C1:Spiciness rhetoric C2:Aroma & wok hei C3:Texture rhetoric C4:Soundscape ASMR C5:Visual appetite cues

Localized Identity Construction	denotes the narrative articulation of regional authenticity and symbolic belonging through spatial markers, linguistic styles, social roles, and heritage references.	D1:Toponyms D2:Human roles D3:Dialect & speech style D4:Night economy scene D5:Brand/heritage shop
Socio-Cultural Value Framing	refers to the embedding of normative cultural values and collective meanings, such as nostalgia, craftsmanship, hospitality, and regional pride, within narrative expression.	E1:Everyday ethics E2:Nostalgia E3:Craftsmanship&inheritance E4:Hospitality & sociality E5:Identity pride E6:Health/comfort framing
Platformized Engagement Strategy	captures the narrative incorporation of platform-specific interaction and conversion mechanisms, such as hashtags, evaluative framing, audience interaction, and calls to action, to facilitate algorithmic visibility and participatory dissemination.	F1:CTA conversion F2:Hashtags & trends F3:KOL/UGC style F4:Comment engagement

4.4. Mechanism Pathways of Xiang Cuisine Cultural Narrative

Integrating the coding results (Table 4) with the structural dimensions (Table 5), the cultural narrative of Xiang cuisine short videos can be characterized as a multi-level process comprising macro-level framing, meaning-construction pathways, and platformized diffusion mechanisms (see Figure 2).

At the macro framing level, cultural meaning is configured through culinary symbolic systems, localized identity cues, and socio-cultural value frames. At the level of meaning construction, two complementary pathways are observed: a cognitive pathway centered on processual narration and an affective pathway driven by sensory-affective rhetoric. At the diffusion level, narrative expression is embedded within platform-specific interaction mechanisms, facilitating audience engagement and participatory dissemination.

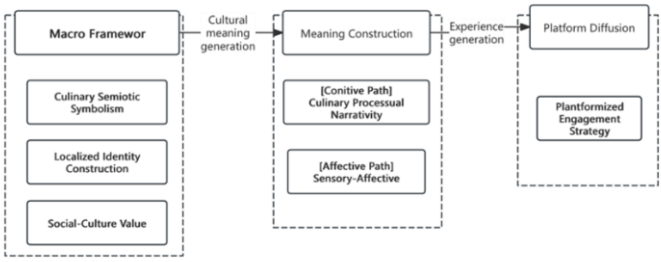


Figure 2. A Multi-Level Framework of Cultural Narrative Generation and Diffusion

5. Discussion and Conclusion

5.1. Discussion

Building on the empirical identification of cultural narrative structures in Xiang cuisine short videos, this study advances understanding of how digital tourism content generates cultural meaning. Prior research has predominantly adopted information-processing or stimulus-response frameworks, conceptualizing user-generated content (UGC) as an

external informational input that influences attitudes and behaviors through mediators such as image formation, risk perception, or experiential evaluation [4][5][7]. While effective in explaining outcomes, this tradition pays limited attention to how the internal organization of content contributes to the ongoing construction of cultural meaning. In contrast, cultural narrative theory emphasizes that meaning is continuously produced within structured narrative configurations composed of symbolic arrangement, contextual embedding, and emotional mobilization [11][16].

From this perspective, the findings indicate that Xiang cuisine short videos operate as structured narrative systems rather than mere information carriers. Cultural meaning does not arise directly from isolated symbols or emotional cues; rather, it emerges through the coordinated operation of multiple narrative components. This shifts analytical focus from variable-centered explanations of content effects toward structure-oriented analyses of meaning construction, offering a clearer account of how local culinary culture is perceived and interpreted on digital platforms.

The results further reveal that cultural narrative in short-video UGC operates through a multi-level integrative structure. Symbolic, identity-based, value-oriented, processual, sensory, and platform-related elements do not function independently; rather, they jointly shape how cultural meaning is organized, interpreted, and circulated on digital platforms. Cultural meaning is therefore generated through the coupling of narrative structure and platform logic rather than through any single dimension acting in isolation.

At the mechanism level, this study identifies a dual-pathway configuration through which cultural narrative operates. The cognitive pathway, centered on processual narration, enhances learnability and cross-cultural interpretability, while the affective pathway, driven by sensory and emotional rhetoric, activates embodied imagination and resonance. These two pathways function in parallel and reinforce one another, demonstrating that cognition and emotion jointly constitute the core mechanism of cultural narrative in digital short-video contexts.

Methodologically, by integrating multimodal recognition with multilabel modeling, this study operationalizes cultural narrative as a set of identifiable and computable structural patterns. This approach extends cultural narrative research beyond conceptual discussion and small-sample interpretation, providing a scalable analytical pathway for examining complex, multimodal digital content.

5.2. Research Conclusion

Using Xiang cuisine short-video UGC as the empirical context, this study constructs a multimodal deep learning-based cultural narrative recognition framework and systematically examines how local culinary culture generates meaning on digital platforms. The findings demonstrate that Xiang cuisine cultural narrative is organized as a multidimensional structural system comprising symbolic construction, localized identity embedding, socio-cultural value framing, processual explanation, sensory-affective evocation, and platformized engagement.

Rather than a loose aggregation of elements, this structure operates as an integrated pathway linking macro narrative framing, meaning-construction mechanisms, and platform-based diffusion. By modeling cultural narrative as a structured and computable mechanism, this study deepens understanding of how local culinary culture is organized, produced, and circulated in digital environments.

5.3. Practical Implications

This study offers multiple practical implications for the expression and dissemination of local culinary culture on digital platforms. Cultural symbols and localized identity cues constitute the foundational layer of narrative construction. Content creators and destination managers should ensure the consistent presentation of ingredients, utensils, spatial settings, linguistic styles, and character identities to establish clear cultural anchoring.

The effectiveness of cultural narrative depends on the joint operation of cognitive and affective pathways. Structured explanation of cooking processes enhances interpretability, while multisensory expression strengthens immersion. Digital content should therefore move beyond showcasing final outcomes to foregrounding production logic, technical explanation, and sensory detail, enabling audiences to engage with culture as an experiential process.

Platform mechanisms play a constitutive role in meaning generation. Hashtags, interactional language, comment engagement, and calls to action shape not only dissemination scope but also narrative rhythm and participation modes. Aligning narrative structure with platform algorithmic logic is essential for achieving coordinated cultural expression and diffusion.

5.4. Limitations and Future Research

Despite its contributions, this study has several limitations. First, the dataset includes only 238 Xiang cuisine short videos from TikTok and Twitter, limiting platform comparison and the broader generalizability of the findings. Second, the proposed framework is derived mainly from structural content analysis and does not directly examine audience perceptions or behavioral responses. Future research should therefore combine this framework with surveys, experiments, or mixed method designs to test how identified narrative dimensions are received and interpreted by viewers. Its broader applicability could also be assessed by extending it to other cultural domains, such as clothing, fashion, or other forms of cultural content, as well as to comparative contexts involving Chinese and international cultural perception.

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Beyond Prediction: Explainable AI for Gender Segment Classification in Fashion E-Commerce

Filiz ERSÖZ[a,1], Taner ERSÖZ[b] and Deniz Özdal GENÇ[a]
[a] *OSTIM Technical University, Ankara, Turkey*
[b] *Karabük University, Karabük, Turkey*
ORCID: Filiz Ersöz https://orcid.org/0000-0002-4964-8487
Taner Ersöz https://orcid.org/0000-0001-5523-5120

Abstract. This study examines whether order-line product and transaction data can be used to classify items into female and male segments in fashion e-commerce. Sales amount, discount amount, size, color group, and product type were used as predictors, and SVM, KNN, Decision Tree, and Random Forest algorithms were compared. Random Forest delivered the best overall performance. To move beyond predictive accuracy, SHAP, LIME, and DiCE were employed to investigate how the model formed its decisions. The findings show that the model relies primarily on financial variables, especially sales amount and discount amount, while product type and other categorical variables provide secondary but still meaningful contributions. Local explanations further indicate that the decision structure is not fully symmetric across female and male classes and that several predictions depend strongly on sales amount thresholds. By combining order-line classification with multi-layered explainability, the study contributes a methodologically grounded perspective on data-driven segment differentiation in fashion e-commerce.

Keywords. Fashion e-commerce, Gender segment classification, Explainable AI, Order-line classification, Model interpretability

1. Introduction

The accelerating digitalization of retail has transformed the nature of transactional data available to firms. Contemporary e-commerce platforms capture granular order-line observations; prices, discounts, product types, sizes, and color attributes creating rich opportunities for classification-oriented analysis. The dominant research tradition has, however, focused on user-level outcomes such as purchase probability and session conversion [1], [2], [3], leaving order-line product segment classification comparatively underexplored, particularly in fashion. The female–male product distinction is analytically consequential in fashion e-commerce because product attributes, price structures, and purchasing patterns vary systematically between segments. Sheikh et al. [4] established that size and fit variables carry substantial predictive weight for customer satisfaction and Castenetto [5] documented the growing role of AI in fashion recommendation. Schreiner [6] demonstrated that female and male consumers follow

[1] Corresponding Author: Filiz Ersöz, filiz.ersoz@ostimteknik.edu.tr

different preference structures in online apparel shopping; These findings collectively suggest that order-line data may carry sufficient discriminative signal to support gender segment classification, with direct implications for pricing, merchandising, and inventory management.

A parallel concern is model interpretability. High-performing classifiers frequently operate as black boxes, limiting their usefulness in business contexts where decisions must be justified. This study treats explainability not as a post hoc diagnostic but as a core analytical objective: to establish which variables govern the model's decisions, whether its logic operates symmetrically across classes, and where predictions are most sensitive to feature variation. Two methodological contributions follow: the unit of analysis is shifted from user sessions to individual order lines, and model behavior is evaluated simultaneously through global, local, and counterfactual explanation methods.

2. Literature Review

2.1. Machine learning and classification in e-commerce

Machine learning methods have been extensively applied in e-commerce to predict conversion rates, purchase likelihood, and consumer decision-making. Wen et al. [1] employed explainable machine learning to examine consumer segmentation, Chen et al. [3] demonstrated that product and price variables dominate purchase behavior models within a Random Forest framework, and Bastos and Bernardes [2] highlighted the complementary roles of behavioral and transactional features in explaining online purchases. Despite the richness of this literature, its predominant focus on session- or customer-level tasks leaves order-line product segment classification largely unaddressed.

2.2. Explainable AI approaches

SHAP [7] decomposes predictions into additive feature contributions grounded in cooperative game theory, providing both global importance rankings and instance-level explanations. LIME [8] fits a locally faithful surrogate model around individual observations to yield fine-grained, instance-specific decision accounts. DiCE [9] generates diverse counterfactual scenarios that identify the minimal feature changes sufficient to alter a given prediction. Used in combination, these three methods permit a comprehensive examination of model behavior across global, local, and counterfactual dimensions a depth of analysis no single technique can achieve in isolation. Recent applications in credit scoring and operational risk assessment have confirmed the practical utility of such multi-method XAI frameworks [10].

2.3. Product attributes and the research gap

In fashion e-commerce, consumers cannot physically examine products before purchase, which elevates the analytical importance of size, fit, color, and product category as both purchase determinants and classification signals. Sheikh et al. [4], Castenetto [5], and Schreiner [6] collectively establish that these attributes encode meaningful latent structure relevant to both recommendation and segmentation tasks. Nevertheless, existing studies predominantly rely on a single XAI technique and rarely address order-

line-level segment classification. The present study addresses both gaps by applying SHAP, LIME, and DiCE jointly to a gender segment classification task conducted at the order-line level.

3. Research Framework and Analytical Procedure

The study draws on May 2021 sales records from a fashion retailer on an online platform in Türkiye. After removing incomplete and inconsistent observations, 12,407 order lines were retained from an initial 19,289 records. The analytical workflow proceeds through three stages data preparation, model training and selection, and explainability analysis as summarized in Figure 1.

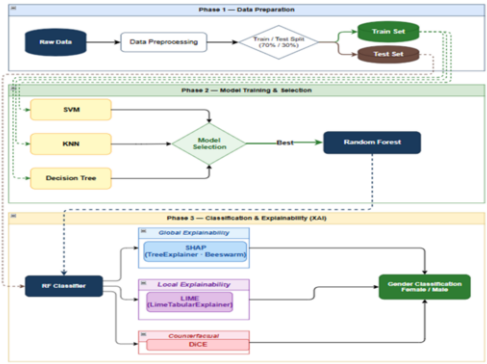


Figure 1. Analytical framework of the study

Product names were standardized against the European Commission's Access2Markets textile taxonomy, yielding four categories: Upper Body, Lower Body, Whole Body, and Sets & Ensembles. Predictor variables comprise sales amount, discount amount, product type (one-hot encoded), size (ordinal), and color group. The pronounced class imbalance in the raw data (78.4% Female, 21.6% Male) was corrected in Python prior to training. The dataset was split 70/30 for training and testing, and four classifiers were compared: SVM, KNN, Decision Tree, and Random Forest [11], evaluated on accuracy, F1, Cohen's Kappa, and ROC AUC.

3.1. Explainability methods and parameter settings

LIME [8] was configured with quartile discretization, 5,000 synthetic samples per query observation, and reporting of the ten most influential features (random_state = 42). SHAP [7] was implemented via TreeExplainer, which is optimized for tree-based models; beeswarm plots were produced separately for Female (class 0) and Male (class 1). DiCE [9] generated five diverse counterfactual examples per query (desired_class = 'opposite'), with feature ranges and changeable variables constrained to ensure practical plausibility.

4. Findings

The dataset (n = 12,407) exhibits a mean sales amount of 35.04 (SD = 21.34) and mean discount amount of 6.74 (SD = 4.73). Size distribution peaks in the middle range: M

(29.8%), L (25.9%), S (22.6%), XL (16.1%). T-shirt & Vest dominates product type (62.1%), followed by Blouse (9.9%), Trousers (9.7%), and Shorts (9.5%). Black Tones are most frequent in color (42.5%), followed by White (17.2%) and Green (11.8%). These distributional characteristics provide essential context for interpreting the classification results presented below.

Table 1. Model performance metrics

Model	Class F1(0)	Class F1	Accuracy	Cohen's Kappa	ROC AUC
SVM	0.92	0.92	0.86	0.50	0.89
KNN	0.96	0.97	0.95	0.86	0.97
Decision Tree	0.98	0.96	0.93	0.78	0.93
Random Forest	0.97	0.98	0.96	0.88	0.99

As shown in Table 1, Random Forest achieved the strongest results across all criteria — accuracy 0.96, Cohen's Kappa 0.88, ROC AUC 0.99 — and was therefore selected as the basis for all explainability analyses.

4.1. Global Explanation (SHAP)

Having confirmed Random Forest as the best-performing classifier, the analysis turns to the mechanisms underlying its predictions. Global explanation is examined first, as it reveals the aggregate feature importance structure before instance-level variation is considered. Figure 2 presents the SHAP beeswarm plot derived from TreeExplainer, where each point represents a single observation, horizontal displacement reflects the direction and magnitude of a feature's contribution, and color encodes the feature value from low (blue) to high (red).

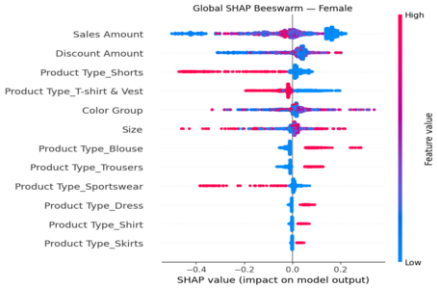


Figure 2. SHAP global explanation plot

The SHAP beeswarm plot in Figure 2 reveals that sales amount and discount amount are the two dominant predictors: higher values consistently shift the model output toward the Female class, while lower values favor Male. Among product types, elevated Shorts and T-shirt & Vest values associate with Female predictions, while lower values of Dress, Shirt, and Skirts favor Male. Color group and size contribute meaningfully but at secondary magnitude. The global explanation indicates that the classifier's decision logic is anchored principally in financial transaction features, with product-type variables providing important secondary signal.

4.2. Counterfactual and Local Explanations for a Male-Segment Observation

To probe the model's decision logic at the instance level, a correctly classified Male segment observation was selected specifically, the test-set case assigned the highest

predicted probability for the Male class. DiCE counterfactual analysis and LIME local explanation are applied in sequence to this observation, with the former mapping the class boundary and the latter accounting for the feature configuration that placed it on the Male side.

ORIGINAL INSTANCE

	Sales Amount	Discount Amount	Size	Color Group	Product Type_Blouse	Product Type_Dress	Product Type_Shirt	Product Type_Shorts	Product Type_Skirts	Product Type_Sportswear	Product Type_T-shirt & Vest	Product Type_Trousers	Gender
0	22.99	4.6	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	1

COUNTERFACTUALS

	Sales Amount	Discount Amount	Size	Color Group	Product Type_Blouse	Product Type_Dress	Product Type_Shirt	Product Type_Shorts	Product Type_Skirts	Product Type_Sportswear	Product Type_T-shirt & Vest	Product Type_Trousers	Gender
3057	24.99	5.0	1	1	0	0	0	0	0	0	1	0	0
2247	24.99	3.8	1	1	0	0	0	0	0	0	1	0	0
11910	24.99	5.0	2	1	0	0	0	0	0	0	1	0	0
11204	24.99	5.0	2	1	0	0	0	0	0	0	1	0	0
2796	24.99	3.8	2	1	0	0	0	0	0	0	1	0	0

Figure 3. DiCE output, Male Segment

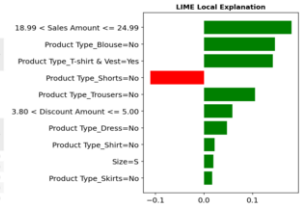


Figure 4. LIME output, Male Segment

While the counterfactual scenarios in Figure 3 delineate the conditions under which the prediction would change, they do not account for the specific feature weights that produced the original Male classification. Figure 4 addresses this through the LIME local explanation.

A correctly classified Male observation (sales amount = 22.99, discount = 4.6, size = 1, color group = 1, T-shirt & Vest = 1) was analyzed in detail. The DiCE output in Figure 3 shows that all five counterfactuals raise sales amount to 24.99 and shift T-shirt & Vest from 1 to 0, indicating that the class boundary reflects an interaction between financial variables and product-type information rather than a single threshold. The LIME explanation in Figure 4 corroborates this: the strongest positive contributor is sales amount in the 18.99–24.99 range, followed by T-shirt & Vest = Yes and Blouse = No. The Male prediction is thus governed by the conjunction of a specific sales-amount interval and a consistent product-type configuration.

4.3. Counterfactual and Local Explanations for a Female-Segment Observation

The same analytical sequence is applied to a correctly classified Female-segment observation the test-set case assigned the highest predicted probability for the Female class. Comparing the results with those obtained for the Male observation allows the symmetry, or lack thereof, of the model's decision logic across the two classes to be directly assessed.

ORIGINAL INSTANCE

	Sales Amount	Discount Amount	Size	Color Group	Product Type_Blouse	Product Type_Dress	Product Type_Shirt	Product Type_Shorts	Product Type_Skirts	Product Type_Sportswear	Product Type_T-shirt & Vest	Product Type_Trousers	Gender
0	18.99	3.8	4.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0

COUNTERFACTUALS

	Sales Amount	Discount Amount	Size	Color Group	Product Type_Blouse	Product Type_Dress	Product Type_Shirt	Product Type_Shorts	Product Type_Skirts	Product Type_Sportswear	Product Type_T-shirt & Vest	Product Type_Trousers	Gender
2439	22.99	3.5	4	4	0	0	0	0	0	0	1	0	1
3365	22.99	4.6	4	4	0	0	0	0	0	0	1	0	1
1322	22.99	3.5	3	4	0	0	0	0	0	0	1	0	1
1178	22.99	3.5	5	4	0	0	0	0	0	0	1	0	1
2160	22.99	3.4	5	4	0	0	0	0	0	0	1	0	1

Figure 5. DiCE output, Female Segment

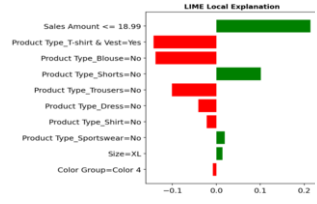


Figure 6. LIME output, Female Segment

Whereas Figure 5 identifies the feature changes that would shift this observation across the class boundary, Figure 6 provides the complementary account of why it was classified as Female in the first instance.

The Female-segment observation (sales amount = 18.99, discount = 3.8, size = 4, color group = 0, T-shirt & Vest = 1) reveals a structurally distinct decision profile. All five DiCE counterfactuals in Figure 5 require only a sales amount increase to 22.99, with

product-type variables remaining largely unchanged — establishing that the class boundary here is organized around a financial threshold rather than a product configuration. The LIME output in Figure 6 reinforces this: Sales Amount ≤ 18.99 is the single dominant contributor, while the T-shirt & Vest coefficient reverses sign relative to the Male case, confirming that the model applies this variable asymmetrically across classes.

5. Conclusion

This study has addressed two interrelated questions: whether order-line product and transaction data can support accurate gender segment classification in fashion e-commerce, and whether the resulting model's decision logic can be rendered sufficiently transparent to be analytically meaningful. Both questions receive affirmative answers. Random Forest achieved an accuracy of 0.96, a Cohen's Kappa of 0.88, and a ROC AUC of 0.99, demonstrating that the feature set available at the order-line level carries substantial discriminative power consistent with prior evidence that product and price variables constitute strong predictors of segment-related outcomes [3]. At the global level, sales amount and discount amount function as the primary axes of class separation, with product-type variables contributing secondary but non-negligible signal. This pattern extends Schreiner's [6] observation on gender differentiated price sensitivity by showing that financial transaction features are not merely correlates of segment membership but its dominant classificatory signals. At the instance level, the Male and Female predictions are governed by qualitatively different feature configurations: the former depends on a specific sales-amount interval in conjunction with a product-type pattern, while the latter is organized predominantly around a lower financial threshold. The sign reversal of the T-shirt & Vest coefficient across the two cases demonstrates that the model does not treat categorical product attributes as stable discriminators a finding that would remain entirely invisible under standard accuracy-based evaluation. These results carry both methodological and practical implications. Methodologically, the coordinated deployment of SHAP, LIME, and DiCE yields a qualitatively richer account of classifier behavior than any single technique affords, and order-line data constitute a viable and underutilized unit of analysis for segment classification tasks. Practically, the identified asymmetry in decision logic suggests that retailers should exercise caution in extrapolating feature importance across segments. Future research should examine whether enriched feature sets incorporating behavioral signals, textual product descriptions, or temporal purchase patterns can produce more balanced and interpretable decision boundaries across a broader range of retail contexts.

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Demystifying How AI Transforms HRM Practices Through the Lens of Employee Life Cycle

Ljupcho EFREMOV [a, 1] and Gorjan BOSHKOVSKI [b]
[a] *Liberal Arts Department, American University of the Middle East, 54200, Egaila, Kuwait*
[b] *International Slavic University, St. Nicholas, North Macedonia*
ORCiD ID: Ljupcho Efremov https://orcid.org/0000-0002-2660-4422
ORCiD ID: Gorjan Boshkovski https://orcid.org/0009-0006-3490-3381

Abstract. The paper examines how artificial intelligence (AI) is transforming core human resource management practices. It focuses on key themes that have emerged from the application of AI across human resource management (HRM) practices examined through employee life cycle (ELC). For this purpose, adapted ELC model (building on the work of Gladka et al.) consisted of 6 stages: attraction/recruitment; onboarding; development; retention; performance and offboarding. The aim of the paper is to identify how AI reshapes each practice throughout employee life cycle. A scoping review combined with emergent qualitative coding was used to map AI application areas in human resource (HR) practices for each stage. The review covered 28 peer-reviewed studies that directly address the use of AI in human resource management. Overall, across all six areas, AI tends to take over routine, data related tasks (such as screening, tracking and documentation), while at the same time enabling more personalized practices and common risks: bias, transparency and privacy. The end results is framework for employee lifecycles consisting of: attraction and recruitment (search and match - entry gate), onboarding (orient and engage), development (e-learning and personalization), retention (turnover estimates and wellbeing systems), performance management (data based continuous feedback), and offboarding (exit procedures). The recommendations are in line with the framework and are about provision of clear guidelines and to keep humans "in the loop" in all stages in order to reduce legal and ethical problems. The findings outline the main uses of AI in HR from an employee view point and as such, propose practical recommendations for organizations considering or expanding AI adoption in their HR practices.

Keywords. Adoption, Engagement; Workforce, Planning, AI literacy

1. Introduction

AI is spreading more and more in every company and department, especially when all processes are becoming digital. Efremov and Pruthi [1] argued that technological innovation has fundamentally reshaped modern societies, changing how people live,

[1] Corresponding Author: Ljupcho Efremov, Liberal Arts Department, American University of the Middle East, 54200, Egaila, Kuwait; E-mail: Ljupcho.efremov@aum.edu.kw

work, and interact across the globe. Human Resource Departments (HRD) have started utilizing AI as technology in every step of interaction with potential, current and former employees. Similar to consumer journey when individuals as customers are treated and companies strive for positive experience at every touch point, HRD use AI to elevate positive experience with employees at points of interactions [2]. Many empirical studies show increased usage of AI. For example, the findings of Malagi and Ramya [3] confirm this idea. Most of their respondents said their organizations already use AI in HRM. The research also shows that AI implementation in HRM brings different important improvements in organizations. Many respondents noted that AI helps a lot in hiring, career development, performance evaluation and talent management. Besides, they mentioned using AI for employee training, which shows how AI contributes to personal learning opportunities. Although most people were positive about AI effects, some claim that there are no changes or had doubts about the value of AI usage in certain areas. In general, this study offers good insights on how common AI is in HRM practices and what impact it has. Additionally, many authors argue that artificial intelligence has strong potential to support core human resource functions such as selection, recruitment, and training and development. Mupaikwa and Yadav [4] discuss how AI can be applied across these critical HR activities. Their chapter reviews 85 peer-reviewed journal articles, selected from 197 downloaded papers, to map how AI is being used in practice. The review finds that adopting AI technologies can lower the costs of selection, recruitment, and employee training and development. The most commonly used AI tools in these areas are machine learning applications and chatbots. However, there are several barriers which still limit wider adoption like concerns about algorithmic bias, data privacy and security. Also, there is a general lack of AI skills and technological infrastructure. The authors therefore call for more advanced research on AI-driven solutions that can better support selection, recruitment, training, and development while addressing these challenges. The abovementioned aspects accent the importance of scientific examination of AI usage by HR professionals and therefore this paper focuses on application of AI among each of the human resource functions from a perspective of employee life cycle (incorporating all experiences on employee path from hiring to leaving the organization).

2. Application of AI in Human Resource Management Practices

The following part provides an overview of usage of AI by HR departments. It starts with findings about usage of AI with specific focus of AI in HRM practices and continues with explanation of the study of Gladka et al. [2], which is used as a basis for the employee life cycle (ELC). Ng et al. [5] reviewed changes in HRM practices for the past 30 years. They concluded that in recent years, the role of HRM has clearly shifted, with much more attention now on strategic issues rather than only administration. When organizations use AI in HRM, they gain extra time, more value added insights and strong analytical support. This helps them manage people in a more effective and data driven way. On the other hand, Kasubi et al. [6] show that AI is becoming more integrated into HRM and that it brings both important benefits and new challenges. The main topics in the review are talent acquisition, performance analytics, ethical issues, and automation of decisions. The authors also map the most influential researchers and sources and point out new directions for future work. They conclude that AI is already changing HRM practice, but that ethical, legal, and human-centered questions are still

not studied enough. Future research should look more at cross-cultural differences, long term effects on the workforce, and how to design inclusive AI systems for effective HRM practices. The results about usage of AI by different groups of professionals, offers useful guidelines for HR departments and managers when they plan tasks, design AI training, and try to support productivity and wellbeing at work. One example is the study by Efremov et al. [7] who investigated how IT professionals use AI in their daily work. The survey asked which AI tools they use, for which tasks, and how often they rely on them. The results show that AI is now part of many areas of IT work, with task checking, coding assistance, and technical documentation among the most common uses. The results suggest that AI is used for different tasks into their workflows and it is used for more than simple automation of tasks.

Abdalla [8] examined how artificial intelligence (AI) affects human resource management, especially in recruitment, employee retention and development. AI improves recruitment by automating candidate evaluation and reduces subjective decisions. The usage of predictive analytics offers managers opportunities to identify employees at risk of leaving and create strategies to improve retention. Also, AI helps in designing learning programs that match employee skills, goals and company needs. Thus, it makes training more effective for personal growth and overall business success. However, besides gains in efficiency and better decisions, using AI in HR raises ethical issues like privacy, bias and fairness in processes. This paper stresses the need for accountability in AI applications to ensure fair and consistent HR practices. In this way, organizations can use strengths of AI while keeping decisions fair and avoiding discrimination at work.

The work of Gladka et al. [2] was used as a basis in order to identify the stages of employee life cycle as starting point. Their work shows many different stages with different names, but for the purpose of this paper, the following 6 stages are used: attraction/recruitment; onboarding; development; retention; performance and offboarding. All of the models reviewed by Gladka et al. share most of the stages used in the adapted model (attraction/recruitment, onboarding, development, retention, and exit/offboarding). The main distinction is the addition of performance as a separate stage, making it a clearly defined separate phase from development in the adapted ELC model. Although performance is not always managed directly by HR, it is included here because many HR functions measure and support it, often overlapping with managerial roles, and performance indicators are typically monitored by the HR department. The adapted model emerged from the definition of the authors. Gladka et al. suggest a new definition of the employee life cycle in an organization. They define it as the full period of interaction between the employee and the employer, starting from the moment the organization attracts a potential employee from the labor market and ends when the employment relationship is terminated. During this time, the employer develops and uses personnel marketing actions in two main cycles: attraction and retention (to shape and deliver its employee value proposition both outside and inside the organization). These actions guide the employee through several stages of employment, where the level of engagement changes in a cyclical way. In contrast to earlier definitions, this view clearly stresses that the employee life cycle is the whole interaction period and that it is marked by repeating shifts in engagement and by targeted marketing measures used throughout attraction and retention.

Taking the abovementioned perspectives into account (especially the work of Gladka et al.), it becomes of vital importance to discover how AI is incorporated into HR practices throughout the employee life cycle. Clearly, AI is used in HR practices

and will be used more and more and this notion adds strong imperative for mapping these practices throughout all phases of employee experience. In order to contribute to this discussion and address this crucial gap, this research tries to identify which AI practices are used in all stages of employee life cycle. Therefore, the main goal of this paper is to identify how AI redefines each practice throughout employee life cycle.

3. Methodology

The research technique used in this paper is a scoping review combined with emergent qualitative coding. A scoping review was chosen because the research question is broad and the aim is to find and map available and emerging evidence on the use of AI in HRM. This approach follows several structured steps [9]: defining clear aims and research questions, developing a protocol, systematically searching the literature, screening and charting the studies, and then analyzing and presenting the findings, so having clear aims at the beginning is essential to keep all steps coherent and focused.

The inclusion criteria targeted studies written in English in the last 6 years that examined the application of AI in human resource management practices. The search strategy started with broad keywords related to technology and HRM, including "application", "artificial intelligence", "AI", "human resource management", and "human resource practices". These were later combined with life cycle specific terms to reflect the six HRM areas of interest. For attraction/recruitment the combinations included "artificial intelligence" or "AI" with "recruitment", "talent acquisition", "hiring", and "ATS"; for onboarding, with "onboarding" and "employee onboarding"; for development, with "development", "training", and "learning at work"; for retention, with "employee engagement", "retention", "turnover", and "wellbeing"; for performance, with "employee performance evaluation" and "performance management"; and for offboarding, with "offboarding", "exit interviews", "attrition", and "departure". The initial review identified 50 papers using the common search words and key words per domain. This number at the end decreased to 28 papers (after removal of duplicates and irrelevant papers). The search was performed on Google Scholar according to the adapted ELC model consisting of the following 6 stages: attraction/recruitment; onboarding; development; retention; performance and offboarding. The screening process is presented in table 1 below.

Table 1. Flow of Literature Screening and Inclusion (PRISMA format)

Phase	Description	Records (n)
Retrieval	Search and identification of records	50
Screening	Records after title/abstract screening	39
Eligibility	Eligibility assessment of texts	33
Exclusion	Records excluded (duplicates and irrelevant papers)	5
Inclusion	Final studies included	28

The analysis was focused on finding application areas where AI is already implemented in HR practices. The process of coding the application areas started immediately. The search for papers was conducted until saturation was reached (except for offboarding where only 2 papers were found). The materials were read by the two researchers and written in a common file with descriptions of each application. The

researchers held regular debriefings while doing the analysis. Similar applications of AI were grouped together. The summary of application areas is presented in results.

4. Results

This part presents the results found through the scoping review. The studies are grouped according to the ELC adapted model. Adapted model showing summary of studies with a complete list of 28 references used is shown in table 2 below.

Table 2. Adapted model showing studies included in the review

Areas	Study (Author, year, title of study, number of reference)
Attraction/ Recruitment	El Ouakili O (2025). The impact of artificial intelligence (AI) on recruitment process. [10] Hawrysz (2025). Artificial Intelligence in Candidate Screening: Opportunities and Challenges. [11] Malin et al. (2025). Rejected by an AI? Comparing job applicants' fairness perceptions. [12] Madanchian (2024). From Recruitment to Retention: AI Tools for Human Resource Decision-Making. [13] Albassam (2025). The power of artificial intelligence in recruitment: An analytical review of current AI-based recruitment strategies. [14]
Onboarding	Jahanshahi (2025) The role of AI tools in the onboarding stage in hybrid workplaces. [15] Jasiak-Kaczmarek (2025) Implementation of artificial intelligence for employee onboarding in light of literature review. [16] Tariq (2024). Enhancing onboarding with AI: designing a modern conversational agent for onboarding. [17] El Garem (2024). Impact of AI on Employee Onboarding Processes By Investigating How AI Tools Can Streamline and Enhance the Onboarding Experience for New Hires. [18]
Development	Muehlemann (2025). Artificial intelligence adoption and workplace training. [19] Madhumithaa et al. (2025). Leveraging AI for Personalized Employee Development: A New Era in Human Resource Management. [20] Oladele et al. (2025) AI-Powered Personalization in Employee Training and Development Programs. [21] Ramachandran (2024). Developing AI-powered Training Programs for Employee Upskilling and Reskilling. [22] Chowdhury (2025). How AI is reshaping employee training and development: insights from HR professionals. [23] Bohra (2025). The Impact of Digital Learning and AI on Employee Training and Development. [24]
Retention	Alhamad et al. (2024) Predicting employee turnover through advanced HR analytics: implications for engagement strategies. [25] Basnet (2024). The impact of AI-driven predictive analytics on employee retention strategies. [26] Kumaresh et al. (2025). Impact of artificial intelligence for humanizing retention approach. [27] Appoh (2025) Leveraging AI for employee development and retention: a new paradigm in human resource development. [28] Ramy (2025). AI-Enabled Human Resource Practices and Quality of Work Life: Evidence from the Saudi Telecommunications Sector. [29] Valtonen et al. (2025) AI and employee wellbeing in the workplace: An empirical study. [30]
Performance	Rabby et al.(2025). The Impact of AI-Driven HR Technologies on Performance Management and Employee Development: A Study of the Telecommunications Sector in Bangladesh. [31] Kaur (2024). A systematic review of artificial intelligence techniques in HRM: An assessment of performance evaluation and employee engagement. [32] Chuchu and Kyongo (2025). Performance Management and Artificial Intelligence (AI): Enhancing Personalized Development with Continuous Feedback and Data-Driven Decisions. [33] Gupta et al. (2024). Examining the impact of artificial intelligence on employee performance in the digital era: An analysis and future research direction. [34] Mohamed et al. (2025). Unveiling the potential of artificial intelligence in human resource management: a systematic review of adoption strategies, challenges, and future directions. [35]
Offboarding	Saha and Chhapola (2023). Robotic process automation (RPA) in onboarding and offboarding: impact on payroll accuracy. [36] Kambhampati (2024). Advancing Employee Attrition Models: A Systematic Review of Machine Learning Techniques and Emerging Research Opportunities. [37]

The next part is a description of findings for each of the six employee life cycles. The analysis, as expected, shows that AI is used by HR department and there are several patterns which will be outlined. The text below shows patterns detected for each of the six areas. Regarding the first area (attraction & recruitment), AI is mostly used for searching and matching of respective candidates through different methods (ATS filters, predictive scores and chatbots) and through different modes (interviews, gamified tests, virtual assessments, social media screening). It is clear that usage of AI brings efficiency and standardization and customization and it is data driven and more objective (not under subjective judgment). However, there are concerns about bias, low transparency and fairness of this process as this is the entry gate. Usage of AI enables recruiters to focus on relationships and spend less time on routine filtering, but ethics emerges as byproduct. For this area (recruitment), it should be noted that evidence is dominated by perception based designs and there is always a balance between advantages (efficiency gains) and disadvantages (ethical and fairness risks).

In onboarding processes AI provides support through automated workflows, role based checklists, chatbots and generated content that give new hires reasonable orientation in a quick period of time. The end results are evident in integration, fewer administrative mistakes and early engagement as a result of personalization. At the same time, organizations should strive to keep human contact and avoid bots dependence. Also, data protection emerges as important area (privacy and data security). In onboarding studies, the limitations are related to generalization and small surveys. It is clear that this process and especially personalization is improved with blind spots about privacy and decisions to which extent to rely on human contact.

The results for development show that AI is used in adaptive e-learning and learning analytics. This gives employees a chance to advance in new skills and carve own career path. AI usage focuses on professional development through provision of relevant trainings. Again, concerns are related to surveillance, data control and possible bias in algorithms (in a sense of narrow specialization). Across development studies, the results are driven by narratives, case examples from companies and limited comparative designs. Additionally, personalization, flexibility, engagement and adaptation are benefits with main disadvantages related to algorithmic decisions, surveillance (absence of autonomy) and potential biases.

As far as retention is concerned, analytics based on AI is used to create prediction models for turnover risk estimation, track engagement (e.g. sentiment, surveys) and understand reasons for leaving. Companies using such tools can create interventions to prevent leaving and provide wellbeing system. However, monitoring is bad for trust and well-being if there is a lack of transparency and good governance. The retention and well-being studies are organized around reviews, cross-sectional surveys and don't offer much information about long-term effects. Although these studies are positioned to support well-being, they partially address effects of different groups and are dependent on country specific contexts.

In performance management, AI is used for tracking and adjusting of Key Performance Indicators (known as KPI's) and creating predictive performance models. The aim of these tools is to provide data based insights, continuous feedback, fair evaluation and alignment with personal and organizational goal. The process is fairer as there is a written footprint. In this case the risk is about overreliance on AI (not only as support) and should be used only as additional insight to the managerial judgment. The important thing is to notify and explain to employees in advance how their data will be used and for what purpose. The performance studies show clear links between usage of

AI technologies and outcomes like performance, engagement, and development, but there is absence on not long term effects or harmful effects. Conceptually, the narrative shows usage of AI as fairer, data driven and personalized evaluation with potential limits related to bias, specific national contexts or objectivity.

Regarding offboarding, AI helps to automate many tasks (removal of data, documentation and analysis of exit interviews). Case evidence shows lower security risk, less errors and more time for other core tasks in relation to HR practices. AI based digital outplacement can turn offboarding into a useful tool for knowledge transfer, apart from routine administration. Offboarding studies show limited insights for organizational or employee centered results. However, it should be noted that there were only two studies in this area. The benefits for this area are related to accuracy and prediction, while the limitations are about ethics and generalization and fairness of these tools.

The above-mentioned findings are extracted from the reviewed studies and provide basis for creation of employee lifecycle framework intended for leveraging usage of AI in HR departments (shown in conclusions).

5. Conclusions

The general conclusion is that in every area, AI takes over routine, data related tasks (screening, checking, tracking, documenting), but at the same time enables makes personalized experiences (targeted and adaptive data driven insights which are customized). Another pattern noted in the reviews is about shifts going on in HR roles. As a result of the automation and customization, HR work moves away from manual processing towards more strategic tasks. Employees in HR have more time for building relationships, developing and practicing ethical guidelines and communicating with employees across the employee lifecycles. It should be noted that across all six stages, HR needs new skills in AI literacy and change management in order to use AI responsibly as a support tool, not as a decision maker. The end results of the scoping review is proposed new framework for employee lifecycle consisting of the six stages (that include AI): attraction and recruitment (search and match - entry gate), onboarding (orient and engage), development (e-learning and personalization), retention (turnover estimates and wellbeing systems), performance management (data based continuous feedback), and offboarding (exit procedures). The results align with Costa's [38] study, which explored how Microsoft applies AI. It shows that AI is used across recruitment, talent management and retention, employee engagement, and performance appraisal. Key tools used include LinkedIn Talent Insights for predictive analytics (serves for improving hiring quality), Microsoft Viva (in house product for boosting employee empowerment, engagement, and collaboration) and Dynamics 365 (for performance tracking and HR analytics). These applications have shown positive outcomes which are well received by all different stakeholders. They are reflected in improved decision-making, reduced bias in recruitment and hiring, alignment in employee skills development, and expanded growth opportunities. All used tools contribute to continuous improvement. However, the study highlights some challenges which need careful handling (dealing with data, ethical issues, algorithmic transparency) in order to maintain the human in the loop in these highly automated systems. Microsoft's case illustrates how planned and ethical usage of AI in HR can transform practices in large multinationals using such software. Additionally, parts of

the study results are aligned with the results of Madanchian [13]. This study explored AI tools across employee lifecycle stages and offers notable benefits and reveals key research gaps. In onboarding, robotic process automation and digital platforms streamline workflows and data management and improve communication and efficiency especially for remote workers. It should be noted that studies on employee experience with these automations remains scarce. Performance management leverages predictive analytics for continuous tracking and unbiased real-time evaluations, but it lacks exploration of the impact of AI on long-term career development as it is a relatively new tool. For employee development, adaptive learning systems and intelligent tutoring systems deliver customized skills training, with. Sentiment analysis in employee engagement track morale effectively, but more research is needed on keeping long-term engagement. Finally, predictive analytics and machine learning in retention are used for prediction of attrition and enable personalized strategies. Also, it is noted that ethical implications are area which demands further study. It should be accented that the study of Madanchian did not examine offboarding. The study presented in this paper is one of the first which includes offboarding in reviews.

Regarding limits, this study is limited from the focus on English language publications and searches that are mainly conducted via Google Scholar. The limit is that relevant work in other languages, databases or grey literature is missed. In addition, as a scoping review with inductive coding, the analysis is descriptive rather than quantitative and reflects certain subjectivity in how studies and categories were interpreted and grouped. Future studies should build on this scoping review with more focused empirical research (surveys, experiments, longitudinal case studies) to test the proposed framework and long term effects of specific AI applications in HR practices. Another variable that should be included are employee outcomes in each life cycle stage. These studies should examine employees and managers experiences of AI in HRM in different contexts with a goal to leverage current HR practices. Future research agenda should be focused on reducing bias and building trust.

Important finding is that across all six domains, similar risks are found. Namely, those are related to bias in decisions, fairness and lack of transparency, privacy/surveillance concerns, and possible loss of human contact and loss of trust if systems are perceived as “black boxes”. The practical implications that stem from the study are related to smart adaption of AI. This positions AI as support for automation of data related tasks while providing information to HR managers. Additionally, decisions should be reached by humans based on many different criteria and therefore AI literacy trainings with focus on responsibility are needed for HR managers. Policy makers should develop specific bylaws that tackle potential biases, surveillance and appeals related to potential cases. Final word is about transparency as employees and applicants need to know where, how and why AI is used in each stage of the lifecycle and what safeguards exist. The study offers valuable insights from the perspective of an employee as it tackles all employee stages, includes offboarding and drafts a new framework based on employee life cycles that could be useful for comprehensive HR software. The paper provides a strong overview of employee perspective and the employee life cycle though a framework that helps HR departments leverage the use of AI and, as such, contributes to AI literacy.

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A Predictive Smart Supply Chain Performance Integrated Marketing Index Approach Using SCOR and Topic Modeling Early KPI Detection

Rui-Yang Chen[1]
[a]*Department of Business Administration, Aletheia University, TAIWAN*

Abstract. The core value of integrating the entire supply chain into a Smart Manufacturing KPI framework lies in the ability to gain deep insights into business performance and process efficiency. Accordingly, this paper proposes a predictive approach for smart supply chain performance based on the SCOR DS (Supply Chain Operations Reference Digital Standard) model and the LDA (Latent Dirichlet Allocation) topic modeling algorithm. The architecture of this AI-driven model is formulated by integrating manufacturing indices, SCOR metrics, and customer marketing indices. The experimental analysis was implemented using Google Colab to generate a KPI structure for exploring AI-driven supply chain predictions. Experimental results show that topic classifications are defined by metrics such as flexibility, reliability, product transformation, asset efficiency, and product inspection/testing (categorized as Topic 1). Notably, Topic 1 reveals that the Customer Retention Rate is a more significant index than other marketing metrics. Consequently, this experiment establishes a relationship of influence that serves as a predictive foundation for the KPI structure.

Keywords. Topic modeling, Latent Dirichlet Allocation (LDA), AI-driven SCOR DS model, KPI

1. Introduction

Nowadays, smart manufacturing has already evolved into a human-robot collaborative production environment using AI and digital technologies. This efficiency enhances overall business performance across the supply chain process. This process utilizes Key Performance Indicators (KPIs) to monitor the performance of all workflows, including manufacturing processes that use context-aware workflows [1]. These workflows facilitate data processing via information technology applications, such as model-driven Fog applications. [2]. One of the main objectives of the smart manufacturing process is the ability to transform data collected from the entire supply chain into KPIs to gain insight into the business performance and efficiency of the process. To that end, it is necessary to predict KPIs through data processing to identify

[1] Corresponding Author: Rui-Yang Chen, Professor, Department of Business Administration, Aletheia University, TAIWAN; Email: a168.cloudy@msa.hinet.net
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potential efficiency improvements. However, even if efficiency is enhanced by AIoT (AI and the Internet of Things) transformation, supply chain processes are dynamic, and inherent problems are still likely to occur. Accordingly, it is vital to determine how to predict future performance using this index data. Topic models are popular for mining keywords from text to identify and collect topics from a document corpus. This significantly impacts the competitiveness of smart businesses and can compromise the accuracy of smart supply chain performance metrics. Accordingly, it is crucial to predict smart supply chain performance in advance through smart manufacturing powered by enterprise AI. Enterprise AI is an emerging digital technology that integrates advanced AIoT solutions such as Generative AI and machine learning. Recent advancements in enterprise AI have led to AI-integrated product innovation that emphasizes operational efficiency [3]. However, timely action alone is not enough to achieve intelligent competence; therefore, early detection mechanisms are prioritized to ensure business performance accuracy across the entire supply chain. In the context of AI-driven supply chains, smart manufacturing performance must be anchored by a supply chain backbone that has become increasingly complex due to technological advancements and human-robot collaborative environments. The central issue is determining which supply chain process model to use to highlight smart efficiency through KPI prediction, thereby solving accuracy problems in AI-driven solutions.

This paper adopts the SCOR (Supply Chain Operations Reference) model as the process framework. The KPIs focuses on the smart manufacturing system index integrated with the marketing benefit index throughout the SCOR model. Existing literature discusses supply chain KPIs from various perspectives; for example, Saleheen and Habib [4] proposed an Integrated Supply Chain Performance Measurement (ISCPM) model with a customer service outlook based on the SCOR model. These SCOR-based KPIs can be utilized as predictive metrics for supply chain performance. In this study, the author combines a smart manufacturing index with a marketing benefit index to serve as predictive metrics for supply chain KPIs, based on the SCOR model within an enterprise AI architecture. Thus, this study adopts a topic modeling algorithm to identify KPIs as keywords. Topic modeling is an AI-driven, NLP-based unsupervised machine learning classification approach used to discover hidden patterns and clusters of similar words within a corpus. Accordingly, this paper utilizes topic modeling to identify KPIs as keywords within a document dataset, categorizing them into topics relevant to the smart supply chain process. This method aims to uncover latent KPI topics characterizing a set of supply chain processes to predict 'smart efficiency.' To identify these latent topics, the paper employs Latent Dirichlet Allocation (LDA). Among topic models, LDA is the most frequently used for predicting KPI performance status. Therefore, this study uses LDA as a predictive method for mining supply chain processes. Ultimately, the author proposes a KPI prediction approach using the NLP-based LDA technique as a topic modeling algorithm integrated into an enterprise AI system for the SCOR model.

Accordingly, this paper proposes a predictive approach for smart supply chain performance based on the SCOR model within Enterprise AI architecture. The remainder of the research is organized as follows: Section 2 discusses related work, including AI-driven SCOR models and topic modeling with LDA. Section 3 formulates the design architecture for AI-driven SCOR, integrating both AI information technology and the SCOR framework. Finally, Section 4 details the development of cross-KPIs—integrating a smart manufacturing index with a marketing benefit index—and presents the results of the experimental simulated analysis conducted using

the LDA topic modeling method within the AI-driven SCOR framework. Section 5 is the conclusion.

2. Related Works

2.1. AI-driven SCOR DS model

Kushwaha et al. [5] proposed a content analysis method based on social media analytics to enhance customer experience for B2B enterprise chatbots. In this paper, enterprise AI serves as the AIoT system architecture throughout the supply chain process. Accordingly, this enterprise AI framework integrates the SCOR (Supply Chain Operations Reference) management methodology with topic modeling as the primary AI algorithm. The SCOR model is a well-established, performance-based framework for managing supply chain activities, providing a robust evaluation mechanism through various indicators and metrics. Core performance attributes of the SCOR model, such as reliability, responsiveness, cost, flexibility, and asset efficiency [6], have been extensively discussed in the literature [7]. Within the SCOR framework, the manufacturing system is primarily situated in the 'Transform' stage, one of the six core processes. The Transform stage encompasses production processes that create finished products to satisfy forecast or actual demand. Consequently, SCOR model KPIs must be embedded into the manufacturing system for predictive applications

2.2. Topic modeling with LDA

Topic modeling is a Natural Language Processing (NLP) technique used to mine keyword patterns and classify similar topics within document corpora. Latent Dirichlet Allocation (LDA) is a popular probabilistic method for topic modeling that uncovers latent themes and classifies keywords based on their probability distributions. There is a pressing need to develop effective classification approaches for supply chain research using the LDA method. LDA has already been used to identify influencing factors in various business processes, such as quality and safety traceability in agricultural supply chains [8]. However, most existing studies lack accurate prediction models based on robust detection and tracking mechanisms. Because these periods are characterized by constant change, it is essential to track and trace these statuses to achieve reliable predictions. This paper emphasizes the use of accurate prediction to extract latent business performance topics distributed across smart supply chain KPI features.

3. The design architecture of AI-driven SCOR

In this section, the design architecture of the AI-driven SCOR DS model is formulated by integrating AI information technology with the SCOR framework. This enterprise AI architecture integrates all software systems across internal business processes—such as product development, marketing, manufacturing, finance, and human resources—and external cross-functional processes involving suppliers, customers, and other stakeholders, as illustrated in Figure 1.

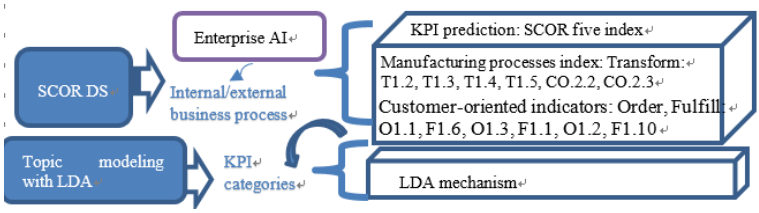


Fig. 1. The design architecture of AI-driven SCOR model

To perform enterprise AI operations, this paper adopts two modules: a management methodology utilizing the SCOR DS model and an AI algorithm utilizing topic modeling with LDA, as illustrated in Figure 1. The management methodology module aims to provide a process baseline to construct management knowledge for optimizing business performance. In this study, the author adopts the SCOR DS model as the management methodology to streamline the supply chain process. Meanwhile, the AI algorithm module aims to provide an AI-enabled mechanism for constructing an intelligent system to achieve 'smart efficiency.' Specifically, the author employs topic modeling with LDA as the AI algorithm to predict business performance accuracy within a smart human-robot collaboration environment. These modules are described in further detail below.

3.1. KPI using SCOR DS model

The SCOR DS model contributes to innovative resilience solutions through its methodology, benchmarking, and practice forms based on a seven-stage framework (Orchestrate, Plan, Order, Source, Transform, Fulfill, and Return) to ensure reliability, consistency, and efficiency. The SCOR model enhances supply chain processes by utilizing performance-based Key Performance Indicators (KPIs). These KPIs are categorized into five performance attributes—reliability, responsiveness, agility, cost, and asset management efficiency—which are measured across the SCOR model's four process levels: Level 1 (strategic), Level 2 (tactical), Level 3 (operational), and Level 4 (detailed). Therefore, establishing supply chain KPIs is a critical strategic activity for achieving the overall goals and objectives of business functions.

Currently, AI-driven technology is already being embedded into firm and industry operations to transform them into a competitive advantage for businesses. As such, SCOR model operations must evolve to meet the standards of AI-driven smart efficiency. AI enables the SCOR model to enhance efficiencies in areas such as prediction, prevention, and autonomous capabilities to optimize processes. However, it is vital to understand how the SCOR model fits into an AI-based supply chain. Thus, this paper proposes a SCOR KPI approach to determine whether AI-driven supply chains achieve true performance accuracy within human-robot collaborative production environments. The SCOR KPI approach is described as follows.

This study utilizes partial manufacturing KPI categories adapted from Maretto et al. and SCOR metrics to propose specific performance measurements in Table 1. These include system productivity (e.g., productive force and lean efficiency as *T1.2: Schedule Production Activities*), resource utilization (e.g., capacity utilization and efficiency as *T1.3: Issue Raw Material or Components*), process time (e.g., throughput time and makespan as *T1.4: Transform Product*), maintenance (e.g., Mean Time Between Failure and Mean Time to Repair as *T1.5: Inspect and Test Product*), and

costs (e.g., inventory carrying cost as *CO.2.3* and material acquisition cost as *CO.2.2*). Given the "Order" and "Fulfill" stages of the SCOR model, it is crucial to collaborate through customer interaction and quick-response integrated manufacturing systems to understand cause-and-effect relationships and enhance problem-solving capabilities. Consequently, this study integrates a marketing perspective into SCOR KPIs within the manufacturing system. Furthermore, these manufacturing KPIs consider key SCOR performance attributes identified in literature reviews, such as reliability, responsiveness, cost, flexibility, and asset efficiency.

Table 1. SCOR metrics

T1.2:Schedule Production Activities	It includes Master Production Schedule (MPS) and shop floor order sequencing, with production scheduling primarily based on two types of requirements: Make-to-Order (MTO) or Make-to-Stock (MTS).
T1.3: Issue Raw Material or Components	When a work order is initiated, a picking list is generated, which automatically explodes the required raw materials for each process station based on the Bill of Materials (BOM) structure
T1.4: Transform Product	There are generally two methods for producing final products: fabrication (processing) and assembly
T1.5: Inspect and Test Product	Both product warehousing and shipping require inspection and testing. The purpose of inspection is to determine whether the product can be accepted into inventory.
O1.1: Receive Customer Information	It primarily refers to the use of digital software to automatically capture customer information, including customer complaints, interactions, and purchasing activities
O1.2:Apply Customer Loyalty/ Prioritization Status	Identify customer identity information to analyze their loyalty or prioritization status, in order to determine the service model for subsequent customer service operations
O1.3:Build Order	When a sales order is created, it typically undergoes a review of order data and a customer credit check. Once verified, the official order is established according to the customer's requirements
F1.1: Receive Order Signal	Once a customer issues an order, the supplier receives and interprets the order details (e.g., item, quantity, and lead time), which then triggers subsequent production work orders or finished goods shipment.
F1.6:Notify and Confirm Shipment Window	It involves coordinating and defining clear schedules for cargo activities between suppliers and customers, including specific time windows for 'when the goods depart from the warehouse' and 'when they arrive at the destination
F1.10: Obtain Proof of Delivery or Customer Acceptance	When shipping, the supplier must obtain proof of delivery or customer acceptance data to ensure effective control over order fulfillment
CO.2.3 Inventory Carrying Cost	It refers to all related expenses incurred for holding and maintaining inventory, including warehousing, storage facilities, insurance, and more
CO.2.2 Material Acquisition Cost	It refers to all related costs incurred during the procurement (Source) process, including administrative costs and incoming inspection costs.

Simultaneously, this paper describes the features of marketing process indicators used to interconnect manufacturing processes with these specific metrics. These indicator features help clarify the influence of manufacturing, thereby establishing a cognitive system for the performance evaluation of the supply chain. Several criteria derived from these features aim to measure the efficiency of marketing processes

through AI-driven intelligent systems. Such systems are a prominent current trend, exemplified by AI-based Customer Relationship Management (CRM). Based on the points mentioned above, this study presents the criteria for these features, the features of marketing indicators, and marketing indicators aligned with SCOR metrics—such as Customer Acquisition Cost (CAC), Customer Lifetime Value (CLV), and Customer Retention Rate (CRR) as shown in Table 2. This table primarily discusses three significant customer-oriented indicators. In other words, manufacturing KPIs within the SCOR framework relates to the marketing efforts required to identify and address customer needs. Accordingly, this study proposes a management methodology using the SCOR model across three primary KPI categories: SCOR KPIs, manufacturing process indicators, and marketing indicators. These three categories are interconnected through a hierarchical structure, ensuring a cohesive and organized approach to performance evaluation.

Table 2. Customer-Oriented Indicators

	CAC [9]	**CLV [10]**	**CRR [11]**
Features	sales and marketing expenses, new customer quantity	tracking customer experience and value customer relation-ships timespan	meeting customer expectations enriching the customer experience (CX).
Criteria	overhead costs related to sales and marketing, attractive degree	historic customer lifetime value, predictive customer lifetime value, engagement degree	perceived service quality, deepening customer loyal-ty degree
SCOR metrics	O1.1: Receive Customer Information F1.6: Notify and Confirm Shipment Window	O1.3: Build Order F1.1: Receive Order Signal	O1.2: Apply Customer Loyalty/ Prioritization Status F1.10: Obtain Proof of Delivery or Customer Acceptance

3.2. AI algorithm using topic modeling with LDA

This paper utilizes topic modeling as an AI algorithm for supply chain prediction. Topic modeling is a text mining method applied to document formats such as manufacturing work orders. This approach enables the unsupervised classification of these documents. By clustering similar words into topics based on specific proportions, the model demonstrates that each document consists of a mixture of topics, and each topic consists of a mixture of words, where the same word may appear across multiple topics. Accordingly, the purpose of this topic modeling is to predict unknown topics within documents, even when the specific objectives are not initially clear. Building upon the SCOR KPI prediction, this paper aims to identify unknown topics that convey specific business meanings. These meanings uncover the causal relationships and the hierarchical structure of the three KPI categories, which collectively define the accuracy of business performance. The logic of this approach involves analyzing each document to identify a mixture of words associated with specific topics. To achieve this, the paper adopts the Latent Dirichlet Allocation (LDA) method, a widely used

technique for topic modeling. Proposed by Blei et al. [12], the LDA method identifies topics within a large corpus by applying the "bag-of-words" technique. This technique identifies each topic based on word frequency within a document by calculating the simultaneous frequency (co-occurrence) of different words. As a result, these identified topics are derived from across various documents based on the probability distribution of words. This mechanism is described as follows: The LDA is generative probability model described some symbols as follows. Let i denotes the total number of document, K be the total number of topics and j be the total number of words from each topic can belong to. A corpus is a collection of i documents. Sampling from a Dirichlet distribution α generates the topic distribution θi for document i. For SCOR KPIs metrics, first of all, for each KPIs reports, this mechanism samples the topic distribution $\Theta(i)$ of the whole document and the word distribution $\varphi(k)$ on each topic. Next, for each word j in the document, it samples the topic Z(i,j) from the given topic distribution, and then sample the word in the word distribution $\varphi(Z(i,j))$ to get w(i,j).

Using supply chain KPIs as an example, this mechanism first samples the topic distribution for each KPI report and the word distribution for each specific topic. Next, for each word within the document, it samples a topic from the provided topic distribution and then samples a word from the distribution to obtain. This logical framework aims to derive the document-topic distribution probability matrix and the topic-word distribution probability matrix based on the prior parameters and. To validate this mechanism, this paper utilizes evaluation metrics such as perplexity and coherence. For the evaluation analysis, the study adopts the UMass Coherence Score to assess the LDA model. Generally, a higher coherence score indicates better performance.

4. Experimental Simulated Analysis and Result

The development of cross-KPIs using a smart manufacturing integrated marketing benefit index is achieved through experimental simulated analysis utilizing the LDA (Latent Dirichlet Allocation) method of topic modeling, based on an AI-driven SCOR model. This study incorporates a corpus consisting of customer reviews from e-commerce websites. Accordingly, this research is built upon the retrieval of 100 documents focused on SCOR metrics and marketing consumer behavior topics. Considering the SCOR KPIs and process levels, this paper proposes using LDA topic modeling to predict KPI performance and integrated marketing benefits for the SCOR DS model. This approach functions by determining which KPIs to prioritize and identifying the relationships that enable the topics to achieve precise and predictable performance. Thus, the proposed method leverages advanced topic modeling and Natural Language Processing (NLP) capabilities to understand and execute complex smart manufacturing tasks efficiently, integrating the SCOR model with marketing-related topics. The experimental analysis is described as follows. Step 1: Constructing the KPI Structure. This structure integrates smart manufacturing process indices and marketing indices into a unified SCOR KPI framework. For this simulated experiment, the KPIs are captured from the "Transform" and "Order and Fulfill" stages at Level 3 of the SCOR model. Step 2: Collecting the Simulated Dataset. A dataset consisting of 100 customer reviews from Kaggle.com serves as the document corpus. These documents are tagged with manufacturing and marketing KPI terms based on industrial knowledge and the previously defined KPI structure. Step 3: Executing LDA

and UMass Coherence Analysis. To categorize the topics, this study utilizes the LDA method within the Google Colab environment to fulfill the proposed AI prediction approach. The results for "Topic 1" are illustrated in Figure 2 and Table 3. Based on the coherence analysis, the model reveals parameters of, four top documents, and three topics. Step 4: Discussion of Supply Chain Performance Prediction. In this experiment, the six most relevant words associated with the KPI structure for Topics 1–3 is identified, with Topic 1 showing the highest relevance. These words are ranked by their frequency across the corpus relative to specific topic distributions. The classifications for Topic 1 are defined by flexibility, reliability, transform_product, asset_efficiency, and inspect_test_product. Notably, Topic 1 reveals that the Customer Retention Rate (CRR) is a more significant indicator than other marketing metrics.

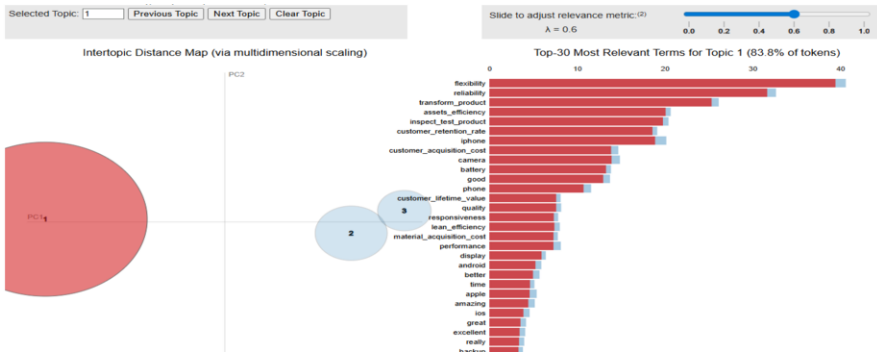


Fig. 2. LDA result at google Colab

Table 3. Topic 1 Interpret Discussion

Keywords	flexibility	reliability	transform_product	assets_efficiency	inspect_test_product	Customer Retention Rate
Percentage%	35.32	28.35	22.68	18.99	18.71	16.30
Discussion: These percentages reflect the probability distributions of the words, signifying their substantial contribution to Topic 1. Consequently, this topic is defined as 'supply leanness and product delivery capability.' It emphasizes the supply chain's flexibility in responding to market shifts, ensuring product reliability and high production efficiency, which ultimately enhances customer retention						

Consequently, this experiment allows us to gain insights into relationship influences as a means of predicting KPI performance. This paper explains how these topics categories can be used to predict production performance efficiency in advance. Finally, the experiment explores AI-driven prediction of supply chain KPIs to ensure the accuracy of smart supply chain performance forecasting. The objective is to establish a probabilistic model of a corpus that assigns high probability not only to existing members but also to "similar" unseen documents. Future research will involve more detailed quantitative results for practical case studies with real-world data.

5. Conclusion

Based on the design architecture of enterprise and the simulated experiment mentioned above, we know that marketing indices, when integrated with SCOR metrics in smart

manufacturing, can predict early supply chain KPI performance using LDA AI algorithms. The findings then outline the relationships within the KPI structure. However, this KPI structure specifically applies to this e-commerce customer review case. In other words, different cases will have different KPI detections. Therefore, collecting customer review cases for a certain period reflects the relevance of specific KPIs of products manufactured by the preceding supply chain process. Consequently, if these KPIs can be improved early, customer reviews in the subsequent period are likely to be more positive. The contribution of this study, therefore, is to propose a KPI structure AI algorithm based on SCOR DS. Within the trend of developing a human-computer collaborative intelligent manufacturing environment, the approach proposed in this study can use KPIs as a driving factor to evaluate overall supply chain operation performance. This evaluation can then provide feedback for improvements in intelligent manufacturing. Furthermore, future research will involve more detailed quantitative results from practical case studies using real-world data.

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Research on Financial Risk Analysis and Identification Control Algorithm Based on Data Mining

Borui Zhang[1]
University of Nottingham Ningbo, Zhejiang 315100, China
ORCiD ID: Borui Zhang https://orcid.org/0009-0008-1023-2311

Abstract. This paper addresses the increasingly complex risk management challenges in the financial sector by proposing a financial risk analysis and identification control method based on data mining and an improved whale optimization algorithm, referred to as the Improved Whale Optimization-based Financial Data Mining Algorithm (IFD-WO). Under the new economic normal, the development of fintech and the widespread application of big data provide a data foundation for corporate risk monitoring. By constructing corporate relationship networks, financial institutions can be assisted in assessing corporate creditworthiness, while regulatory authorities can better prevent systemic financial risks. The proposed algorithm integrates recurrent neural networks, graph neural networks, long short-term memory networks (LSTM), and gating mechanisms to achieve efficient mining of financial time series data. Fault signal features are extracted through variational modal decomposition, combined with parameter search optimization using the whale optimization algorithm. For empirical analysis, we collect daily adjusted closing prices of listed companies from the Shanghai Stock Exchange, Shenzhen Stock Exchange, and Hong Kong Stock Exchange over the sample period from 2010 to 2024, and convert them into logarithmic returns as the primary data type. Using these data, we construct a financial risk contagion network and compare it with linear threshold models, independent cascade models, and algorithms based on collaborative filtering. The results demonstrate that the proposed method outperforms other algorithms in both Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) metrics while significantly improving computational efficiency, proving its effectiveness and practicality in financial risk prediction and control.

Keywords. Financial risk management; Improved whale optimization algorithm; Variational modal decomposition; Systemic financial risk

1. Introduction

Driven by robust economic growth, China has achieved rapid industrial upgrading and a positive shift in its development philosophy. The country has transitioned from extensive growth to efficiency-driven intensive development, with innovation-driven strategies taking center stage — ushering in the era of the "new normal"[1]. Under this paradigm,

[1] Corresponding Author, Borui Zhang, University of Nottingham Ningbo, Zhejiang 315100, China; Email: biybz17@nottingham.edu.cn

the urgency of leveraging fintech to advance financial reforms, inclusive banking services, and green finance is increasingly prominent [2]. Meanwhile, the widespread adoption of financial technologies and emerging business models necessitates accelerated development of fintech regulatory frameworks by local governments and financial regulators to address evolving financial security challenges [3]. In this context, big data is emerging as a pivotal catalyst for financial development, with industries becoming increasingly reliant on data-driven insights. The massive data demand has prompted regional governments and financial regulators to establish big data platforms, creating essential foundations for regional enterprise risk monitoring [4]. Corporate financial records document business interactions and financial relationships, enabling financial institutions to assess creditworthiness and growth potential through network analysis while providing actionable references for first-time loans [5]. From a regulatory perspective, predicting corporate risks and preventing collateral chain crises remains crucial for mitigating systemic financial risks [6].

Data mining is a technology with limitless potential. Financial data is predominantly expressed in time series format [7]. The proposed data mining algorithms can efficiently extract high-value insights from massive financial time series datasets, significantly advancing research in financial data analysis systems. Additionally, constructing and analyzing enterprise relationship networks enables financial institutions to gain multidimensional insights into corporate creditworthiness [8]. This approach also assists governments and regulators in preventing systemic financial risks, demonstrating substantial theoretical and practical significance.

2. Literature Review

Developed countries represented by the UK and the US have long prioritized financial risk monitoring and management [9]. Through sustained efforts, they have established robust social credit systems and legal frameworks, effectively driving high-quality economic growth while mitigating credit risks at their source [10]. However, existing research predominantly focuses on guarantee relationships and asset valuation, with insufficient attention paid to monitoring risks within guarantee networks [11]. Systemic financial risk refers to the probability of a complete collapse or dysfunction of the entire financial system [12]. It is closely linked to individual financial risks, and under contagion effects, a single risk may rapidly spread to other institutions and markets, triggering systemic turbulence that directly threatens national financial security [13]. This has made systemic financial risk a critical research focus for international organizations and academia [14].

In recent years, technologies such as artificial intelligence and machine learning have demonstrated remarkable potential in anti-fraud and financial risk identification [15]. Models trained on historical transaction data can detect abnormal behaviors, while integrating time series analysis and keyword recognition effectively supports telecom fraud detection and network traffic monitoring [16]. As financial markets grow increasingly complex with surging data volumes, traditional analytical methods struggle to handle nonlinear relationships and latent pattern mining [17]. Neural networks, leveraging their superior pattern recognition capabilities, when combined with genetic algorithms, enhance model parameter optimization and deepen understanding of market mechanisms. Graph neural networks have also garnered significant attention in recommendation systems [18]. By utilizing graph structures to facilitate information

dissemination and feature learning between users and items, they not only improve recommendation accuracy and diversity but also effectively address cold-start challenges for new users and products, providing powerful tools for modeling complex relationships in financial scenarios [19].

3. Algorithm Design

This paper proposes an improved whale optimization-based financial data mining algorithm (IFD-WO). By integrating variational modal decomposition with whale optimization algorithms and employing adaptive parameter determination, the method achieves effective feature extraction of fault signals from financial time series data, thereby enhancing the accuracy and stability of subsequent risk identification. Variational modal decomposition adaptively decomposes signals into multiple eigenmodal functions, effectively avoiding modal aliasing phenomena. The decomposition performance primarily depends on two key parameters: the number of decomposed modes KK and the penalty factor αα. To overcome the subjectivity in manual parameter selection, this study utilizes whale optimization algorithms to automatically optimize (K,α) parameters. To avoid the compensation effect where a low sum of entropies may conceal individual components with high entropy, this study redefines the fitness function as the maximum sample entropy among all modal components. Minimizing the maximum entropy ensures that every decomposed component maintains low entropy, thereby effectively suppressing modal aliasing and improving decomposition quality. Alternative definitions such as weighted sums or penalty terms were also considered, but the max-entropy criterion proves most robust against compensation issues. The whale optimization algorithm employs global optimization strategies mimicking humpback whales' encirclement predation, spiral updates, and stochastic search mechanisms. Specifically, (K,α) parameters are encoded as position vectors of whale individuals, with iterative updates of search agent positions targeting minimum sample entropy. The algorithm alternates between contraction encirclement and spiral movements while enhancing global exploration capabilities through stochastic searches to avoid local optimization traps.

Based on the aforementioned mechanism, the IFD-WO algorithm flow designed in this paper is illustrated in Algorithm 1.

Algorithm 1: Improved Financial Data Mining Algorithm Based on Whale Optimization (IFD-WO)

1: Initialize whale population $X_i(i = 1,2,\dots,n)$
2: Set parameters such as maximum iteration count
3:Combine the number of decompositions K and the penalty factor αas node positions, and randomly generate initial parameter combinations (K, α)
4: Calculate the current fitness of each search node (maximum sample entropy across modal components)
5: Set as X_1^* the optimal search node
6: Perform variational mode decomposition on fault signals based on different parameter combinations, and calculate the maximum sample entropy among all components
7: **for** $\mathbf{t = 1}$ **to T then**
8: **for** each search node **do**
9: Update parameters a, C, D, l, and p
10: **if** $\mathbf{p < Pe}, |\mathbf{C}| < \mathbf{1}$ **then**
11: Update the current node's position (contracting bounding mechanism)
12: **else if** $|C| \geq 1$

```
13:        Randomly select a search proxy X_rand and update the current location
14:      else if p ≥ Pe then
15:        Update current location (spiral update mechanism)
16:      end if
17:      Calculate fitness for the new position
18:      if the new fitness value is lower than the previous one then X_t^* = X_t
19:    end for
20:end for
```

4. Numerical Examples

4.1. Data Sources

To further demonstrate the effectiveness of the proposed IFD-WO algorithm, we conduct an empirical test on systemic financial risk contagion using data from Chinese listed companies. Three representative models are selected as baselines for comparison: the Linear Threshold (LT) model, the Independent Cascade (IC) model, and the project-based collaborative filtering (ICF) algorithm. In our empirical study, the LT model is used to simulate the threshold-based propagation of financial distress, where a company becomes affected only when the cumulative influence from its already-affected neighbors reaches a certain level. The IC model is employed to emulate probabilistic risk diffusion, where each affected company independently influences each of its neighboring companies with a certain likelihood. The ICF algorithm is adapted to predict risk transmission by identifying companies that share similar historical risk exposure patterns and aggregating their risk statuses as a collaborative filter. These three models are implemented on the same financial risk contagion network constructed from listed companies in Shanghai, Shenzhen, and Hong Kong, using identical training and test splits (90%/10%) as the proposed IFD-WO method. Their performance is evaluated using RMSE and MAE, and the results are compared against our method. The empirical data covers listed companies from 2010 to 2024, with enforcement-related and financing data sourced from Wind and GTA (Guotai'an Information Technology Co., Ltd.) databases, and verified and corrected using the CSMAR (China Stock Market & Accounting Research Database) database. The official websites of the databases are as follows: Wind (http://www.wind.com.cn), GTA(http://www.gtadata.com), and CSMAR(https://data.csmar.com). Sample Selection and Industry Coverage. Our initial sample includes all constituent companies of the major stock indices from the three markets: the CSI 300 Index for the Shanghai and Shenzhen Stock Exchanges, and the Hang Seng Composite Index for the Hong Kong Stock Exchange, covering the period from 2010 to 2024. This ensures that our sample represents the broad market conditions and reduces survivorship bias. We include all available companies across all industries, including the financial sector, to preserve the full diversity of the market.

To account for potential industry-specific heterogeneity in risk contagion mechanisms, we incorporate industry dummy variables as control variables in all regression and network analyses. This approach allows us to isolate the general risk contagion effects while acknowledging that different industries may exhibit different baseline risk levels and transmission patterns. We also conduct sensitivity analyses by excluding one industry at a time to verify that our main results are not driven by any single industry. All non-virtual continuous financial variables underwent Winsorization

at the 1% level, followed by normalization of indicators. The financial risk contagion network constructed from listed companies serves as the core framework of regional financing circles, closely mirroring the actual conditions of local industrial association networks. The relationship chain in the financing network defines financing partnerships among enterprises, including mutual investments, loan guarantees, entrusted loans, non-operating fund occupation, and large-scale business contracts. During network construction, a list of listed companies in Shanghai, Shenzhen, and Hong Kong was compiled, with preliminary financing relationship networks established through screening guarantees and equity participation events, supplemented by additional financing information from major unlisted group companies.

This model is implemented using the PyTorch framework and Python, employing joint training of HAN and CNN to optimize a shared loss function. Through multiple rounds of experimentation, the final parameter settings were determined as follows: the dimensionality of named entity features and user node features is 100 and 125 respectively; HAN incorporates 8 multi-head attention mechanisms with hidden layer units of 4; CNN convolution kernels are configured with sizes of 3×3, 3×3, and 1×1 respectively, initialized using Xavier, with a learning rate of 0.001, batch size of 256, and 100 training iterations. The dataset is split into training and test sets at a 90%:10% ratio, with negative samples randomly generated to maintain a 1:1 positive-negative sample ratio, thereby enhancing training stability and preventing overfitting.

4.2. Data Analysis Results

Table 1 presents a performance comparison of the proposed IFD-WO algorithm against classical methods. Our method consistently achieves higher accuracy across all datasets. For datasets including Alibaba, Walmart, and Amazon, our algorithm achieves RMSE values 25%-65% lower than competing methods, while its MAE values show 25%-55% improvement on the same datasets, confirming superior accuracy. As shown in Table 2, the IFD-WO algorithm consistently outperforms other methods by minimizing overall dataset loss.

Table 1. Comparison results of algorithms based on RMSE and MAE

Algorithm name	Listed company on the Shanghai Stock Exchange		Listed companies on the Shenzhen Stock Exchange		Listed company on the New Third Board	
	RMSE	**MAE**	**RMSE**	**MAE**	**RMSE**	**MAE**
LT	0.927912	0.918322	0.936718	0.910201	0.912158	0.908244
IC	0.919203	0.912353	0.917246	0.908439	0.898459	0.890435
ICF	0.831040	0.800902	0.820374	0.801587	0.855111	0.811470
IFD-WO	**0.232002**	**0.203568**	**0.301903**	**0.282040**	**0.250774**	**0.249711**

Note: Values in bold indicate corresponding models with good performance.

Table 2. Comparison of Algorithm Execution Time Results

Dataset name	LT	IC	ICF	IFD-WO
Listed company on the Shanghai Stock Exchange	2262.36606	1700.22039	2007.77943	**76.67991**
Listed companies on the Shenzhen Stock Exchange	2127.77946	2026.26633	1626.34413	**86.98029**
Listed company on the New Third Board	2341.68791	1739.57414	3243.61756	**31.40181**

Note: Values in bold indicate corresponding algorithms demonstrate good performance.

5. Conclusion

With the deepening development of digital technologies, financial risk management is undergoing profound transformations. Traditional methods relying on experience and linear models have gradually been replaced by big data and AI-based risk analysis approaches due to insufficient accuracy and poor adaptability. Technologically, establishing unified data platforms through data governance and real-time stream processing enables millisecond-level response to potential risks. Intelligent algorithms such as deep learning and graph neural networks learn risk characteristics from massive datasets while integrating explainable tools to balance performance and transparency. In practical applications, frameworks combining ensemble learning with time-series models have been widely deployed, forming complete closed-loop systems from data collection to real-time monitoring, effectively enhancing risk control capabilities for credit defaults and fraudulent transactions. The increasing prominence of technical and systemic risks also necessitates incorporating data breaches and model biases into comprehensive risk frameworks with strengthened prudential assessments. From regulatory and compliance perspectives, institutions like the China Banking and Insurance Regulatory Commission (CBIRC) support standardized big data risk management through technology supervision platforms and penetrative oversight, improving financial institutions' internal governance and system resilience against external shocks. In summary, big data and intelligent algorithm-based risk control methods play a pivotal role in enhancing identification accuracy, response speed, and systemic resilience. As technology and regulations continue to evolve, financial risk management will transition toward integrating intelligent prediction with real-time prevention, laying a solid foundation for stable financial institution operations and long-term financial system stability.

Our empirical results show that the proposed IFD-WO algorithm consistently outperforms LT, IC, and ICF models across all three markets, achieving significantly lower RMSE and MAE as well as much faster computation. The practical implications are threefold: financial institutions can use our method for early risk warning; regulators can monitor systemic risk in real time; and corporate managers/investors can better anticipate contagion effects. This study has three main limitations: the data period (2010–2024) may not cover all crisis scenarios; the network construction excludes some interdependence channels (e.g., supply chains); and model interpretability could be improved. Future research should explore dynamic network updating, cross-border risk contagion, and integration of alternative data (e.g., news sentiment, ESG).

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The Role of Professionals in Bookkeeping and Administration in the Era of Big Data

Mohamad Reeduan Mustapha[a,1], Hafiza Aishah Hashim[b] and Fam Seng Choy[c]
[a]*Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia*
[b]*Faculty of Business, Economics & Social Development, Universiti Malaysia Terengganu, Malaysia*
[c]*Malaysian Association of Certified Bookkeepers and Administrators, Malaysia*
ORCiD ID: Mohamad Reeduan Mustapha https://orcid.org/0000-0003-0836-3028
ORCiD ID: Hafiza Aishah Hashim https://orcid.org/0000-0002-5630-7912

Abstract. The increasing use of Big Data technologies is reshaping the nature of professional work across various sectors, particularly in the accounting and administrative functions. While most existing studies have focused on how these developments are affecting accountants, attention has been relatively limited to bookkeepers and administrators, despite their critical role in supporting the financial management and operations of organizations. Therefore, this study aims to explore how Big Data is affecting the roles, competencies, challenges, and career paths of bookkeeping and administrative professionals. A qualitative approach was used through semi-structured interviews with seven experienced professionals from the accounting, finance, consulting, and administrative sectors. Participants were selected using purposive sampling based on their professional experience and level of familiarity with digital financial systems. Interview data were analyzed using thematic analysis to identify recurring patterns related to technological change, job transformation, new skill requirements, and professional adaptation. The findings of the study indicate that Big Data is reshaping the profession by reducing the emphasis on routine transaction processing, while increasing expectations for analytical capabilities and roles in decision support. Five key themes were identified: automation of routine tasks, increasing analytical expectations, the emergence of hybrid competencies, the challenges of adaptation, and the development of new digital career opportunities. The study suggests that bookkeeping and administrative professionals will rely heavily on their ability to adapt to the digital environment and engage in continuous professional learning.

Keywords. Big Data, Bookkeeping, Administration, Accounting Transformation, Digital Skills.

1. Introduction

The growing use of Big Data technologies has substantially changed the way organizations gather, manage, and make use of information in their daily operations. In general, Big Data refers to the vast amount of both structured and unstructured data that organizations can analyze to support more informed decision-making [1]. As

[1] Corresponding Author: Mohamad Reeduan Mustapha, Faculty of Industrial Management, Universiti Malaysia Pahang Al-Sultan Abdullah, Kuantan, Malaysia. Email: reeduan@umpsa.edu.my.

organizations increasingly integrate data analytics into their operational processes, the nature of many professional roles has also begun to evolve, particularly those related to financial management and administrative coordination. This shift is especially evident in positions that traditionally focused on record keeping and administrative support, which are now becoming more data-oriented and technology-driven [2].

Within accounting and administrative functions, recent technological developments such as cloud-based accounting platforms, artificial intelligence applications, automated reporting systems, and digital document management tools are gradually reshaping traditional job responsibilities. Tasks that were once performed manually are increasingly being supported or replaced by digital systems, changing how work is organized and executed. Traditionally, bookkeepers and administrators were mainly responsible for recording financial transactions, maintaining accounting records, and ensuring the accuracy of supporting documentation. At the same time, administrative professionals typically handled responsibilities such as document management, scheduling, coordination of meetings, and communication support within organizations. However, as digital technologies become more embedded in organizational processes, these roles are evolving to include greater interaction with information systems and data-driven workflows [3].

The growing use of digital platforms has also reduced the reliance on manual record-keeping and paper-based processes. Tasks that once required considerable time and human effort are now routinely handled by automated systems that can process information more quickly and with greater accuracy. As a consequence, the value of bookkeepers and administrators is no longer defined solely by their ability to perform routine tasks, but increasingly by their capacity to work with digital systems, interpret financial and operational data, and contribute to organizational decision-making processes. However, comparatively little attention has been given to bookkeeping and administrative personnel, even though they play a critical role in ensuring the smooth operation of financial and information management processes. This lack of attention suggests a gap in the current literature, particularly in understanding how technological change is affecting these essential but often overlooked these professional groups.

Therefore, this study seeks to examine how Big Data is influencing the evolution of bookkeeping and administrative professions. Specifically, this study addresses the following objectives:

1. To investigate the challenges and opportunities arising from Big Data.
2. To assess potential shifts in roles, responsibilities, and career pathways of professionals in bookkeeping and administration.

By addressing these objectives, this study provides insights into how technological transformation affects not only high-level professionals but also operational support roles within accounting and administrative environments.

2. Big Data and the transformation of accounting and administrative functions

Big Data has become a critical driver of change within accounting and administrative functions. The ability to process large datasets enables organizations to move beyond historical reporting toward predictive analysis and strategic planning. According to Warren et al. [4], Big Data technologies allow accounting professionals to expand their roles from financial reporting toward business advisory functions. Similarly, Cockcroft and Russell [5] argue that data analytics capabilities are becoming essential

competencies in modern accounting environments. As organizations increasingly rely on real-time information, the ability to interpret data is becoming more valuable than the ability to merely record it. This transformation also affects bookkeeping roles, which traditionally involved transaction recording. With automation capable of performing many recording functions, bookkeepers must increasingly shift toward monitoring automated processes and ensuring data quality.

Administrative work has also undergone a significant transformation due to digital technologies. Electronic document management systems, enterprise collaboration tools, and workflow automation platforms have changed how administrative functions operate. According to Bessen [6], administrative roles are increasingly becoming coordination roles that involve managing information flows rather than handling physical documentation. This suggests that administrative professionals must become comfortable working with digital platforms and managing information systems.

The technological change requires a transformation of professional skills. The World Economic Forum in 2023 [7] identifies analytical thinking, digital literacy, and adaptability as among the most important future skills. This indicates that bookkeepers and administrators must develop both technical competencies and human skills. While digital literacy enables professionals to work effectively with data, human competencies such as critical thinking and communication remain important for interpreting and applying information.

This shift in skills is closely linked to the broader transformation brought about by Big Data in accounting and administrative functions. Big Data has fundamentally changed how these roles operate, moving them beyond routine record-keeping toward more strategic and insight-driven activities. Rather than focusing solely on historical data, organizations can now utilize real-time information, apply predictive analytics, and enhance transparency in decision-making. As a result, accounting professionals are increasingly positioned to contribute to organizational strategy. In public administration, the integration of Big Data with Internet of Things (IoT) technologies has further expanded opportunities to improve efficiency, enhance service delivery, and support evidence-based policymaking [8].

At the organizational level, the adoption of Big Data has reshaped performance management and control systems by embedding data analytics into decision-making processes. This reflects a broader socio-technical transformation, where the success of technological implementation depends not only on the tools themselves but also on their alignment with organizational structures, employee competencies, and internal control mechanisms [9]. Consequently, professionals in accounting and administration are expected to strengthen their data literacy, analytical thinking, and interdisciplinary skills to interpret complex datasets and support strategic objectives.

However, the increasing reliance on Big Data also introduces significant challenges. Concerns around governance, accountability, and ethical data use have become more pronounced, as data-driven systems may blur traditional decision-making boundaries and raise questions about the limits of administrative authority. Addressing these issues requires stronger regulatory frameworks to ensure transparency, protect stakeholders' interests, and maintain public trust [10]. Therefore, while Big Data offers substantial potential to enhance efficiency and innovation, it also necessitates a re-evaluation of professional roles, organizational practices, and regulatory structures within accounting and administrative domains.

3. Methodology

3.1. Research design

This study adopts a qualitative research design to gain in-depth insights into the transformation of bookkeeping and administrative roles. A qualitative approach is appropriate because the study seeks to explore professional experiences, perceptions, and interpretations of technological changes.

3.2. Sampling

Purposive sampling was employed in this study to ensure that participants possessed relevant knowledge and experience aligned with the research objectives. The selection criteria included individuals with a minimum of eight years of professional experience, exposure to digital systems, and those holding professional or managerial positions. In addition, participants were required to have expertise in accounting or administrative functions to ensure informed and contextually rich insights. All participants were drawn from organizations operating in Malaysia. In total, seven experts were selected to participate in the study. This number is considered adequate to achieve thematic saturation in qualitative research, where no new significant themes emerge from additional data collection, as supported by Guest et al. [11]. While seven participants were sufficient to reach thematic saturation within this specific professional context, it is acknowledged that the relatively small sample size limits the generalizability of the findings.

3.3. Data collection

Data were collected through semi-structured interviews, which allowed participants to elaborate on their experiences while aligning with the study objectives. Each interview lasted between 45 and 60 minutes and was conducted through physical face-to-face sessions and via online platforms, depending on participants' availability and convenience. The interviews were conducted following a structured protocol to ensure consistency and alignment with the study objectives. Participants were first briefed on the purpose of the study, provided informed consent, and informed that their responses would be recorded for accuracy. The protocol then guided the discussion through several key areas, including the impact of Big Data on daily work, changes in job responsibilities, the emergence of new skill requirements, career opportunities, and challenges in adapting to technological advancements. All interviews were recorded and subsequently transcribed verbatim to ensure the reliability and accuracy of the data for analysis.

3.4. Data Analysis

Data analysis in this study was conducted using thematic analysis, guided by the six-phase proposed by Braun and Clarke [12]. This approach enabled a systematic and rigorous examination of qualitative data to identify, analyze, and report patterns (themes) within the dataset. The analysis began with familiarization with the data, where interview transcripts were read repeatedly to gain a deep understanding of the content. This was followed by the generation of initial codes, capturing meaningful segments of the data.

Subsequently, codes were organized into potential themes, which were then reviewed and refined to ensure coherence and relevance. In the next stage, themes were clearly defined and named to reflect their essence accurately. Finally, the findings were reported in a structured manner, linking themes to the research objectives and supporting them with relevant excerpts from the data. To enhance the efficiency and organization of the coding process, the qualitative data analysis software ATLAS.ti was used.

4. Findings

4.1. Profile of interview participants

A total of seven experts participated in this study. The respondents were selected using purposive sampling to ensure relevant professional expertise in accounting, finance, administration, and organizational management. The respondents represent senior and mid-career professionals, indicating that the findings reflect informed professional perspectives on the transformation of bookkeeping and administrative roles. Table 1 presents the profile of respondents.

Table 1. Profile of respondents

Respondent	Gender	Age Range	Education	Position
R1	Male	50–59	PhD	Director
R2	Male	30–39	Degree	Manager
R3	Female	40–49	Master	Head of Human Capital
R4	Female	30–39	Degree	Consultant
R5	Male	60+	PhD	Consultant
R6	Female	50–59	Degree	Manager
R7	Male	60+	PhD	Group CEO

Source: Authors' own creation

4.2. Challenges and opportunities arising from Big Data

The findings of this study reveal significant changes in the roles and competencies of bookkeepers and administrators in response to ongoing digital transformation. Analysis of the data indicates that technological advancements, particularly in automation and data-driven systems, are not only altering routine tasks but also reshaping the overall expectations of these professions. From the patterns identified, three key themes emerged, reflecting the nature and direction of this transformation.

Theme 1: Automation is redefining routine bookkeeping and administrative functions

A dominant finding from the interviews is that automation technologies are significantly transforming traditional bookkeeping and administrative tasks. Respondents consistently identified routine processes such as data entry, reconciliations, reporting, payroll, and transaction processing as areas most affected by automation. R2 explained, "*Manual data entry is reducing because most transactions are now captured automatically by accounting systems."* Similarly, R6 stated that "*Automated checking and reconciliation eliminate non-value-added activities and improve efficiency*." R5 further emphasized, "*Recording may be automated, but decision-making still requires human judgment*."

These responses suggest that technology is shifting professional roles away from manual processing toward monitoring and verification responsibilities. This finding

aligns with Davenport and Kirby [13], who argue that automation typically replaces repetitive tasks rather than entire professions. Similarly, Frey and Osborne [14] suggest that occupations involving routine activities face higher automation risks, while roles involving judgment and interpretation remain resilient.

The analytical interpretation of the findings indicates a clear transition in the role of bookkeepers and administrators, shifting from a traditional processing role to a more supervisory role. This transformation reflects a significant change in how routine tasks are managed, particularly with the increasing integration of digital technologies in organizational processes.

The findings suggest that bookkeepers and administrators are no longer primarily engaged in processing transactions. Instead, they are evolving into controllers of digital processes, where their responsibilities focus more on monitoring, validating, and interpreting system-generated outputs. This shift highlights the growing importance of oversight, analytical thinking, and decision-making capabilities in the digital era.

Theme 2: Shift toward strategic and analytical responsibilities

The second theme reveals that bookkeeping and administrative professionals are increasingly expected to provide analytical insights and support managerial decision-making. R7 noted, "*Professionals are moving from transactional record-keeping to becoming strategic partners in governance and sustainability*." R1 similarly stated, "*The role is evolving from mundane data entry to analytics and higher value contribution*." R3 emphasized that "*There will be more supervision and assurance roles rather than clerical work*."

These responses indicate a clear movement toward knowledge-based roles that require interpretation rather than recording. This finding supports Warren et al. [4], who argue that Big Data enables accounting professionals to transition from financial reporting toward decision analytics. Similarly, Cockcroft and Russell [5] note that accounting support roles are increasingly contributing to organizational intelligence rather than merely maintaining records.

Theme 3: Hybrid competency requirements in the Big Data environment

The third theme highlights the evolving competency requirements for bookkeepers and administrators in the context of Big Data and technological advancements. Respondents consistently emphasized the need for both technological and human-centered skills. For example, R4 noted that "*IT skills and knowing how to use AI prompts are becoming important*," while R5 highlighted the importance of analytical capabilities, stating that "*Critical thinking is necessary to challenge AI outputs and ensure reliability*." R7 stressed the need for systemic thinking, explaining that "*Professionals must understand how systems connect across business, technology, and stakeholders*." R1 also emphasized the human element, adding that "Human touch remains important despite automation."

The skills identified by respondents can be broadly categorized into three main domains: technical, cognitive, and human competencies. From a technical perspective, respondents emphasized the growing importance of data analytics, artificial intelligence (AI) literacy, cloud accounting systems, enterprise resource planning (ERP) knowledge, and the use of digital workflow tools. These competencies highlight the increasing

integration of digital technologies into routine financial and administrative functions, requiring professionals to move beyond traditional manual processes.

In addition to technical expertise, cognitive competencies were identified as equally critical. These include critical thinking, strategic thinking, problem solving, and analytical reasoning. Such skills enable professionals to interpret complex data, make informed decisions, and contribute to organizational strategy. Complementing these are human competencies, which encompass communication, ethical judgment, adaptability, and collaboration. These interpersonal and behavioral skills remain essential in ensuring effective teamwork, ethical decision-making, and the ability to navigate dynamic work environments.

These findings are consistent with the World Economic Forum 2023 report, which predicts that future professionals must integrate digital literacy with strong human-centric skills [7]. Furthermore, the results support the concept of T-shaped professionals, referring to individuals who possess deep specialized expertise in a particular domain alongside the ability to collaborate, adapt, and integrate knowledge across multiple disciplines. This combination of technical proficiency and cross-functional capability is increasingly essential in navigating the complexities of modern, data-driven organizational contexts.

From an analytical perspective, the findings indicate a clear transformation in professional roles. The traditional role of a bookkeeper is evolving into that of a digital finance professional, while administrative roles are shifting towards becoming information coordinators. This transition reflects a broader trend of professional hybridization, where individuals are required to combine technical, analytical, and interpersonal competencies to remain relevant in an increasingly digitalized and interconnected work environment.

Theme 4: Transition risks and organizational readiness challenges

The fourth theme highlights the risks and barriers that organizations face during the transition to Industry 5.0, despite the opportunities it presents. Respondents identified several challenges related to technological adaptation and organizational readiness. For example, R3 expressed concern that "*Resistance to change and technology skills gaps remain major challenges*," while R6 noted that "*Digitalization may be too fast for some organizations to catch up*." R2 emphasized the financial aspect, stating that "*Implementation cost can be difficult, especially for SMEs*." R5 also highlighted potential workforce implications, adding that "*There may be manpower reduction if reskilling does not occur*."

These concerns suggest that technological change is not purely a technical issue but also a human and organizational adaptation challenge. This finding supports Bessen [6], who argues that technological displacement often results from skill mismatch rather than technology itself. Furthermore, the transition challenges identified in this study can be systematically categorized, as presented in Table 2. This categorization highlights the multidimensional nature of the challenges, encompassing not only technical competencies but also cognitive and behavioral aspects.

Table 2. Multidimensional nature of the challenges

Challenge type	Description
Skills gap	Lack of digital competencies
Cultural resistance	Mindset barriers
Financial barriers	Technology investment cost

Pace of technological change	Rapid digital transformation
Workforce anxiety	Fear of job loss

Source: Authors' own creation

Theme 5: Emergence of new digital and hybrid career pathways

The fifth and final theme highlights the emergence of new digital and hybrid career pathways. A particularly important finding is that most respondents believe that technological advancements will create new professional opportunities despite the risks associated with automation. For instance, R1 noted that "*New roles such as accounting data analyst and digital bookkeeping specialist are emerging*," while R7 identified governance-related roles, stating that "*ESG systems integrator and ethical AI validator will become important*." R5 highlighted AI-focused careers, adding that "*Prompt trainer and AI oversight specialist will become new professional roles*," and R6 suggested leadership positions in digital finance, noting that "*Cloud accounting manager and financial business analyst roles will increase*.

These findings indicate that career paths are expanding rather than contracting. This aligns with Autor [15], who argues that technological change primarily alters task composition rather than eliminating occupations entirely. Table 3 presents the analytical interpretation of the data, highlighting the emergence of new professional roles because of technological advancement and digital transformation. The findings indicate a clear shift from traditional job titles towards more specialized and digitally oriented roles.

Table 3. Emergence of new professional roles

Traditional roles	Emerging roles
Bookkeeper	Digital bookkeeping specialist
Accounts clerk	Accounting data analyst
Admin clerk	Digital workflow coordinator
Finance assistant	Financial business analyst
Record officer	AI oversight specialist

Source: Authors' own creation

This pattern reflects a broader trend of role transformation driven by the integration of automation, data analytics, and artificial intelligence into organizational processes. Rather than eliminating jobs entirely, technology appears to be reshaping the nature of work by redefining responsibilities and elevating the level of expertise required. Consequently, these findings suggest that the impact of technological change is better understood as career evolution rather than career disappearance, where existing roles are augmented and reconfigured to align with the demands of a digital and data-driven environment.

5. Discussion

The impact of Big Data on bookkeeping and administrative professionals can be understood through three key dimensions of transformation: task, skill, and role. In terms of task transformation, the findings reveal a clear decline in routine, repetitive activities, which are increasingly automated, alongside a corresponding rise in analytical and value-adding tasks. Professionals are no longer confined to data entry or basic administrative functions but are expected to engage in data interpretation, monitoring, and decision-support activities.

From a skill transformation perspective, the study highlights the necessity of integrating both technical and human competencies. While digital skills such as data analytics, AI literacy, and system knowledge are becoming essential, they must be complemented by cognitive and interpersonal abilities, including critical thinking, communication, and ethical judgment. This integration reflects the complexity of modern work environments, where professionals are required to navigate both technological systems and human interactions effectively.

In terms of role transformation, the findings demonstrate a shift from traditional support roles to more strategic enabling roles within organizations. Bookkeeping and administrative professionals are increasingly contributing to organizational performance by providing insights, coordinating information flows, and supporting strategic decision-making processes. This evolution signifies a move towards higher-value roles that are integral to organizational success.

These findings support the augmentation theory of technology, which posits that digital tools are more likely to enhance professional capabilities rather than replace them entirely [13]. In line with this perspective, the study proposes that the future bookkeeping and administrative professional will be characterized by strong digital capability, advanced analytical thinking, heightened strategic awareness, sound human judgement, and a high degree of technological adaptability. These attributes are essential for navigating the demands of a rapidly evolving, data-driven, and technology-enabled work environment.

This study's conceptual framework (see Figure 1) has been developed after qualitative findings, further discussed.

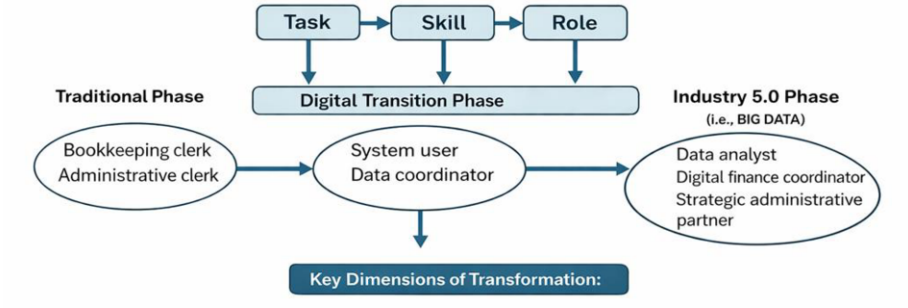


Figure 1. Conceptual framework
Source: Authors' own creation

5.1. Objective 1: to investigate the challenges and opportunities arising from Big Data.

The findings of this study provide clear alignment with the research objectives, particularly in relation to understanding the challenges and opportunities associated with the impact of Big Data on bookkeeping and administrative professionals. In addressing Objective 1, the study identifies several key challenges faced by professionals during this transition. These include a significant skills gap, resistance to change among employees, cost barriers associated with adopting new technologies, and difficulties in adapting to rapidly evolving digital systems. These challenges highlight the complexity of technological transformation, which extends beyond system implementation to include human readiness and organizational support.

At the same time, the findings reveal substantial opportunities arising from this transformation. Automation has enhanced operational efficiency by reducing time spent on routine tasks, while also creating new digital roles that require higher-level competencies. In addition, there is a noticeable expansion of strategic responsibilities, with professionals increasingly involved in decision-support functions and organizational planning. These opportunities suggest that, despite the challenges, technological advancement can lead to meaningful career development and value creation within organizations. Table 4 summarizes the key challenges and opportunities associated with the impact of Big Data on bookkeeping and administrative professionals

Table 4. Challenges and Opportunities

Aspect	Key Findings
Challenges	Skills gap, resistance to change, cost barriers, and difficulty in adapting to new technologies
Opportunities	Automation efficiency, emergence of new digital roles, expansion into strategic roles, and increased involvement in decision-support functions

Source: Authors' own creation

Table 4 highlights that the integration of Big Data technologies presents both challenges and opportunities for bookkeeping and administrative professionals. The challenges include skills gaps, resistance to change, cost barriers, and difficulties in technology adaptation, reflecting the need for continuous professional learning, strong organizational support, and effective change management strategies to ensure a smooth transition to a data-driven environment. Conversely, the opportunities illustrate the potential benefits of Big Data, such as increased efficiency through automation, the creation of new digital roles, the expansion of strategic responsibilities, and greater involvement in decision-support functions.

5.2. Objective 2: to assess potential shifts in roles, responsibilities, and career pathways of professionals in bookkeeping and administration.

In relation to Objective 2, the findings demonstrate a clear shift in professional roles, reflecting the evolving expectations of the workplace. Traditional roles such as data recorders and clerks are transitioning into more analytical and value-driven positions, including data validators and analysts. Similarly, administrative support roles are evolving into information coordinators, while bookkeepers are becoming digital finance specialists. More broadly, the role of a processor is transformed into that of a decision support partner. These shifts indicate a move away from routine task execution towards roles that emphasize analysis, interpretation, and strategic contribution, reinforcing the broader theme of professional evolution in the digital era. Table 5 illustrates the transformation of professional roles from traditional, task-oriented positions to more analytical and strategic roles.

Table 5. Role Shifts

Previous Role	Emerging Role
Data recorder	Data validator
Clerk	Analyst
Admin support	Information coordinator
Bookkeeper	Digital finance specialist
Processor	Decision support partner

Source: Authors' own creation

The data shows a clear progression, where roles such as data recorders, clerks, and administrative support staff are evolving into positions like data validators, analysts, and information coordinators. Similarly, bookkeepers are transitioning into digital finance specialists, and processors are becoming decision support partners. This shift reflects the broader impact of digitalization, where routine tasks are increasingly automated, and professionals are expected to contribute through analysis, interpretation, and strategic insight. Overall, the trend of role enhancement and professional evolution rather than job displacement.

6. Conclusions

This study demonstrates that Big Data is significantly transforming the roles of bookkeepers and administrators. While automation reduces the need for routine processing tasks, it simultaneously increases the importance of analytical thinking, digital literacy, and strategic awareness. This study concludes that the future relevance of these professions depends not on their ability to perform routine work but on their capacity to adapt to technology-driven environments. Professionals who embrace digital transformation and engage in continuous professional learning to develop new competencies are likely to remain relevant, whereas those who resist change may face increased career risks. Ultimately, the study highlights that Big Data is not eliminating bookkeepers and administrators but reshaping them toward higher-value roles that emphasize analysis, coordination, and decision support.

6.1. Implications

The findings of this study offer several important managerial implications for organizational leaders navigating the impact of Big Data. First, organizations must recognize that investment in technology should be complemented by equal investment in the workforce. Implementing advanced digital systems without equipping employees with the necessary skills may limit the effectiveness of such initiatives. Training and development programs are therefore essential to ensure that employees can adapt and fully utilize new technologies, thereby maximizing the returns on digital transformation efforts.

Second, organizations should consider redesigning job scopes to place greater emphasis on analytical and value-adding contributions rather than routine processing tasks. As automation increasingly handles repetitive functions, professionals need to transition into roles that involve data interpretation, problem-solving, and strategic input. This shift not only enhances organizational performance but also supports employee career development by aligning roles with future workplace demands.

Third, the findings highlight the importance of fostering a culture of lifelong learning within organizations. With the pace of technological change accelerating, continuous learning is no longer optional but a necessity. Encouraging employees to regularly update their knowledge and skills will help organizations remain competitive while ensuring that their workforce stays relevant in a rapidly evolving environment.

Finally, organizations should implement structured digital upskilling programs to ensure workforce readiness. These programs should be systematically designed to address both technical competencies, such as data analytics and digital tools, and complementary cognitive and human skills. By doing so, organizations can build a

resilient and adaptable workforce capable of navigating the complexities of a data-driven and technology-enabled future.

6.2. Limitations and future research directions

This study has several limitations that should be considered when interpreting the findings. First, the research is based on a small qualitative sample, which may limit the generalizability of the results to a broader population. While the qualitative approach provides in-depth insights, future research could enhance generalizability by employing larger sample sizes and incorporating quantitative methods to validate and extend the findings.

Second, the study focuses on selected industries, which may not fully capture the diversity of experiences across different sectors. As the impact of Big Data and digital transformation may vary by industry, future studies could undertake comparative analyses across sectors such as manufacturing, the public sector, and financial services to provide a more comprehensive understanding.

Third, the study examines professional perceptions rather than directly measuring actual performance outcomes. Although perceptions are valuable in understanding experiences and expectations, future research could investigate the tangible effects of digital transformation on productivity, efficiency, and organizational performance to provide more objective evidence.

Finally, future research could explore the development of competency frameworks specifically tailored for bookkeepers and administrators in the Big Data era. Such frameworks would help define the critical skills and capabilities required, offering practical guidance for educators, organizations, and policymakers in preparing the workforce for ongoing technological advancements.

Acknowledgment

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Enhanced Digital Twin Framework for Natural Disaster-Aware Critical Infrastructure Simulation

Georgi KIROV[a], Plamena ZLATEVA[b,c] and Dimiter VELEV[b1]
[a]*International Business School, Botevgrad, Bulgaria*
[b]*University of National and World Economy, Sofia, Bulgaria*
[c]*Institute of Robotics, Bulgarian Academy of Sciences, Sofia, Bulgaria*
ORCiD ID: Plamena Zlateva https://orcid.org/0000-0002-0153-5811
Dimiter Velev https://orcid.org/0000-0003-3030-1819

Abstract. This paper proposes a reference model for a Digital Twin enhanced framework that extends traditional High-Level Architecture (HLA) based simulations toward disaster-aware critical infrastructure management. The framework introduces a disaster-aware conceptual architecture and associated operational views to structure the interaction of simulation components, data flows, and decision-making processes. Real time data streams from sensors, Internet of Things (IoT) devices, and external information sources are integrated with AI driven analytics to create continuously updated, living digital twins of critical infrastructures, urban environments, and relevant natural systems. By embedding these digital twins within standardized HLA federations, the proposed approach enables interoperable, scalable, and reusable simulation components across heterogeneous disaster scenarios. The framework enhances situational awareness, supports continuous risk assessment, and allows decision-makers to simulate, analyze, and compare disaster response and mitigation strategies under dynamically changing conditions. The reference model defines core architectural elements, data exchange mechanisms, synchronization principles, and operational viewpoints required to couple digital twins with HLA - compliant simulations.

Keywords. Digital Twin Technology, High Level Architecture, Critical Infrastructure Simulation, Natural Disaster.

1. Introduction

Over the past decade, natural disasters have emerged as one of the main systemic risks to the sustainable functioning of critical infrastructure (CI), with their frequency, intensity and spatial extent showing a clear upward trend [1, 2, 3].

World Meteorological Organization data confirm that recent years have been the warmest on record, which directly correlates with an increase in extreme hydrometeorological events as intense rainfall, floods, heat waves, droughts and wildfire [4].

[1] Corresponding Author: Dimiter Velev, University of National and World Economy, 19 December 8th Str., 1700 Sofia, Bulgaria; E-mail: dgvelev@unwe.bg.

Critical infrastructure is a complex socio-technical system composed of interconnected and interdependent subsystems, including electricity networks, water supply and sanitation, transport, telecommunications, healthcare and digital services [5]. Critical infrastructure systems are essential for societal functioning and economic stability, particularly during natural disaster situations where their disruption can have severe cascading impacts [6, 7]. In this context, the impact of natural disasters is rarely limited to local physical damage [8]. Instead, cascading failures are often observed, in which initial damage to one subsystem, such as the electricity grid, leads to secondary disruptions in water supply, communications, healthcare services and logistics chains [9, 10].

Effective disaster management therefore requires advanced tools that support preparedness, real time situational awareness, and coordinated response across multiple infrastructure domains [11, 12].

It is important to point out that digital twins can adequately provide virtual representations of physical systems [13, 14]. Therefore, the digital twins of the critical infrastructure can successfully ensure continuous monitoring, what-if analysis, and impact assessment under natural disasters [15, 16].

In parallel, the High-Level Architecture (HLA) standard offers a robust and interoperable framework for distributed simulation, enabling the integration of heterogeneous models [17, 18, 19]. The combination of digital twin technology and HLA based simulation creates a powerful foundation for natural disaster-aware critical infrastructure management, supporting the analysis of cascading failures, response strategies, and recovery planning [20, 21].

This paper explores the integration of HLA and digital twins to simulate and manage critical infrastructure systems effectively under natural disaster and emergency scenarios. The complexity and interdependence of these systems make them vulnerable to disruptions. The paper builds upon previous research on the HLA standard [22, 23], which focused on modeling federated interactions among infrastructure domains like power, water, and transportation. However, the HLA framework lacked real-time responsiveness and predictive capabilities, highlighting the need for a more comprehensive approach to managing critical infrastructure systems.

The main purpose of this paper is to propose enhanced framework and describe a **conceptual architecture** that integrates **Digital Twin technology** with the **High-Level Architecture (HLA)** standard to support natural disaster-aware simulation and management of critical infrastructure systems.

The proposed conceptual architecture includes a digital twin layer to ensure successful real-time data integration, dynamic state mirroring, and predictive analytics. Thus, the enhanced framework can adequately represent a variety of scenarios related to changing hazard conditions, critical infrastructure destructions, and cascading damage effects during natural disasters.

2. Problem Statement

Despite advances in disaster modeling and critical infrastructure simulation, existing approaches often rely on static or loosely coupled models that cannot adequately represent the dynamic, data-driven nature of real-world disaster situations.

Traditional High-Level Architecture (HLA) based simulations provide interoperability and scalability but typically operate with predefined scenarios and

limited real-time data integration. Conversely, digital twin technologies enable continuous state mirroring and predictive analytics through real-time data streams, yet they are often implemented as isolated systems lacking standardized mechanisms for large-scale, distributed simulation.

This fragmentation limits their effectiveness in supporting disaster preparedness, response, and resilience analysis for complex, interdependent critical infrastructure systems. There is therefore a need for an integrated, disaster-aware framework that combines the real-time adaptability of digital twins with the interoperability and federation capabilities of HLA, enabling coherent simulation, analysis, and decision support under rapidly evolving disaster conditions.

High Level Architecture [19], developed by the U.S. Department of Defense, facilitates interoperability among simulation components (federates) through a standardized Run-Time Infrastructure (RTI). Each federate represents a distinct subsystem, such as power distribution, water management, or emergency response, and communicates with others via RTI to maintain synchronized simulation timelines and shared data states.

Digital twin technology allows operators to monitor system performance, detect anomalies, and simulate future scenarios based on current conditions. The integration of digital twins into HLA-based simulation environments is a significant advancement, introducing real-time data streams and adaptive behavior (Figure 1).

This fusion allows federates to respond to live conditions, enhancing the realism and relevance of simulations. Digital twins also provide a feedback loop between the physical and virtual worlds, enabling predictive analytics and proactive infrastructure management.

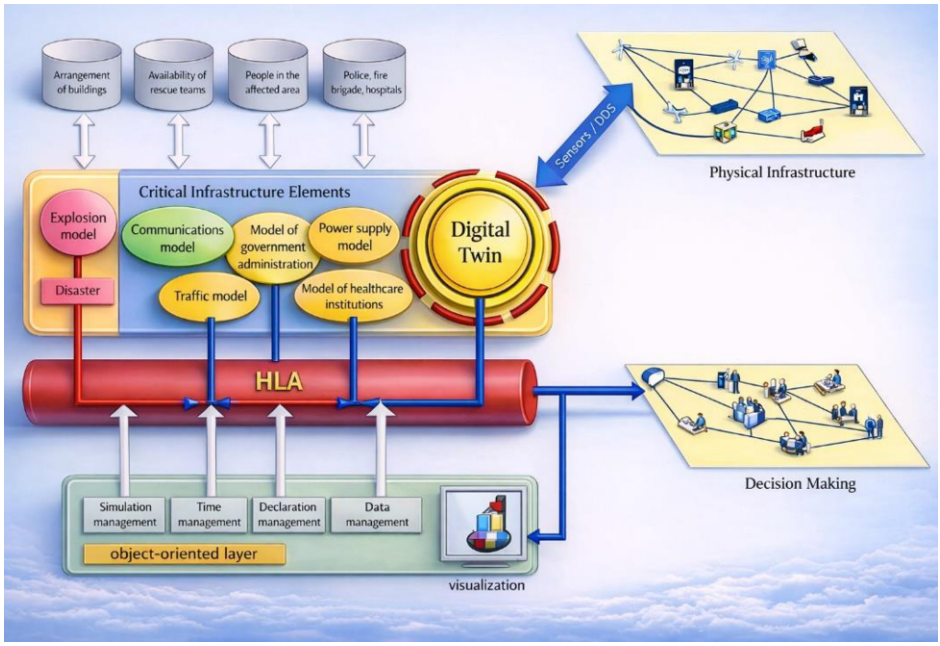


Figure 1. Integration of digital twins into HLA-based simulation.

3. Digital Twin-Enhanced HLA Interaction Framework

The proposed framework is centered on the integration of the High-Level Architecture with digital twin technology to enable the simulation and management of critical infrastructure systems in natural disaster and emergency contexts within a modular, scalable, and synchronized environment (Figure 2). Each infrastructure domain such as power distribution, water supply, and healthcare is represented as a distinct federate within the HLA simulation framework. Domain-specific logic, operational parameters, and behavioral models are encapsulated within these federates, allowing subsystem dynamics to be simulated independently while maintaining interoperability through the Run-Time Infrastructure (RTI).

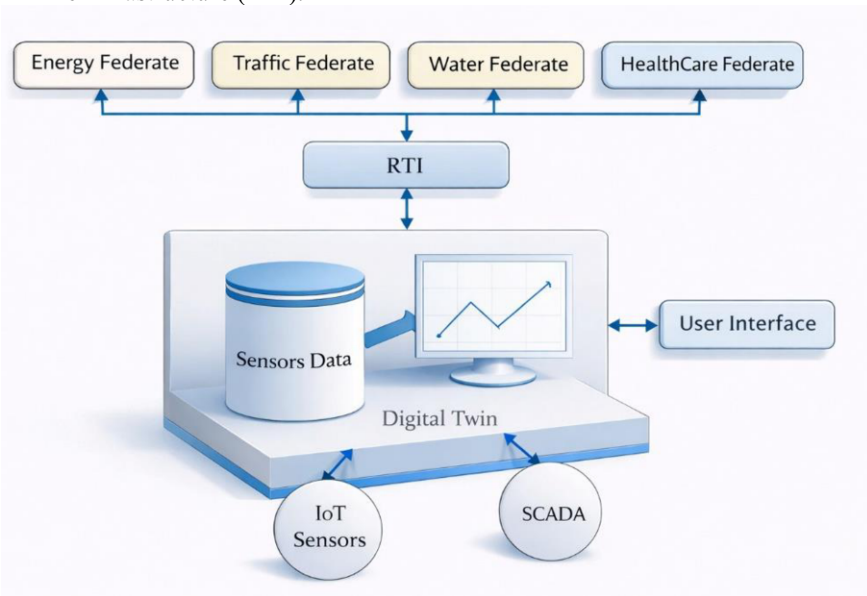


Figure 2. Conceptual diagram of HLA simulation of critical infrastructure with a digital twin.

The RTI serves as the backbone of the simulation environment, facilitating time management, data exchange, and event synchronization among federates [8]. As illustrated in Figure 2, the RTI connects the Digital Twin layer with multiple domain federates, including Energy, Traffic, Water, and Healthcare federates. It ensures that simulation events are executed in a coherent and temporally consistent manner, even when federates operate at different time steps or levels of abstraction.

The digital twin layer is a real-time interface between physical infrastructure and the HLA federation. Data originating from IoT sensors and SCADA systems are continuously collected and stored within the Sensors Data module of the Digital Twin. Since sensor streams may operate at heterogeneous update frequencies and communication latencies, a timestamp-based synchronization mechanism is introduced before data dissemination through the RTI. Each incoming data sample is associated with a global simulation timestamp and temporarily buffered within a sliding synchronization window to enable temporal alignment among heterogeneous data sources.

To address the time-step matching problem between continuous real-time sensor streams and discrete-event simulation federates, the Digital Twin applies multi-rate data alignment strategies. High-frequency sensor streams are down-sampled, whereas low-

frequency measurements are interpolated using linear interpolation or Kalman filter based estimation to generate synchronized state vectors corresponding to the federation logical time step t. The aligned data is then published to federates through the RTI using HLA object attribute updates for continuous state variables and HLA interactions for event-driven notifications such as alarms or abnormal operating conditions.

HLA time management services, including time-regulating and time-constrained modes, are employed to coordinate federate execution and maintain causality across the federation. Specifically, the RTI manages logical time advancement using Time Advance Request (TAR) and event-ordering mechanisms to ensure that federates process synchronized sensor updates in chronological order. In addition, adaptive buffering and latency compensation techniques are applied within the Digital Twin layer to mitigate communication delays and reduce temporal inconsistencies between real-world data acquisition and simulation execution.

A user interface that offers dashboards, alarms, and interactive controls is used to visualize simulation outcomes. Real-time scenario injection, system performance monitoring, and reaction strategy evaluation are all possible for operators. A decision support system that evaluates simulation data and produces practical suggestions for infrastructure management is also fed the results.

Operational scenarios are defined using triggers, responses, and performance metrics, while data exchange formats are standardized using XML and JSON schemas to ensure interoperability and integration with external systems.

4. Natural Disaster-Aware Conceptual Architecture and Operational Views for Critical Infrastructure Simulation

The proposed conceptual framework is designed to integrate the High-Level Architecture (HLA) with digital twin technology for the simulation and management of complex, interdependent critical infrastructure systems. At the core of this architecture, several distinct layers and components are organized to interact cohesively, enabling real-time monitoring, predictive analytics, and coordinated decision-making.

The real-world infrastructure systems, which include areas like power grids, water supply networks, traffic, and healthcare systems, are where the architecture starts. These systems are outfitted with a range of sensor networks, including as SCADA systems and Internet of Things devices that continuously gather operating data.

The digital twin layer, which serves as a virtual mirror of the actual infrastructure, receives the gathered data. Real-time sensor data ingestion, processing, and interpretation fall under the purview of this layer. It employs predictive algorithms to anticipate possible disruptions or failures and keeps a current picture of the infrastructure's operational state. In order to improve situational awareness, the digital twin also facilitates scenario modeling and anomaly detection.

The *HLA simulation environment* is connected to the digital twin and comprises multiple federates, each representing a specific infrastructure domain. These federates are implemented as autonomous simulation modules that model system behaviors and interdependencies. Communication and synchronization among federates are managed by the *Run-Time Infrastructure (RTI)*, ensuring consistent time management and data exchange throughout the simulation.

The digital twin uses real-time data to update federate states, enabling simulation of responses to current and hypothetical scenarios. This allows for real-time monitoring and

scenario injections, including natural disasters and cyberattacks. The simulation outputs are transmitted to a user interface layer, which provides visualization tools and a decision support system that synthesizes simulation results and generates actionable recommendations for infrastructure management.

This chapter title clearly indicates that it contains multiple operational views and aligns with architectural documentation standards like *DoDAF (Department of Defense Architecture Framework)* [24].

4.1. High Level Operational Concept: OV-1

The OV-1 (Operational View 1) describes the overarching operational concept for integrating Digital Twin technology with the High-Level Architecture (HLA) framework to simulate and manage critical infrastructure systems and their interdependencies. It illustrates the mission context, operational objectives, and primary interactions among the participating infrastructure domains - such as energy, water, transportation, and communication as well as their interfaces with external entities and real-world data sources (Figure 3).

This view captures how real-time data from physical assets, collected through sensors and IoT systems, are mirrored in the digital twin environment and synchronized across federates within the HLA simulation. The OV-1 emphasizes the dynamic exchange of information between the digital twin layer, the federated simulation components, and decision-support interfaces used for operational monitoring and scenario analysis.

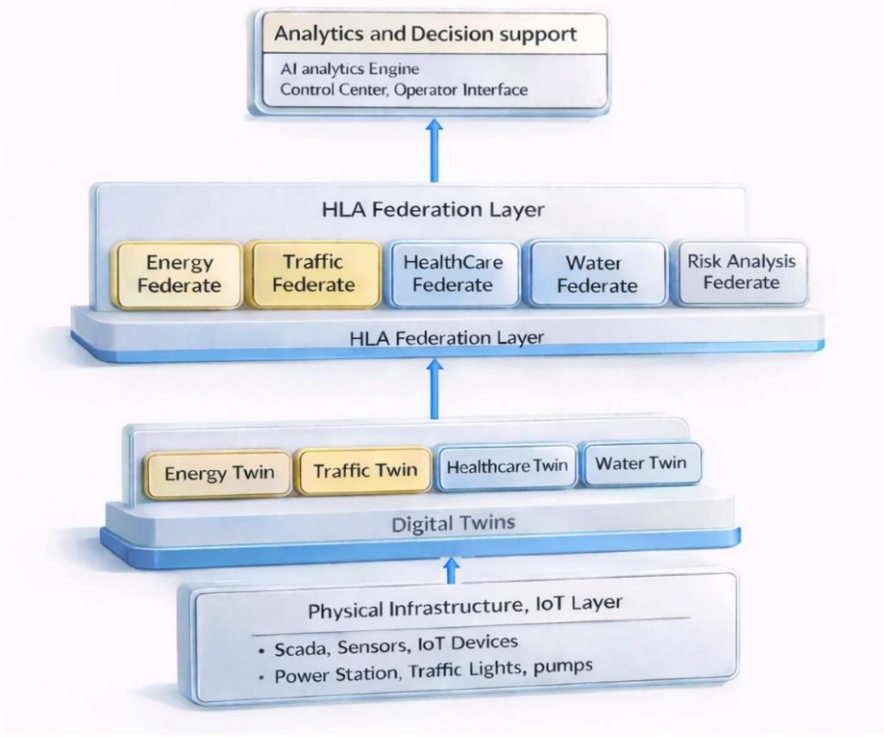


Figure 3. OV-1 – High-Level Operational Concept (Context Diagram).

4.2. Operational Node Connectivity: OV-2

The OV-2 diagram illustrates a tightly integrated network of operational nodes that work together to simulate, monitor, and manage critical infrastructure. It highlights the importance of real-time data, modular simulation components, and coordinated decision-making in ensuring infrastructure resilience and efficiency (Figure 4).

The Sensor Network Node is the primary data acquisition layer in the architecture, consisting of real-world sensors deployed across various infrastructure domains. These sensors collect operational data, which is transmitted to the Digital Twin Node. The Digital Twin Node processes and mirrors real-time data, maintaining a dynamic virtual representation of the physical infrastructure. It acts as a bridge between the physical world and the simulation environment, ensuring accurate information. Connected to the digital twin are multiple Federate Nodes, each representing a specific infrastructure subsystem. These federates are autonomous but interoperable, relying on the RTI Node for communication and synchronization. The RTI ensures that federates exchange data in a time-consistent manner, preserving causality and enabling coordinated simulation.

The User Interface Node offers visualization and control capabilities, aggregating simulation outputs from federates for operators and analysts. The Decision Support Node synthesizes this information to generate actionable insights, using analytical models and predefined rules to recommend mitigation strategies, resource allocation, and operational adjustments. Connectivity between nodes is defined by structured data flows, with sensor data flowing from the Sensor Network Node to the Digital Twin Node, updated system states from the Digital Twin Node to the Federate Nodes, and simulation events managed by the RTI Node.

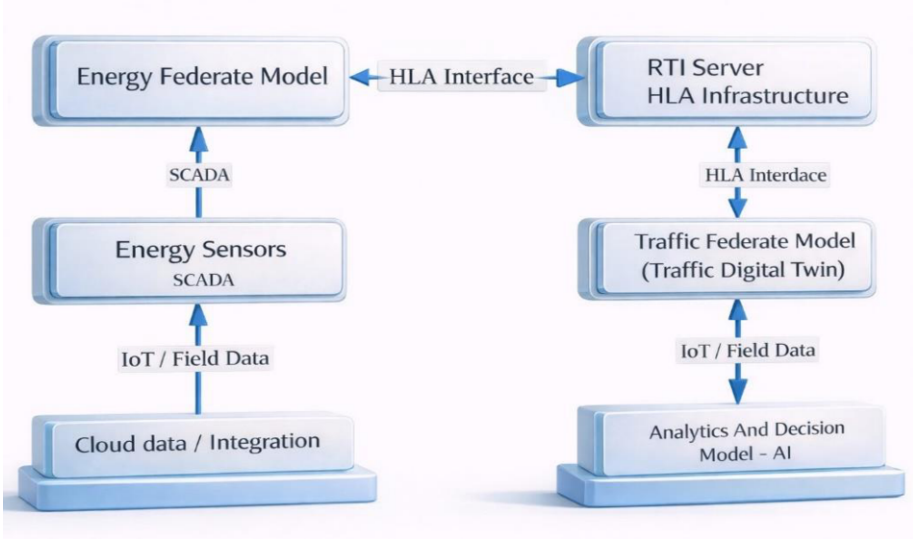


Figure 4. OV-2 – Operational Node Connectivity Description.

4.3. Operational Information Exchange Matrix: OV-3

The OV-3 view provides a comprehensive matrix that describes the **information exchanges** between operational nodes within the simulation framework. It defines the nature, format, and frequency of data flows that enable coordinated simulation and

decision-making across federates, the digital twin, and user-facing components (Figure 5). This view is essential for understanding how data moves through the system, ensuring interoperability, and maintaining synchronization between components.

The OV-3 matrix is based on the Sensor Network, which is the primary source of real-time data from environmental sensors, infrastructure monitoring devices, and control systems embedded in physical assets. These sensors generate data streams that are transmitted to the Digital Twin Node, which processes this data and updates its internal models to reflect the current state of the physical infrastructure. The Digital Twin Node then communicates updated system states to the relevant Federate Nodes, which represent domain-specific simulation components like power grid, water supply, transportation, and emergency services. Interdependencies between these domains are represented through shared state variables and event-driven interactions exchanged via HLA object models and interaction classes. The information exchange includes object updates, state variables, and disruption events formatted according to HLA object models. The frequency of these updates depends on the nature of the data and simulation requirements.

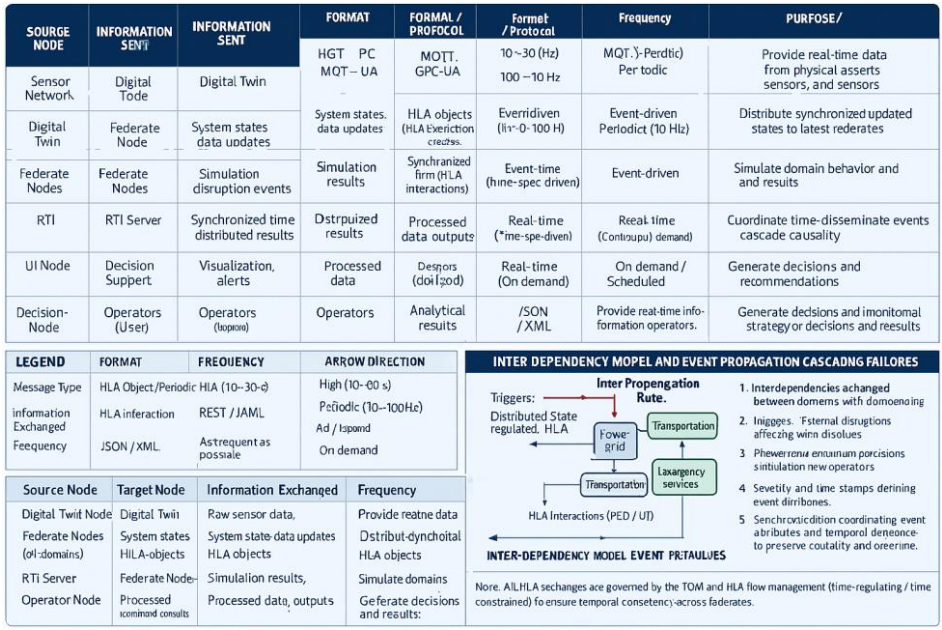


Figure 5. OV-3 – Operational Information Exchange Matrix

Federates receive updated states and simulate responses and interactions, including cross-domain cascading effects caused by natural disasters or infrastructure disruptions, which are communicated to the Run-Time Infrastructure (RTI) for synchronization. Event propagation rules are implemented through HLA interactions that transmit failure events, severity levels, timestamps, and affected infrastructure regions among federates. The RTI coordinates event dissemination and temporal synchronization to preserve causality during cascading failure propagation. The RTI forwards simulation results to the User Interface (UI) Node, which aggregates and visualizes data for human operators. This includes graphical dashboards, alerts, scenario playback, and system performance

metrics. The frequency is real-time, allowing operators to monitor system behavior. The Decision Support Node receives processed outputs and applies analytical models to generate recommendations, such as resource allocation strategies or emergency response plans. The information is typically delivered in structured reports, alerts, or notifications.

4.4. Organizational Relationship: OV-4

The **OV-4 diagram** is a framework for understanding the organizational relationships and roles involved in the operation, development, and use of a simulation framework. It focuses on how technical and operational stakeholders interact within the system and how responsibilities are distributed across entities. The top organizational hierarchy includes governing bodies and regulatory authorities, who define strategic objectives, compliance requirements, and operational standards that guide the simulation framework.

System integrators and simulation architects design and maintain the HLA-based simulation environment, ensuring interoperable, scalable, and compliant components. **Domain experts and infrastructure operators** provide operational knowledge to model real-world systems accurately, while data providers and IT support teams manage sensor networks, data acquisition systems, and cloud infrastructure. Simulation users, including emergency responders, infrastructure managers, and analysts, interact with the system through the user interface, injecting scenarios, monitoring system behavior, and using decision support tools to guide real-world actions (Figure 6).

4.5. Operational Activity Model: OV-5

The **OV-5** diagram outlines the operational activities performed within the simulation framework and the relationships between those activities (Figure 7). It provides a functional view of how tasks are structured, sequenced, and coordinated to achieve the system's objectives - namely, the real-time simulation, monitoring, and management of critical infrastructure systems.

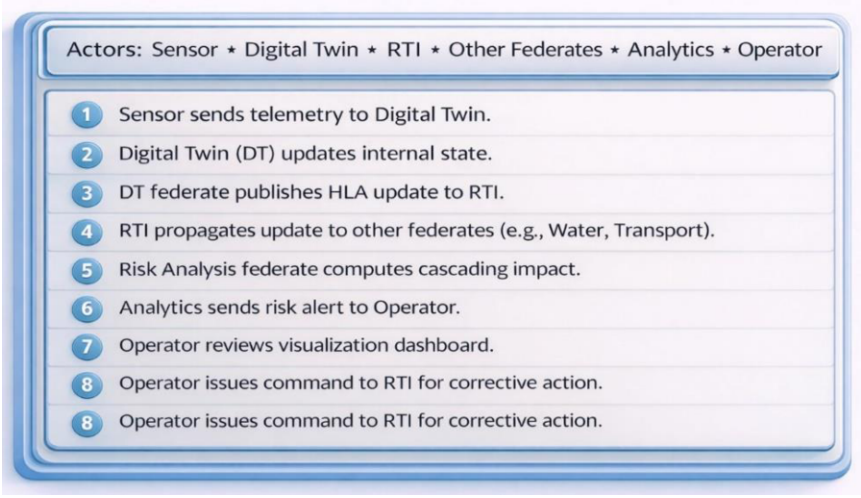


Figure 6. OV-4 the organizational relationships diagram.

The operational process begins with data acquisition from critical infrastructure domains like power, water, transportation, and emergency services. Embedded sensors monitor operational parameters, providing automated inputs to the simulation environment. Data processing and integration are performed within the digital twin layer, which updates its internal state to mirror physical infrastructure conditions and supports predictive analytics and anomaly detection. Predictive models within the Digital Twin are primarily trained and calibrated offline using historical data and simulation outputs, while real time sensor data are used for online state estimation and inference during execution. This approach ensures stability and consistency within the time-managed HLA simulation environment, while still enabling forward-looking analysis. The modular design of the Digital Twin allows alternative predictive techniques, including online or adaptive learning methods, to be incorporated as future enhancements. The simulation execution phase is conducted by federates within the HLA environment, each modeling a specific subsystem. Scenario injection, event propagation, and system response modeling are performed to assess operational dynamics and inter-domain interactions, including cascading effects triggered by disruptive events. Simulation results are transmitted to visualization and decision-support layers, where dashboards and analytical tools provide real-time monitoring and generate actionable insights. Recommendations for mitigation strategies, resource allocation, and response actions are derived to enhance model fidelity and operational resilience.

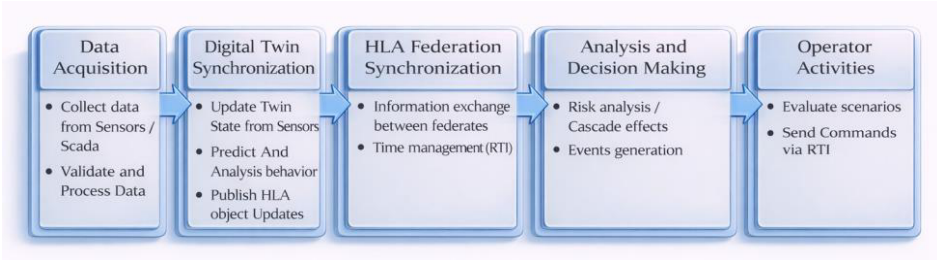


Figure 7. OV-5 - Operational Activity Model (Decomposed Tasks).

5. Conclusion

This paper presented a disaster-aware framework for simulating and managing critical infrastructure systems through the integration of High-Level Architecture (HLA) and digital twin technology. The approach enables real-time monitoring, predictive analytics, and decision support. The current study extends that foundation by integrating a digital twin layer, enabling real-time mirroring of physical infrastructure states. This addition allows the simulation to ingest live sensor data, dynamically update federate states, and provide predictive analytics for decision support. The digital twin enhances situational awareness, supports scenario injections, and improves the fidelity of simulation outcomes. By combining HLA with digital twin technology, this paper presents a more robust and adaptive framework for infrastructure resilience and operational planning.

The disaster-aware conceptual architecture, together with its defined operation-al views, provides a structured and systematic foundation for simulating critical infrastructure systems under disaster conditions. By organizing architectural elements into coherent layers and operational viewpoints, the framework supports a clear

representation of system behavior, data flows, and stakeholder interactions during preparedness, response, and recovery phases.

As a direction for future research, the proposed framework may focus on large-scale validation across multiple interconnected infrastructure domains and geographical regions, as well as on addressing uncertainty management and credibility assessment of simulation results. These extensions would further strengthen the applicability of the proposed disaster-aware HLA digital twin framework for operational deployment and strategic planning.

Acknowledgment

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Emotional Support Dialogue Mechanism Based on Multi-Agent Technology

Liyu Liu[a], Chuyin Huang [b], Ziman Chen [b] and Jing Lyu [a,1]
[a] *School of Public Administration, Guangdong University of Foreign Studies, Guangzhou, China.*
[b] *School of Information Science and Technology, Guangdong University of Foreign Studies, Guangzhou, China*

Abstract. With the growing demand for digital mental health services, existing dialogue systems suffer from problems such as inaccurate emotion recognition, insufficient empathy and lack of controllability in emotional support dialogues. To address these issues, this paper proposes a multi-stage emotional support dialogue framework based on multi- agent collaboration. First, drawing on Gerard Egan's Helping Model, the dialogue is divided into three phases: exploration, understanding, and action. A Hidden Markov Model (HMM) is used to realize macro-stage judgement and dynamic scheduling. Second, based on Allen E. Ivey's micro-counseling skills, five strategic agents are mapped. The Contextual Multi-Armed Bandit (CMAB) algorithm is adopted to achieve optimal matching and dynamic invocation of micro-strategies in complex contexts. Finally, a Global Optimization Integration Model (GOIM) is introduced. Multi-Criteria Evaluation (MCE) and Probability Weighted Mapping (PWM) mechanisms are used to quantitatively score and weight candidate responses. In addition, Kullback-Leibler (KL) divergence is employed to verify semantic consistency and reconstruct the final outputs.

Keywords. Emotional support dialogue; Multi-agent system; Hidden Markov Model; Multi-stage reasoning

1. Introduction

The multi-agent emotional support dialogue mechanism relies on artificial intelligence technology and psychological intervention theory. It integrates emotional support tasks with multi-agent collaborative architectures and multi-stage reasoning. By adopting a structured and stage-oriented approach, this system transforms traditional black-box dialogue generation methods, eliminating barriers and psychological burdens caused by privacy concerns or scarce professional resources when users seek psychological help. The system not only enhances empathic accuracy and professional logical depth in dialogue generation, but also makes the emotional support dialogue process more coherent and traceable, and makes strategy selection and response generation paths more transparent. This improvement helps users build proactive coping abilities against psychological dilemmas. In addition, through heuristic dialogues, it can help users

[1]Corresponding Author: Jing Lyu, School of Public Administration, Guangdong University of Foreign Studies, China; Email: 2857933698@qq.com.
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develop abilities such as fact clarification, self-awareness, and problem-solving, and cultivate critical thinking as well as positive psychological defense mechanisms.

2. Research Status at Home and Abroad

Some studies have attempted to embed professional psychological intervention paradigms such as Cognitive Behavioral Therapy (CBT) into the underlying logic of dialogues. For special groups, research has also extended toward physical interactive hardware (e.g. emotional speakers), aiming to transcend physical space and enhance social presence [1]. However, empirical analyses based on the Technology Acceptance Model (TAM) indicate that superficial anthropomorphic design or hardware media alone cannot bridge the technical gaps of AI in complex emotional resonance and in-depth companionship. Due to the lack of temporal modeling of the counseling processes, existing systems struggle to achieve effective scheduling at the macro stage. Moreover, in dynamic contexts, the invocation of micro-level strategies highly relies on static mapping, lacking the ability to perform dynamic weight allocation and state transition probability inference.

Currently, most existing systems rely on static machine learning calculations or single semantic metrics for final output [2]. This results in unstable and uncontrollable fluctuations in strategy fitness and empathy depth of emotional support content. In addition, such frameworks generally lack a multi-criteria quantitative evaluation and a global consistency verification center. Therefore, to resolve the efficiency conflicts inherent in single-agent systems, we introduce multi-stage reasoning, multi-agent systems (MAS) collaboration, and dynamic strategy matching algorithms. These approaches aim to achieve high-precision, personalized, and interpretable emotional intervention, which has become a core research direction for addressing the key pain points of controllability and professionalism in emotional support dialogues.

3. Design of the Multi-Agent Based Emotional Support Dialogue Framework

This project employs a multi-stage and multi-agent collaborative approach. Referring to the micro-counseling skills proposed by Allen E. Ivey in *Counseling and Psychotherapy*, it modularizes counseling responses and maps them into distinct functions undertaken by five strategic agents (Agent1-5). that work cooperatively [3]. The five agents are: Empathic Restatement, Cognitive Clarification, Emotion Mapping, Summary and Organization, and Action Guidance. Meanwhile, the overall dialogue process is constructed based on Gerard Egan' s Skilled Helper Model, which divides the process into three stages: Stage I: Exploration, Stage II: Understanding, and Stage III: Action, each with specific objectives and dialogue strategies [4]. This staged structure ensures the dialogue proceeds in an orderly manner. A Process Scheduling Agent (Agent 6) is introduced to determine the dialogue stage and schedule appropriate strategy agents according to the current stage. In addition, an Optimization and Integration Agent (Agent 7) is established to assign weights and scores to candidate responses, revise and integrate them based on the weights, and finally generate the output response. (See Figure 1)

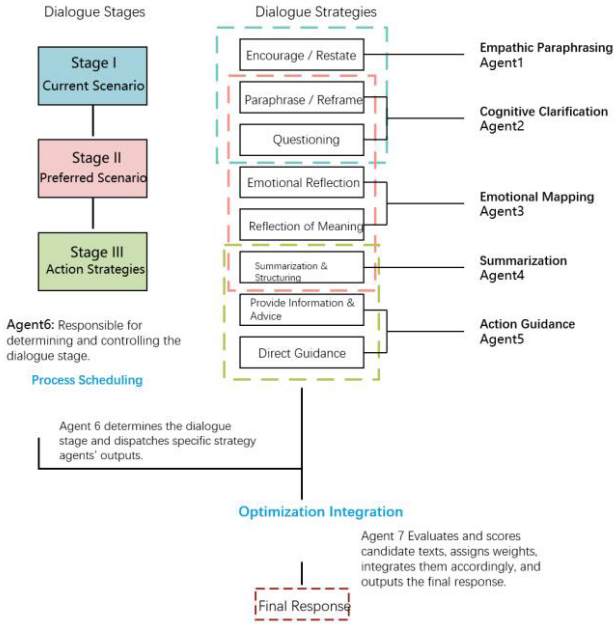


Figure 1 Research Theoretical Model

Stage I: Exploration focuses on helping users clarify what is happening now. Empathic Restatement by Agent 1 and Cognitive Clarification by Agent 2 are assigned higher weights, guiding users to complete self-disclosure with a sense of security and identify core dilemmas. Stage II: Understanding aims to help users clarify what they want. It prioritizes scheduling Agent 3 for emotion reflection and Agent 4 for summarization and organization, encouraging users to examine problems from multiple perspectives, recognize various possibilities, and construct an ideal situation. Stage III: Action mainly focuses on how to achieve goals. It tends to raise the priority of Agent 5, which provides professional suggestions and direct guidance, transforms goals and aspirations into executable strategic plans, helps users make up their minds, and obtain commitments. These three stages together form a complete psychological intervention chain from perception to problem-solving, ensuring that the multi-agent system can continuously evolve with the progress of the dialogue and provide logically targeted emotional support.

The technical architecture of the proposed multi-agent system is founded on a centralized orchestration logic and an asynchronous message-passing mechanism. Agent6 serves as the primary controller, evaluating the dialogue state to determine the appropriate stage and scheduling the corresponding strategy agents through a shared message bus. During the execution phase, Agents 1 through 5 operate in a parallel manner, processing structured data packets that contain user input context and historical interaction data. To resolve potential redundancies or conflicts among the generated candidate responses, Agent7 functions as an integration layer. It assesses each candidate's relevance to the specific objectives of the current dialogue stage and assigns weighted scores accordingly. By synthesizing these multi-dimensional inputs and filtering overlapping information, Agent7 ensures that the final response is logically coherent and provides targeted emotional support without redundancy.

The system ensures controllability and interpretability by transforming the counseling dialogue into a structured, multi-step decision-making process. Initially, the Hidden Markov Model (HMM) identifies the user's latent psychological state and classifies it into a specific dialogue stage, such as the "Current Scenario," to provide a macro-level roadmap that prevents the logical jumps common in end-to-end models. Following this, the Contextual Multi-Armed Bandit (CMAB) algorithm evaluates the current state to schedule the most appropriate strategy agents. This approach ensures that the selection of intervention strategies is based on evidence and contextual evaluation rather than inexplicable black-box outputs. Finally, the Global Optimization and Integration Scoring Model (GDIM) assigns weighted scores to candidate responses, calculating an optimal solution that balances psychological criteria and filters out redundant or conflicting information. The collective integration of HMM for stage-mapping, CMAB for task-scheduling, and GDIM for response-optimization ensures that every step of the generative path, ranging from stage identification to final synthesis, is visible, traceable, and mathematically grounded. Consequently, the system delivers accurate and reasonable emotional support while effectively avoiding empty empathy.

To comprehensively demonstrate the collaborative mechanism of the aforementioned algorithms in a real-world dialogue, we present the system's execution process using a specific emotional support case. In this example, the HMM model first identifies the user's negative input as Stage I (Current Scenario), with Agent6 performing task scheduling via the CMAB algorithm. Subsequently, the system invokes different agents responsible for empathy and cognitive guidance to generate candidate strategies. Finally, Agent7 evaluates these candidates and employs the GDIM algorithm to perform weighted integration, resulting in a comprehensive response that balances emotional resonance with cognitive depth. Next, the three algorithms mentioned above will be explained.

Hidden Markov Model, HMM: To address the sequential characteristics of dialogue stages evolving over time in psychological counseling, this study adopts the Hidden Markov Model (HMM) to equip the central agent (Agent 6) with the ability of macro-stage judgment and coarse-grained scheduling [5]. In this model, the psychological stages of the dialogue are defined as the hidden state space$S = \{s_1, s_2, s_3\}$, corresponding to the three dialogue stages: Exploration, Understanding, and Action. The text features, emotion polarity scores, resistance level, and change motivation from each round of user dialogue are extracted to form the observation vector sequence$\mathrm{O} = \{\mathrm{o}_1, \mathrm{o}_2, \ldots, \mathrm{o}_\mathrm{t}\}$.To ensure rigorous dialogue logic, Agent 6 dynamically captures the transition of counseling progress through the state transition probability matrix$\mathrm{A} = [\mathrm{a}_{\mathrm{ij}}]$, which characterizes the prior probability of shifting from the current stage to the next.During real-time interaction, Agent 6 uses the Viterbi decoding algorithm or the forward algorithm to calculate the most probable hidden state distribution at the current moment:

$$P(Q|O,\lambda) = \pi_{q_1} b_{q_1}(o_1) \prod_{t=2}^{T} a_{q_{t-1}q_t} b_{q_t}(o_t) \quad (1)$$

The parameters of the state transition probability matrix are initially derived from supervised learning on a specialized corpus of high-quality counseling transcripts, representing the standard progression logic of the Skilled Helper Model. To ensure personalized adaptability, the system employs a Bayesian updating mechanism to refine these probabilities online. As the dialogue progresses, the matrix is updated based on the historical intervention effectiveness and user feedback signals, allowing the transition logic to evolve from a generalized prior to a user-specific behavioral pattern.

When the model detects that the posterior probability of the current state transitioning to the next stage exceeds the predefined threshold ϵ, the system automatically adjusts the priority of strategy invocation. This Markov-based scheduling mechanism predicts the most probable current stage based on the immediately preceding state, providing stronger temporal coherence than classification algorithms alone. It enables Agent 6 to deeply perceive shifts in the user's psychological state from dialogue history, effectively avoiding premature entry into the action stage before the user has established sufficient sense of security. In turn, it achieves orderly and robust invocation of strategy modules on a macro time scale.

To illustrate the intuition behind this prosses, consider a simplified scenario where Agent 6 evaluates the probability of transitioning from the Exploration stage ($q_{t-1} = S_1$) to the Understanding stage ($q_t = S_2$). In this case, the state transition probability $a_{q_{t-1}q_t}$ is set at 0.3, reflecting a specialized prior for counseling progression. During a specific interaction, the system extracts an observation vector o_t indicating high user self-disclosure. The emission probability (or observation likelihood) $b_{q_t}(o_t)$ is significantly higher for the Understanding stage ($b_{S_2}(o_t) = 0.8$) than for the Exploration stage ($b_{S_1}(o_t) = 0.4$). By multiplying the transition probability with the current emission probability as defined in the product term of Formula (1), the model computes a heightened probability for S_2. Once this value causes the overall state probability to exceed the predefined threshold ϵ, Agent 6 triggers the stage transition, shifting the system's priority from empathic agents to cognitive clarification agents. This mechanism demonstrates how the model utilizes both historical transition logic and real-time observation to ensure an orderly and robust counseling process.

Contextual Multi-Armed Bandit, CMAB: Although HMM provides guidance at the macro stage, the mapping between stages and agents involves dynamic weight assignment rather than a simple 1:1 physical mapping. Psychological counseling is a continuous, fluid process where skills often overlap and are invoked out of sequence even if the dialogue follows a general direction. Therefore, for the five strategy agents (Agents 1-5), this study constructs a CMAB-based micro-response model to achieve the optimal dynamic matching of micro-counseling skills in complex contexts [6]. To represent the environment, the model encodes diverse information into a contextual feature vector x_t by concatenating a 768-dimensional semantic embedding from a pre-trained RoBERTa-base model, emotional state indicators consisting of Valence-Arousal-Dominance (VAD) scores, and the stage flag determined by Agent 6. Within this framework, the five functional agents are abstracted as candidate "arms," and the system adopts the Upper Confidence Bound (UCB) algorithm to balance exploitation and exploration:

$$Score(a,t) = \mu_a(x_t) + \psi_s(a) + \alpha\sqrt{\frac{\ln t}{N_a(t)}} \tag{2}$$

Where $\mu_a(x_t)$ is the estimated expected reward calculated via ridge regression or neural networks based on x_t, representing historical effectiveness. $\psi_s(a)$ is a prior enhancement factor based on the stage state, which implements soft constraints from Agent 6 by pre-setting weight gains for core agents in the current stage. The term $\alpha\sqrt{\ln\frac{t}{N_a}(t)}$ represents the exploration bonus, where $N_a(t)$ is the selection frequency of agent a. The CMAB module interacts with other components by receiving stage signals from Agent 6, selecting the top-scoring strategy agents to generate drafts, and then

passing these candidates to Agent 7 for final integration. For instance, consider a context where the user displays high anxiety in the Exploration stage. The vector x_t might contain a high "Anxiety" scalar and a [1,0,0] stage flag. For Agent 1 (Empathic Restatement), the model predicts $\mu = 0.75$, adds a stage gain $\psi = 0.2$, and an exploration bonus of 0.05, resulting in a UCB score of 1.0. In contrast, Agent 5 (Action Guidance) might have a lower stage gain ($\psi = 0.02$) and a lower predicted μ, resulting in a score of 0.45, thus prioritizing Agent 1.

Global Optimization & Integration Model, GOIM: As the quality control center of the entire framework, the Integration Agent (Agent 7) is responsible for conducting dynamic micro-examination on the outputs of candidate strategy agents and performing final response reconstruction.

The core logic of this model lies in the professional fusion of Multi-Criteria Evaluation (MCE) and Probability Weight Mapping (PWM) [7].

First, in accordance with Ivey's micro-counseling skills criteria, Agent 7 assigns explicit scores (1-5) to the candidate responses generated by Agent 1-5 across four dimensions: empathy, relevance, logical consistency, and action guidance, thereby constructing a scoring matrix$S_i = \{e_i, r_i, c_i, a_i\}$ and calculating a comprehensive score $S_{total,i} = \sum(\omega \cdot S_i)$ via a weight vector ω.To mitigate the impact of discrete scoring on generation stability, the model introduces a temperature parameter τ and converts the scores into continuous probabilistic weights using the Softmax mapping function:

$$w_i = \frac{\exp\left(\frac{S_{total,i}}{\tau}\right)}{\sum_{j=1}^{5} \exp\left(\frac{S_{total,j}}{\tau}\right)} \tag{3}$$

After determining the weight distribution, the GOIM model further introduces KL Divergence (i.e., Kullback-Leibler Divergence) as a global optimization metric for semantic consistency [8]. It quantifies the divergence between the semantic distribution Q of the final synthesized response and the ideal counseling target distribution P.

$$D_{KL}(P||Q) = \sum P(x) \log\left(\frac{P(x)}{\sum w_i Q_i(x)}\right) \tag{4}$$

This formula guides the global optimization of weight allocation and establishes the authority for system reconstruction by setting a quality interception threshold θ:if the calculated highest comprehensive score $\max\left(S_{total,i}\right) < \theta$ or global deviation fails to meet the requirement $D_{KL} > \gamma$, the generated semantic distribution is judged inconsistent with professional standards.In such cases, Agent 7 will intercept the current output and forcibly trigger the reconstruction mechanism. This scientific transformation from multi-dimensional scoring to probabilistic weights not only ensures the precision of empathic responses but also significantly improves the controllability and rationality of the multi-agent collaborative framework in long-term dialogues.

4. Experimental Results

To verify the effectiveness of the proposed framework, experiments were conducted on the standard emotional support conversation dataset ESConv, and comparisons were made with mainstream large language model (LLM) baselines and traditional single-agent end-to-end models. From the perspective of objective evaluation, owing to the ability of the Hidden Markov Model (HMM) to accurately capture the transition probability of macro stages and the dynamic weight allocation enabled by the Contextual Multi-Armed Bandit (CMAB), the model achieved better accuracy in dialogue stage

scheduling, representing a significant improvement over the traditional generative large model baseline. At the micro level, the hit rate of strategy selection in complex contexts was increased compared with the static mapping mechanism. In addition, the Global Optimization and Integration Model (GOIM), by calculating the KL divergence between the generated distribution and the ideal distribution and performing quality interception, reduced the long-range dialogue semantic offset, greatly improving the semantic consistency of responses.

5. Conclusion

Based on multi-agent collaboration, the emotional support dialogue mechanism references the deep psychological characteristics presented by users across different dialogue stages. It materializes and modularizes abstract counseling strategies, providing emotional feedback and professional guidance during users' behaviors such as self-disclosure, cognitive exploration, and goal setting. This mechanism not only adheres to the theoretical logic of psychology but also enhances the depth of empathy and the coherence of dialogue logic. Through a step-by-step guidance mechanism, it subtly improves users' self-awareness and problem-solving skills. Meanwhile, the strategy scheduling system constructed based on the multi-agent reinforcement learning framework independently updates and iterates based on previous intervention logic. Leveraging modularity, interpretability, and scalability, it forms precision personalized emotional intervention plans to specifically meet the diverse psychological needs of different users. The deep integration of mechanisms such as multi-agent collaboration, multi-stage reasoning, and professional model guidance with traditional psychological counseling effectively addresses the existing issues in current dialogue systems, including coarse-grained empathy, rigid responses, and logical discontinuities.

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From "Responsibility" to "Belonging" the Influence of Perceived Corporate Social Responsibility on Customer Citizenship Behavior in Rural Homestays

Yingjie Liu[a,1] and Min Zhao[a]
[a] *College of Tourism, Hunan Normal University, Hunan, China*
ORCiD ID: Yingjie Liu https://orcid.org/0009-0003-3081-2341
Min Zhao https://orcid.org/0009-0001-7524-2755

Abstract. Rural homestays, as key drivers of rural economic development in China, necessitate systematic research into the structure of their corporate social responsibility (CSR) and its impact on customer behavior and sustainable development. This mixed-methods study developed and tested a CSR scale for rural homestays through a literature review and in-depth interviews with 13 managers. Subsequently, based on the Cognitive-Affective-Conative (CAC) theoretical framework, a research model was developed and empirically tested through questionnaire surveys. The findings reveal a significant positive impact of rural homestay CSR on customer citizenship behavior (CCB), with relationship quality playing a partial mediating role. The development of the scale provides a measurement tool for promoting more empirical research on rural homestay CSR, and offers theoretical and practical insights for rural homestays on how to fulfill their CSR, promote CCB and sustainable development.

Keywords: Rural homestay; Corporate social responsibility; Customer citizenship behavior; Relationship quality; Cognitive-Affective-Conative theory; Scale development.

1. Introduction

The ongoing development of tourism counter-urbanization has positioned rural leisure and vacation tourism as a prominent new trend in mass tourism consumption. According to the 2025 May Day Holiday Hotel Consumption Trends Report by United Hotel Consultancy, bookings for rural tourism during the 2025 May Day period increased by nearly 20% year-on-year, covering 1,230 counties nationwide, with the occupancy rate of vacation farms exceeding 90%. Within this context, the rural homestay, as a non-standardized accommodation type deeply integrated with local resources, has evolved from a mere lodging space into a critical node within the socio-economic and cultural network of rural areas [1].

The roles played by rural homestays in rural revitalization, such as job creation, cultural preservation and promotion, and environmental beautification, cannot be

[1] First & Corresponding Author: Yingjie Liu (1982—), professor and master's supervisor of the School of Tourism, Hunan Normal University, Changsha; email: liuyj@hunnu.edu.cn

simply attributed to service quality enhancement strategies nor to mere sustainable operation practices. In essence, these roles fall within the domain of corporate social responsibility[2]. Corporate social responsibility (CSR) is a normative and voluntary framework that obligates enterprises, beyond their core business operations, to consciously assume ethical and legal obligations toward stakeholders, including the environment, community, and government[3]. As part of rural communities, enterprises' moral and ethical obligations toward rural empowerment and local cultural preservation constitute the core distinction between the humanized character of rural homestays and the standardized services of hotels [4]. While sustainability concerns long-term ecology, it often focuses on operational necessity or compliance with legal requirements. The CSR framework stresses stakeholder interaction and symbiosis. For homestay enterprises deeply embedded in local communities, their value extends beyond mere accommodation provision[3]. Through responsible business practices such as fair employment and community engagement, they enhance community cohesion and resident well-being[2]. This further indicates that the traditional framework of CSR for large enterprises cannot be directly applied to rural homestay.

Customer citizenship behavior (CCB) in tourism enterprises encompasses three dimensions: recommendation, feedback/suggestion, and helping other customers. It represents extra-role behaviors voluntarily and freely decided by tourists throughout the transaction process[5]. Drawing on Social Exchange Theory and Social Identity Theory, customer citizenship behavior is conceptualized as a positive response and emotional reciprocation to corporate social responsibility fulfillment[6]. CSR practices significantly stimulate voluntary customer behaviors, including homestay recommendation, constructive feedback provision, and assistance to fellow travelers—by enhancing customers' sense of engagement, trust, and identification[7]. Investigating the mechanism through which CSR influences CCB aims to reveal how enterprises, by improving social image and trust, can transform customers into voluntary brand advocates and service collaborators, thereby fostering sustainable high-quality customer relationships.

In summary, based on the characteristics of rural homestay enterprises, this study employed grounded theory to conduct interviews with relevant staff. The interview data were organized and coded using NVivo, leading to the development and validation of a multidimensional CSR scale for rural homestays. Furthermore, guided by the Cognitive-Affective-Conative (CAC) theory, a model examining the relationship between CSR perceptions and CCB was constructed to explore the underlying mechanisms.

2. Literature review and hypotheses

2.1 Corporate social responsibility (CSR) and Rural Homestay Corporate Social Responsibility

The concept of CSR was first introduced by Sheldon (1924), which argued that a firm's objective extends beyond profit maximization, and that managers must assume moral responsibilities. Carroll (1991) clarified the distinction between baseline obligations (economic, legal) and higher-level voluntary responsibilities (ethical, philanthropic)[8]. In tourism, due to the industry's high reliance on natural environments, firms must comply with environmental regulations to maintain operations, which constitutes a

baseline obligation[9]. However, when homestay operators further engage in environmental education, cultural heritage activities, or community welfare initiatives, such actions truly embody the voluntary essence of CSR[10].

Given the close relationship between tourism and the natural environment [11], as well as the socio-cultural role of rural homestays embedded within geo-local networks[12], the sustainable development perspective, which integrates economic, environmental, and social responsibilities, serves as a crucial foundation for this study's understanding of CSR in rural homestays. Furthermore, within the operational network of rural homestays, beyond traditional customers, employees, and shareholders, local communities and cultural systems become essential value co-creators[2]. Here, CSR is not merely the moral stance of an enterprise; rather, it is a crucial strategic approach for maintaining relationships with stakeholders, gaining social recognition, and achieving long-term competitive advantages[1]. This stakeholder-theory perspective also provides guidance for explaining how CSR can be translated into specific practices in the tourism environment.

2.2 Customer citizenship behavior (CCB)

CCB refers to voluntary, extra-role actions by customers that exceed core service requirements but benefit the organization, including recommendation, feedback/suggestion, and helping other customers [5]. Recognized for enhancing firm operations[13], its antecedents are studied from customer [14] and organizational perspectives [13]. Recent CSR research highlights its role in stimulating CCB. For instance, Waris et al. (2024) found that environmental CSR in hotels can foster green customer citizenship via green trust and strengthened customer identification.

According to the CAC theory, an individual's behavioral intention (Conation) is directly driven by their cognition[15]. A customer's perception of a rural homestay's proactive fulfillment of CSR in areas such as the economy, culture, community, and environment can directly shape their behavioral intention [16]. Customers tend to view such homestays as ethical and community-minded "social citizens" [17]. This positive perceptual image acts as a powerful social signal. It can, independent of deep emotional bonds, directly motivate customers to support the business through citizenship behaviors such as making recommendations, assisting others, and providing feedback, serving as recognition and reciprocation for the homestay's positive actions [17]. This direct pathway is strongly supported by social exchange theory. Upon perceiving the positive value provided by the homestay that extends beyond basic services, customers will develop a sense of obligation to reciprocate [18]. Therefore, this study hypothesizes that a customer's positive cognition of a rural homestay's CSR can directly lead to positive CCB intention:

H1: The CSR of rural homestays has a positive influence on CCB.

2.3 Relationship quality

The relationship between an enterprise and its customers is measured by relationship quality, which reflects the customer's perception of the host-guest relationship formed throughout the entire transaction process and serves as an assessment of the strength of relationship marketing [19]. The significant mediating role of relationship quality has been empirically supported [20].

CSR practices influence the relationship quality between a brand and its customers [20]. The CSR initiatives of a rural homestay signal corporate reliability, honesty, and ethical integrity to customers, reflecting its benevolence and goodwill [17]. These practices reduce perceived uncertainty and risk for customers, thereby fostering positive affective states such as relationship satisfaction, trust and commitment [21]. These positive affective subsequently motivate customers to develop intentions for citizenship behaviors that exceed basic transactional requirements [13, 21]. Based on the CAC theory, this study posits that rural homestay CSR serves as an external stimulus that triggers customers' cognitive evaluations, which form the foundation for subsequent affective and conative responses [22]. Furthermore, the series of affective responses comprising relationship quality drives the formation of intentions, leading to specific CCBs such as recommendation and helping other customers [22]. The study thus advances the following hypotheses:

H2: The CSR of rural homestays has a positive impact on relationship quality.

H3: Relationship quality has a positive impact on CCB.

H4: Relationship quality plays a mediating role in the impact of the CSR of rural homestays on CCB.

The theoretical model of this study is shown in Figure 1.

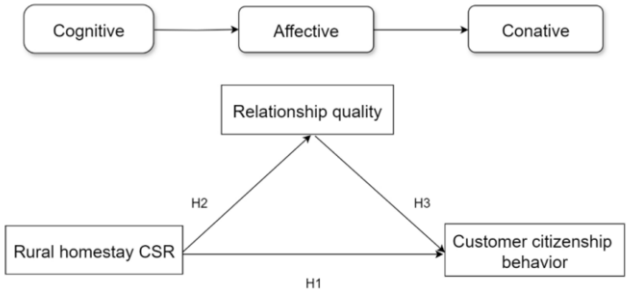


Figure 1. The theoretical research model.

3. Exploration of rural homestay CSR dimensions and scale development

3.1 Research method

Grounded theory generates theory from raw data through constantly comparing concepts and categories and generalizing categories. Based on an extensive literature review and the operational characteristics of rural homestay businesses, this study applied procedural grounded theory coding using NVivo 11 to analyze interview data from homestay owners and employees, distilling CSR dimensions until reaching theoretical saturation.

3.2 Data collection

Confirmation of Interviewees. To ensure sample representativeness and generalizability, this study adhered to the principle of balance in sample selection. The selected individuals had to meet stratified distribution requirements concerning age, gender, education level, and geographic location, with a minimum of two years of involvement

in the rural homestay industry. Ultimately, 13 respondents participated in the in-depth interviews, comprising 8 homestay owners, 3 employees, and 2 homestay investors.

Personal in-depth interviews were conducted in a semi-structured format, following the guiding principles for semi-structured interviews. A broad interview protocol consisting of four modules was designed, covering the core research questions and the fundamental logical framework of the study. Each interview lasted between 30 to 40 minutes, spanning from September to December 2024. Ultimately, approximately 90,000 words of interview materials were formed. Following the approach of Pandit (1996), the data were processed according to the steps and principles of the three-stage coding process, namely open coding, axial coding, and selective coding (see Appendix 1). Two text materials were reserved in advance as test samples for theoretical saturation assessment. After completing the three-stage coding process, these two transcribed texts were subjected to the same three-stage coding. No new concepts or categories were identified during this coding[23]. Additionally, the coding results and the theoretical model were submitted to two domain experts for evaluation and received their endorsement, indicating high reliability and validity of the theoretical model.

4. Quantitative research for rural homestay CSR scale development

The scale development procedure is shown in Figure 2. Based on an extensive literature review, in-depth interview findings, and expert review, an initial 28-item scale for rural homestay CSR was developed using a five-point Likert scale. First, two postgraduate students in hospitality management proposed 32 initial items through literature review and interview-based grounded theory results. Second, two experts reviewed these items, leading to the deletion of four items and minor adjustments, resulting in 28 initial items. Third, a pilot study was conducted to refine the scale structure. Fourth, a formal survey was administered to verify its reliability and validity.

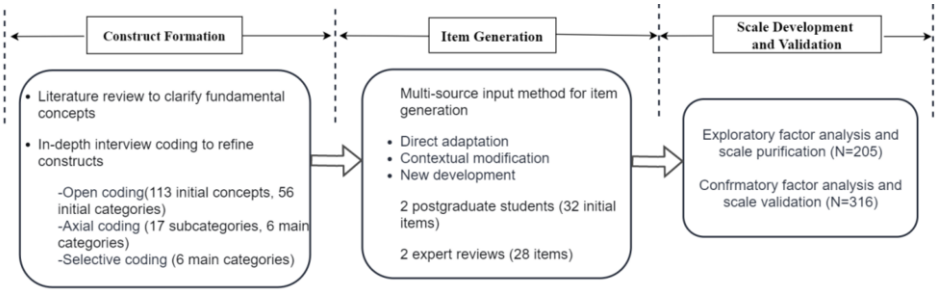


Figure 2. The scale development procedure.

4.1 Exploratory factor analysis (EFA) and scale purification

A survey of 227 rural homestay consumers across six Chinese provinces (Hunan, Yunnan, Zhejiang, Sichuan, Gansu, Anhui) was conducted from February to June 2025, yielding 205 valid responses after screening. This sample ensures representativeness and diversity across China's key homestay regions. Zhejiang and Yunnan represent mature markets in the eastern coastal and southwestern regions, while Sichuan and Hunan are rapidly emerging areas, and Gansu and Anhui are in the policy-driven initial

stage. This stratification reflects the gradient pattern of the national homestay market, covering both resource-rich areas and emerging transitional zones, thereby ensuring sample regional diversity and preliminary generalizability. The item descriptions administered to customers were rephrased from the language obtained from employees to reflect customer-perceived CSR (e.g., "this homestay..." rather than "our homestay...").

Analysis was conducted using SPSS 20. The Corrected Item-Total Correlation (CITC) values were all greater than 0.4, indicating high inter-item correlations. The overall Cronbach's α was 0.902, demonstrating high internal consistency for the scale. Harman's single-factor test was employed to examine potential common method bias. The results showed that no single factor accounted for more than 40% of the total variance, indicating that common method bias did not pose a significant threat.

The results of the EFA showed a KMO value of 0.861 for the sample. The Bartlett's test of sphericity (χ^2 = 6814.574, df = 378, $p < .001$) indicated that the items were suitable for factor analysis. EFA was then conducted using the principal component extraction method. The 28 items were categorized into 6 factors. The Cronbach's α values for all six factors exceeded 0.9, and the cumulative variance explained reached 84.313%, indicating sufficient internal consistency for the scale. The factor loading for each item was above 0.7, demonstrating that the extracted common factors effectively explained the measured variables.

4.2 Confirmatory factor analysis (CFA) and scale validation

CFA was employed to validate the six-dimensional structure of rural homestay CSR obtained through EFA. CFA was conducted using the covariance-based SEM (CB-SEM) module of Smart PLS 4, which provides maximum likelihood estimation and traditional fit indices. A total of 316 valid questionnaires were obtained from other homestays in six provinces for analysis. The model fit indices indicated a good fit for the six-factor model with the measurement data: $\chi^2/df = 1.063$; Root Mean Square Error of Approximation (RMSEA) = 0.014 < 0.05; Goodness-of-Fit Index (GFI) = 0.926, Normed Fit Index (NFI) = 0.950, Tucker-Lewis Index (TLI) = 0.997, Comparative Fit Index (CFI) = 0.997, all exceeding the threshold of 0.9. Furthermore, by comparing single-factor, three-factor, four-factor, and six-factor models to determine the most suitable model structure, the results, as presented in Table 1, showed that the six-factor model provided the most ideal fit.

Table 1. Comparison of model fit indices for confirmatory factor analysis.

Model	χ^2/df	RMSEA	GFI	AGFI	NFI	TLI	CFI
Single factor	3.38	0.087	0.74	0.698	0.835	0.868	0.877
Three factors	2.469	0.068	0.801	0.767	0.881	0.918	0.925
Four factors	1.79	0.05	0.856	0.83	0.914	0.956	0.96
Six factors	1.063	0.014	0.926	0.91	0.95	0.997	0.997

The assessment of construct validity was further subdivided into convergent validity and discriminant validity. As shown in Table 2, the standardized factor loadings for the 28 items ranged from 0.768 to 0.850, all significant at the $p < .001$ level. The Cronbach's α values ranged from 0.829 to 0.945. The Average Variance Extracted (AVE) values for all factors were greater than 0.5, supporting sufficient convergent validity. Additionally, the Composite Reliability (CR) scores for the six factors ranged from 0.829 to 0.945, surpassing the commonly required threshold of 0.7.

Table 2. Results of confirmatory factor analysis.

Factor	Number of	Factor	α	CR	AV
Enhancing rural economic vitality (CSR1)	4	0.811-0.8	0.904	0.9	0.702
Cultural preservation and dissemination	5	0.798-0.8	0.908	0.9	0.665
Community participation and development	9	0.792-0.8	0.945	0.9	0.656
Environmental responsibility (CSR4)	4	0.768-0.8	0.876	0.8	0.640
Employee responsibility (CSR5)	3	0.785-0.7	0.829	0.8	0.617
Standardized operation (CSR6)	3	0.823-0.8	0.869	0.8	0.690

Discriminant validity was tested using the Heterotrait-Monotrait Ratio (HTMT) of correlations. The data in Table 3 show that all HTMT values were below the threshold of 0.85, indicating good discriminant validity among the six factors of rural homestay CSR.

Table 3. Results of discriminant validity test (HTMT).

	1	2	3	4	5	6
CSR1						
CSR2	0.805					
CSR3	0.817	0.821				
CSR4	0.77	0.769	0.775			
CSR5	0.779	0.786	0.788	0.744		
CSR6	0.816	0.791	0.814	0.798	0.837	

5. Validation of the relationship between rural homestay CSR and CCB

5.1 Questionnaire design and data collection

The survey questionnaire consisted of four parts: the Rural Homestay CSR Scale, items measuring relationship quality, items measuring CCB, and respondents' demographic information. The items for rural homestay CSR were derived from the scale developed earlier, which was measured using 28 items across six dimensions. Relationship quality was measured using the scale by De Wulf et al. (2001). CCB was measured using an adapted version of Groth's (2005) scale.

The survey aims to determine which aspects of the CSR of rural homestays constitute the proximal psychological drivers of CCB. Data collection took place from June to September 2025. Questionnaires with completion times under 60 seconds or failed attention-check items were excluded, resulting in 421 valid responses and an effective return rate of 91.9%.

5.2 Hypothesis testing

This study tested the research hypotheses using PLS-SEM with the Bootstrap method (5000 resamples), employing Smart PLS 4 software. The model test results (Table 4) indicate that rural homestay CSR is positively associated with CCB ($\beta = 0.63$, $T = 20.902$, $p < 0.001$), and also demonstrates a significant positive correlation with relationship quality ($\beta = 0.634$, $T = 17.319$, $p < 0.001$). Furthermore, relationship quality has a significant positive effect on CCB ($\beta = 0.135$, $T = 3.065$, $p = 0.002$), and the specific mediating path is also statistically significant ($\beta = 0.085$, $T = 3.011$, $p = 0.003$). Therefore, hypotheses H1, H2, H3, and H4 are all supported.

Table 4. Model test results.

Hypothesis	Path	β	T-value	P-value	Supported
H1	CSR → CCB	0.63	20.902	0***	Yes
H2	CSR → RO	0.634	17.319	0***	Yes
H3	RO → CCB	0.135	3.065	0.002**	Yes
H4	CSR → RO → CCB	0.085	3.011	0.003**	Yes

Further path analysis reveals the intrinsic mechanisms through which various dimensions of CSR influence relationship quality and CCB. Figure 3 illustrates that the relationships between CSR dimensions and the endogenous constructs in the model largely align with our predictions. Notably, employee responsibility exerts no significant effect on relationship quality, yet it demonstrates a significant positive correlation on CCB.

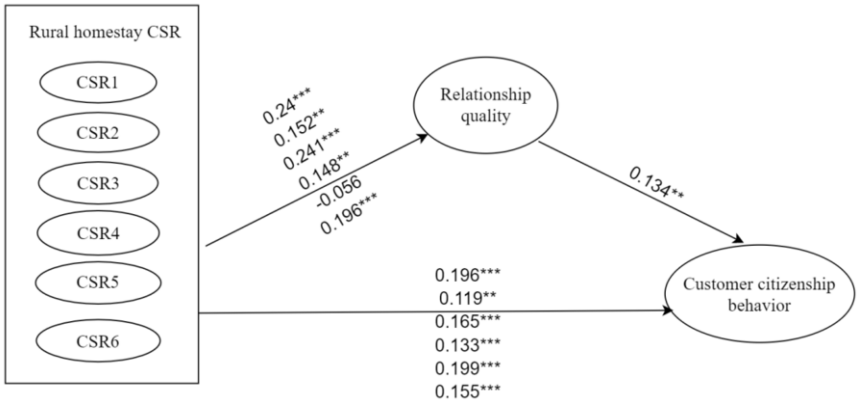


Figure 3. The specific path test results of the CSR dimension. *** p < .001, **p < .05.

Similarly, the mediation path analysis for the various dimensions of CSR further indicates that (see Table 5), with the exception of employee responsibility (β = -0.008, 95% CI [-0.023, 0.003]), the mediating effects of all other dimensions on CCB through relationship quality achieve statistical significance (p < 0.05).

Table 5. Mediating effect test results.

Mediating path	β	T-value	95%CI
CSR1> RO -> CCB	0.032**	2.682	[0.009, 0.057]
CSR2> RO -> CCB	0.02*	2.176	[0.005, 0.041]
CSR3> RO -> CCB	0.032*	2.463	[0.009, 0.06]
CSR4> RO -> CCB	0.02*	2.015	[0.004, 0.042]
CSR5> RO -> CCB	-0.008	1.137	[-0.023, 0.003]
CSR6> RO -> CCB	0.026*	2.48	[0.007, 0.049]

Notes: * indicates p<0.05， ** indicates p<0.01.

6. Discussion

This study develops a six-dimensional CSR scale for rural homestays, revealing unique dimensions of "enhancing rural economic vitality" and "cultural preservation" beyond traditional responsibilities. Using the CAC framework, this study demonstrates a direct positive effect of CSR on CCB, with relationship quality serving a partial mediating role. Notably, employee responsibility shows no effect on relationship quality. This is understandable: when customers learn that a homestay treats its employees well, they may form a moral evaluation ("this is a good enterprise") rather than a relational

experience ("I have been treated well here"). The former may influence customer citizenship behavior through a sense of moral obligation or attribution of goodwill, but it does not serve as a source of relationship quality. Existing research supports this view, suggesting that employee responsibility is likely to operate through pathways such as identification (identification with an enterprise that treats its employees well)[24]. The facilitative effect of corporate social responsibility on customer citizenship behavior is predominantly direct and cognitively driven. Relationship quality plays only a limited and partial mediating role, indicating that while affective relationships constitute one explanatory pathway, it is not the primary mechanism.

7. Conclusions, Limitations and Future Direction

Theoretically, it advances CSR literature by providing a context-specific scale for rural homestays and revealing differentiated pathways through which various CSR dimensions affect customer outcomes. Practically, it suggests operators integrate CSR into core strategy, industry associations develop certification systems, and local governments incorporate CSR performance into policy support.

However, several limitations warrant attention. First, the CSR scale derived from enterprise-based interview data was subsequently administered to customers for measurement and structural model validation. This approach may introduce structural inconsistencies between supply-side CSR practices and customer-perceived CSR, despite the measurement items being appropriately rephrased to capture customer perceptions and having passed both EFA and CFA tests. Future research should conduct measurement invariance tests across different stakeholder groups. Second, the proposed model omits established antecedents of customer citizenship behavior, such as service quality and customer identification. This omission may lead to omitted variable bias and overestimation of the unique effect of CSR. Future studies should incorporate these control factors to isolate the incremental contribution of CSR.

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Appendix 1. Examples of coding records.

Main Category	Sub-category	Initial Categories	Conceptualization (Examples)
Enhancing Rural Economic Vitality	Utilizing Idle Resources	Leasing idle residential buildings; Utilizing idle resources; Transforming idle assets into capital.	A1 Reutilization of idle residential buildings; A2 Abundant remaining land; A3 Increasing land transfer rate ... A7 Transforming assets into capital.
	Revitalizing Rural Industries	Procuring agricultural products for self-use; Procuring handicrafts for self-use; Procuring local services.	A8 Sourcing handwoven accessories from farmers; A9 Procuring local agricultural products ... A13 Purchasing from local specialty companies; A14 Sourcing ingredients locally.
		Facilitating external sales through the homestay platform; Driving the industrial chain; Enabling order-based sales.	A15 Selling products via the homestay platform; A16 Promoting related products ... A24 Using the homestay as a channel for external sales; A25 Enabling order-based sales revenue for surrounding farmers.
	Promoting Entrepreneurial Success for Villagers	Improving villagers' economic benefits; Helping villagers prosper; Providing free entrepreneurial training; Strengthening the collective economy.	A27 The homestay serves as a model case; A28 Inspiring other forms of entrepreneurship ... A35 Developing villager partners; A36 Providing free entrepreneurial training.
Cultural Preservation and Dissemination	Exploring Culture	Exploring local culture; Exploring intangible cultural heritage; Understanding traditional culture; Recognizing local culture.	A37 Ancient Tea Horse Road culture; A38 Services localized for Hui and Dongxiang ethnic groups; A39 Local production and lifestyle.
	Preserving Culture	Preserving original architectural culture; Respecting cultural customs; Protecting local heritage; Transmitting intangible cultural heritage skills.	A45 Inviting intangible cultural heritage inheritors; A46 Re-exploring local culture ... A53 Transmitting intangible cultural heritage handicrafts.
	Disseminating Culture	Intangible cultural heritage performances; In-depth experiential activities; Immersing in local life; Establishing farming education bases.	A54 A platform for showcasing and disseminating local culture; A55 Experiential activities ... A59 Establishing parent-child education and farming research bases.

	Public Service Support	Co-organizing public welfare activities; Participating in disaster relief; Caring for special groups.	A60 Village library ... A66 Visiting solitary elderly individuals.
	Local Job Creation	Providing jobs close to home; Utilizing rural labor force.	A67 Creating rural employment opportunities; A68 Solving local employment issues; A69 Staff composition includes villagers.
Community participation and development	Political Participation	Assisting impoverished households; Providing development suggestions; Formulating development models; Cooperating with government agencies; Liaising with village committees.	A70 Providing feedback or development suggestions ... A75 Leading impoverished households out of poverty.
	Rural civilization Development	Organizing local cultural activities; Promoting positive values; Enhancing villagers' quality; Fostering a civilized atmosphere.	A76 Promoting positive behavioral values ... A80 Personal etiquette training.
Environmental Responsibility	Environmental and Ecological Management	Pollution control; Improvement of living environment; Ecological restoration and protection.	A81 Protecting biodiversity ... A85 Improvement and enhancement of the living environment
	Green Operations	Prioritizing environmental protection; Resource conservation.	A86 Using eco-friendly materials ... A89 Conserving resources and reducing consumption.
	Environmental Education and Demonstration	Promoting environmental awareness; Serving as a demonstration model.	A90 Encouraging guests to protect the environment; A91 Setting an example for the village; A92 Guiding villagers to consciously protect the environment.
Employee Responsibility	Protecting Employee Rights	Providing a safe environment; Emphasizing mental well-being; Guaranteeing employee income.	A93 Protecting the legitimate rights and interests of employees and customers.
	Promoting Employee Development	Fostering team culture; Providing training and learning opportunities for improvement.	A97 Giving employees sufficient respect. A98 Training on processes and rules at star-rated hotels ... A102 Monthly team-building, cultural promotion, and training sessions.

Standardized Operation	Legal and Regulatory Compliance	Operating with integrity; Ensuring safety and compliance; Upholding high standards of business ethics.	A103 Safety awareness training and inspections for the kitchen.
	Quality Assurance	Using high-quality ingredients; Providing reliable service.	A111 Operating with honesty and credibility, ensuring fair transactions.A112 Using authentic and clean ingredients; A113 Maintaining high service standards, from food to hygiene management.

Notes: To assess inter-coder reliability, two independent coders coded interview transcripts. Cohen's kappa coefficient was 0.84, indicating a high level of agreement.

Appendix 1. Descriptive statistics of the sample.

Variable	Variable category	Distribution, n (%) (n = 205)	Distribution, n (%) (n = 316)	Distribution, n (%) (n = 421)
Gender	Male	100 (48.8)	168 (53.2)	232 (55.1)
	Female	105 (51.2)	148 (46.8)	189 (44.9)
Age	⩽18 years	5 (2.4)	22 (7.0)	11 (2.6)
	19–30 years	49 (23.9)	74 (23.4)	134 (31.8)
	31–45years	82 (40.0)	114 (36.1)	162 (38.5)
	Above 45 years	69 (33.7)	106 (33.6)	114 (27.1)
Education	Primary school and below	11 (5.4)	36 (11.4)	29 (6.9)
	Junior high	19 (9.3)	59 (18.7)	62 (14.7)
	Senior high / technical secondary school	41 (20.0)	40 (12.7)	68 (16.2)
	Junior college	49 (23.9)	75 (23.7)	126 (29.9)
	Bachelor	76 (37.1)	93 (29.4)	124 (29.5)
	Undergraduate and above	24 (11.7)	13 (4.1)	12 (2.9)
Monthly income	2000 RMB and below	20 (9.8)	25 (7.9)	35 (8.3)
	2001–5000 RMB	48 (23.4)	120 (38.0)	135 (32.1)
	5001–8000 RMB	79 (38.5)	106 (33.5)	180 (42.8)
	Above8000 RMB	58 (28.2)	65 (20.6)	71 (16.9)

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Job Crafting and Innovative Performance Among R&D Personnel: The Mediating Role of Innovative Self-Efficacy and the Moderating Role of Inclusive Leadership

Jinqiang Xie, Lei Wang[1] and Quanshun Yue
Beijing Wuzi University, Beijing 101149, China

Abstract. In the context of China's high-quality economic development today, innovation has become a powerful engine and important lever for promoting social progress and industrial transformation and upgrading. For enterprises, it is the only way to achieve sustainable and healthy development. R&D personnel are an important force for enterprise innovation, and the improvement of their innovative performance is of great significance to the core competitiveness of enterprises. Job crafting can fully mobilize the work enthusiasm and initiative of R&D personnel, deal with uncertain and challenging issues in the innovation process, help them realize their self-value, and bring high returns to the organization. Accordingly, based on the Job Demands-Resources model and Social Cognitive Theory, this study deeply investigates the influence mechanism of job crafting on R&D personnel's innovative performance and its applicable boundary conditions. Through empirical analysis of 287 valid questionnaire responses, a moderated mediation model is tested. The results show that: (1) job crafting has a positive effect on innovative performance; (2) innovative self-efficacy partially mediates the relationship between job crafting and innovative performance; (3) inclusive leadership positively moderates the relationship between job crafting and innovative performance. This study highlights the positive role of job crafting in promoting R&D personnel's innovative performance by enhancing innovative self-efficacy, and provides useful references for organizations to improve employee innovation through leadership style optimization and job design improvement.

Keywords. Job crafting, innovative self-efficacy, inclusive leadership, innovative performance

1. Introduction

With the rise of the knowledge economy and intensified global competition, innovation has become the core driver of sustainable enterprise development. As key drivers of innovation, R&D personnel's innovation performance directly affects firms' competitive advantage. However, traditional work models often fail to meet the autonomy and flexibility needs of R&D employees. Job crafting—a proactive way to adapt and reshape work—has therefore gained increasing attention [1].

[1] Corresponding Author: Lei Wang, 3389037178@qq.com
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Existing research mostly focuses on the direct effects of job crafting on work engagement and performance outcomes, lacking a systematic explanation of the underlying psychological mechanism through which "individuals translate crafting behaviors into innovative performance" [2]. On the one hand, based on Social Cognitive Theory, individual behavior is driven by cognitive beliefs [3]; innovation activities are characterized by high risk and uncertainty, and thus rely more on individuals' judgment of their own innovative ability than does general performance. Therefore, compared with general psychological variables, innovative self-efficacy directly reflects R&D personnel's confidence and motivation when facing complex innovation tasks, serving as a more targeted key mediating mechanism linking job crafting and innovative performance. On the other hand, the effectiveness of job crafting is highly context-dependent, but extant research has paid insufficient attention to which leadership contexts better unleash its innovative value. Inclusive leadership, through openness, support, and a tolerance-for-failure climate, strengthens employees' resource acquisition and psychological safety, reduces perceived innovation risk, and thus amplifies the translation of job crafting into innovative performance. Hence [4], it serves as a moderator with greater explanatory power for the innovation context. Therefore, this study introduces innovative self-efficacy as a mediator and inclusive leadership style as a contextual moderator to better understand the influence of job crafting on R&D personnel's innovative performance.

2. Theoretical Framework and Hypotheses

2.1. Job Crafting and Innovative Performance

Job crafting was first defined by Wrzesniewski & Dutton as the physical and cognitive changes individuals make in task, relational, and cognitive boundaries [5]. Tims et al. later operationalized job crafting based on the JD-R model into four dimensions: increasing structural job resources, increasing social job resources, increasing challenging job demands, and decreasing hindering job demands[6]According to the Job Demands-Resources model, job resources have motivational properties that enhance employee engagement and performance, while job demands exert dual effects through challenge and hindrance[6]. Specifically: increasing structural job resources helps improve individuals' capability and sense of control, enabling R&D personnel to cope more effectively with complex tasks, thereby facilitating the generation and implementation of innovative ideas; increasing social job resources facilitates information acquisition and knowledge sharing, reduces uncertainty in the innovation process, and increases the probability of innovation success; increasing challenging job demands stimulates individuals' growth motivation and need for achievement, prompting them to actively explore new methods and thereby enhancing innovative output; reducing hindering job demands lowers emotional exhaustion and cognitive burden, allowing individuals to invest more resources in innovative activities. Therefore, we propose:

H1:Job crafting positively affects R&D personnel's innovative performance.

H1a–H1d: Each sub-dimension of job crafting positively affects innovative performance.

2.2. Job Crafting and Innovative Self-Efficacy

Social Cognitive Theory suggests that self-efficacy derives from individuals' cognitive appraisal of resources, experiences, and the environment [3]. Job crafting influences efficacy judgments by altering the task and resource structure in which individuals operate. Increasing structural resources enhances capability foundations and mastery experiences, strengthening the belief "I can innovate"; increasing social resources provides vicarious experiences and social persuasion through feedback and support, reinforcing confidence; increasing challenging demands allows individuals to accumulate mastery experiences in overcoming difficulties, thereby enhancing efficacy; reducing hindering demands lowers stress and negative expectations, maintaining a positive psychological state. Therefore, we propose:

H2: Job crafting positively affects innovative self-efficacy.

H2a–H2d: Each sub-dimension of job crafting positively affects innovative self-efficacy.

2.3. Innovative Self-Efficacy and its Mediating Role

Innovative self-efficacy, as a core cognition of one's innovative ability, directly affects innovation motivation, risk-taking willingness, and sustained effort [7]. Individuals with high efficacy are more inclined to try new approaches and persist in innovation tasks, thereby improving innovative performance. Simultaneously, job crafting indirectly affects innovation outcomes through efficacy, reflecting a "resources → cognition → behavior" transmission mechanism. Therefore, we propose:

H3: Innovative self-efficacy positively affects innovative performance.

H4: Innovative self-efficacy mediates the relationship between job crafting and innovative performance.

H4a–H4d: Innovative self-efficacy mediates the relationship between each sub-dimension of job crafting and innovative performance.

2.4. The Moderating Role of Inclusive Leadership

According to Social Cognitive Theory, inclusive leadership is characterized by openness, tolerance for failure, and resource provision [8], making employees feel trusted and supported by leaders, creating a safe psychological climate, thereby enhancing intrinsic motivation and self-efficacy. This makes employees more willing to experiment and innovate. Therefore, we propose:

H5: Inclusive leadership positively moderates the relationship between job crafting and innovative performance.

H5a–H5d: Inclusive leadership moderates the relationship between each sub-dimension of job crafting and innovative performance.

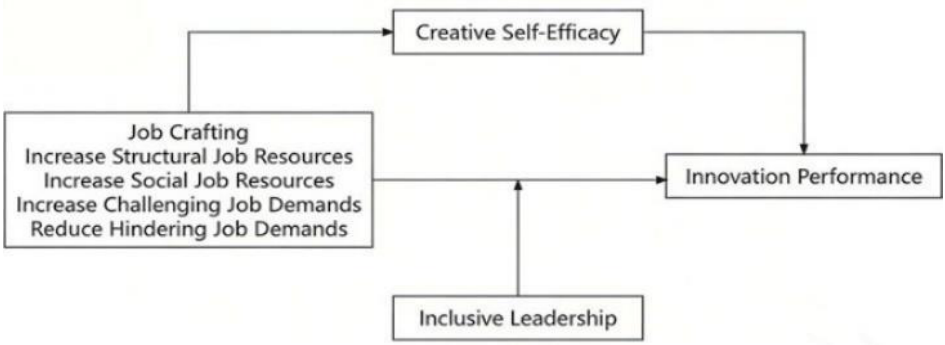


Figure 1. Theoretical Model

3. Research Design

3.1. Data Source

This study used a questionnaire survey to collect data. Companies were selected based on having an R&D department and stable size. The inclusion criteria for the sample were employees engaged in software development, algorithm, or technical support with at least one year of tenure. Questionnaires were distributed both online and offline, with random sampling through corporate contacts. A total of 350 questionnaires were distributed, 323 were returned, 287 valid questionnaires were obtained.

3.2. Variable Measurement

This study adopted well-established scales recognized by domestic and international scholars, all demonstrating high reliability and validity. A Likert 5-point scale was used, where "1" to "5" represent from "strongly disagree" to "strongly agree." Job crafting was measured using the 21-item, four-dimensional scale developed by Tims & Bakker based on the resource perspective [9,10]; Innovative self-efficacy was measured using the 5-item scale revised by Liu Zhiying et al. based on Tierney & Farmer's scale [11,12]; Inclusive leadership was measured using the 9-item three-dimensional scale developed by Carmeli et al.[13]; Innovative performance was measured using the 8-item three-dimensional scale by Han Yi et al., adapted from Janssen & Yperen [14,15]. To eliminate potential confounding effects of demographic factors, gender, age, position, and education level were set as control variables.

4. Data Analysis

4.1. Reliability and Validity Tests

The standardized factor loadings of all items for the four main variables were above 0.6, meeting acceptable standards. Cronbach's α for job crafting, innovative self-efficacy, innovative performance, and inclusive leadership were all above 0.8; composite

reliability were all above 0.8; average variance extracted were all above 0.5, indicating good convergent and discriminant validity. Specifically, for job crafting, Cronbach's α was 0.903, CR was 0.901, and AVE was 0.536. For innovative self-efficacy, Cronbach's α was 0.815, CR was 0.815, and AVE was 0.517. For innovative performance, Cronbach's α was 0.905, CR was 0.902, and AVE was 0.521. For inclusive leadership, Cronbach's α was 0.952, CR was 0.951, and AVE was 0.642.

Next, confirmatory factor analysis (CFA) was conducted using Mplus 7.0. The results showed good discriminant validity among job crafting, innovative self-efficacy, innovative performance, and inclusive leadership. The CFA results (Table 1) indicated that the four-factor model demonstrated good fit and was significantly better than alternative models.

Table 1. Confirmatory Factor Analysis Results

Model	$\chi 2$	df	$\chi 2$ / df	RMSEA	CFI	TLI	SRMR
Four-factor: JC,IL,ISE,IP	1124.56	428	2.63	0.068	0.935	0.928	0.054
Three-factor: JC+IL,ISE,IP	1687.32	431	3.92	0.102	0.871	0.862	0.087
Two-factor: JC+IL+ISE,IP	2245.78	433	5.19	0.136	0.806	0.794	0.112
Two-factor: JC+IL+ISE+IP	3012.45	434	6.94	0.168	0.732	0.718	0.139

Note: JC = Job Crafting, ISE = Innovative Self-Efficacy, IP = Innovative Performance, IL = Inclusive Leadership, same for subsequent tables.

4.2. Common Method Bias Test

Since all key variables relied on self-reports by R&D personnel, Harman's single-factor test was conducted using unrotated principal component factor analysis on all measurement items. The results extracted multiple factors with eigenvalues greater than 1, and the variance explained by the first factor was 36.42%, well below the 50% threshold, indicating that common method bias is not a serious concern in this study.

4.3. Correlation Analysis

Pearson correlation analysis showed that job crafting was positively correlated with innovative self-efficacy ($r = 0.684$, $p < 0.01$), inclusive leadership ($r = 0.660$, $p < 0.01$), and innovative performance ($r = 0.764$, $p < 0.01$). All sub-dimensions also exhibited significant correlations, as shown in Table 2.

Table 2. Confirmatory Factor Analysis Results

Variable	M	SD	JC	JC1	JC2	JC3	JC4	ISE	IL	IP
JC	3.756	0.733	1.000							
JC1	3.909	0.924	0.815**	1.000						
JC2	3.744	0.940	0.793**	0.541**	1.000					
JC3	3.698	0.887	0.781**	0.526**	0.544**	1.000				
JC4	3.685	0.921	0.803**	0.550**	0.469**	0.471**	1.000			
ISE	3.901	0.939	0.684**	0.666**	0.526**	0.515**	0.486**	1.000		
IL	3.592	0.876	0.660**	0.581**	0.588**	0.457**	0.485**	0.536**	1.000	
IP	3.550	0.940	0.764**	0.641**	0.566**	0.622**	0.613**	0.630**	0.607**	1.000

Note: *p<0.05, **p<0.01; JC1 = increasing structural job resources, JC2 = increasing social job resources, JC3 = increasing challenging job demands, JC4 = reducing hindering job demands, same for subsequent tables.

4.4. Hypothesis Testing

The results of hierarchical regression analysis for the main variables are shown in Table 3. From Model 1, job crafting has a positive effect on innovative performance ($\beta = 0.755$, $p < 0.01$), supporting H1. From Model 5, job crafting has a positive effect on innovative self-efficacy ($\beta = 0.668$, $p < 0.01$), supporting H2. From Model 2, innovative self-efficacy has a positive effect on innovative performance ($\beta = 0.606$, $p < 0.01$), supporting H3. When both job crafting and innovative self-efficacy were entered into Model 3, the path coefficient of job crafting on innovative performance decreased but remained significant, indicating that innovative self-efficacy partially mediates the relationship, supporting H4. From Model 4, the interaction term of job crafting and inclusive leadership significantly positively affects innovative performance, indicating that inclusive leadership positively moderates the relationship between job crafting and innovative performance, supporting H5. Figure 2 illustrates the effect of different levels of inclusive leadership on the relationship between job crafting and innovative performance. Compared to employees with low-level inclusive leadership, those with high-level inclusive leadership showed a stronger effect on innovative performance.

Table 3. Hierarchical Regression Analysis Results for Main Variables

	Variable	IP				ISE
		Model 1	Model 1=2	Model 1=3	Model 4	Model 5
Independent	JC	0.755**		0.630**	0.701**	0.668**
Mediator	ISE		0.606**	0.186**		
Moderator	IL				0.195**	
Interaction	JC*IL				0.107*	
Control	Gender	-0.009	0.028	-0.010	-0.006	-0.085*
	Age	0.023	0.091	0.050	0.013	0.048
	Education	0.075	0.029	0.060	0.094	0.057
	Position	-0.179**	-0.159*	-0.170**	-0.165**	-0.102
	R^2	0.603	0.416	0.610	0.627	0.480

Table 3. Hierarchical Regression Analysis Results for Main Variables

Variable	IP				ISE
	Model 1	Model 1=2	Model 1=3	Model 4	Model 5
ΔR^2	0.596	0.405	0.603	0.617	0.471
F	85.505**	39.981**	73.000**	66.856**	51.946**

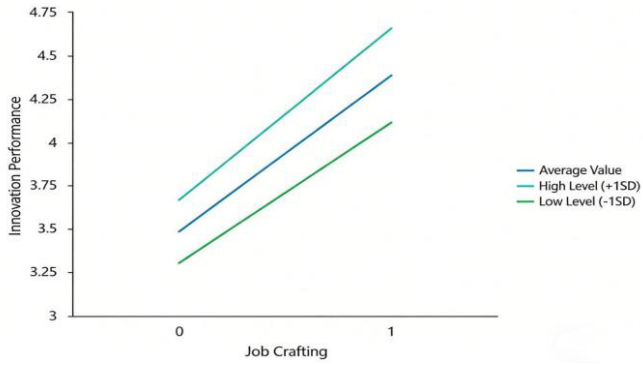


Figure 2. Moderating Effect of Inclusive Leadership

The hierarchical regression analysis results for the sub-dimensions of job crafting are shown in Table 4. The regression coefficients of each sub-dimension on R&D personnel's innovative performance were 0.621, 0.547, 0.616, and 0.585, respectively, all significant at the 0.01 level, indicating that each sub-dimension of job crafting has a significant effect on R&D personnel's innovative performance. Thus, H1a, H1b, H1c, and H1d are supported. As shown in Table 4, the regression coefficients of each sub-dimension on innovative self-efficacy were 0.646, 0.509, 0.498, and 0.459, respectively, all significant at the 0.01 level, indicating that each sub-dimension of job crafting has a significant effect on innovative self-efficacy. Thus, H2a, H2b, H2c, and H2d are supported.

Table 4. Hierarchical Regression Analysis Results of JC Sub-dimensions on IP and ISE

	IP				ISE			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Gender	0.015	-0.057	-0.023	-0.016	-0.055	-0.129	-0.099	-0.095
Age	0.079	0.078	0.096	0.145	0.074	0.09	0.124	0.165
Education	0.077	0.073	0.084	0.036	0.063	0.056	0.063	0.024
Position	-0.196**	-0.213**	-0.276**	-0.179**	-0.106	-0.13	-0.187	-0.111
JC1	0.621**				0.646**			
JC2		0.547**				0.509**		
JC3			0.616**				0.498**	
JC4				0.585**				0.459**
R^2	0.434	0.351	0.434	0.404	0.455	0.304	0.300	0.267
ΔR^2	0.424	0.339	0.424	0.394	0.445	0.292	0.288	0.254

F	45.153**	30.331**	43.158**	38.12**	46.946**	24.602**	24.104**	20.513**

Note: *p<0.05, **p<0.01.

As shown in Table 5, in the mediation analysis of each sub-dimension of job crafting, the regression coefficients c, a, b, and c' were all significant, and a*b had the same sign as c', indicating that innovative self-efficacy partially mediates the relationship between each sub-dimension of job crafting and innovative performance. Thus, H4a, H4b, H4c, and H4d are supported.

Table 5. Results of Mediation Effect Tests

Path	Conclusion	c (Total)	a*b (Indirect)	c' (Direct)	a*b/c (%)
JC=>ISE=>IP	Partial	0.755	0.124	0.63	16.46%
JC1=>ISE=>IP	Partial	0.621	0.226	0.395	36.41%
JC2=>ISE=>IP	Partial	0.547	0.225	0.322	41.22%
JC3=>ISE=>IP	Partial	0.616	0.195	0.421	31.69%
JC4=>ISE=>IP	Partial	0.585	0.192	0.393	32.88%

As shown in Table 6, the interaction term coefficients between each sub-dimension and inclusive leadership were -0.07 (p>0.05), -0.10 (p>0.05), 0.022 (p>0.05), and -0.048 (p>0.05), none of which were significant. Thus, H5a, H5b, H5c, and H5d are not supported. From Table 3, the moderating effect of inclusive leadership on overall job crafting is significant, but not for the sub-dimensions. This may be due to a cumulative effect of job crafting, where multiple crafting behaviors work together to activate the moderating potential of inclusive leadership, whereas the effect of a single dimension is weak and more susceptible to contextual noise.

Table 6. Moderating Effect Analysis of IL on the Relationship Between Each Sub-dimension of JC and IP

	IP			
	Model 1	**Model 2**	**Model 3**	**Model 4**
Gender	0.037	0.002	0.009	0.016
Age	0.011	0.004	0.018	0.047
Education	0.105	0.108	0.12	0.085
Position	-0.178**	-0.19	-0.226	-0.166
JC1	0.399**			
IL	0.336**			
JC1*IL	-0.070			
JC2		0.274**		
IL		0.392**		
JC2*IL		-0.100		

JC3			0.456**	
IL			0.400**	
JC3*IL			0.022	
JC4				0.389**
IL				0.384**
JC4*IL				-0.048
R^2	0.516	0.462	0.549	0.518
ΔR^2	0.504	0.448	0.538	0.506
F	42.476**	34.167**	48.52**	42.781**

5. Conclusions and Implications

The findings show that job crafting and each of its sub-dimensions have a significant positive effect on R&D personnel's innovative performance; innovative self-efficacy plays a partial mediating role; inclusive leadership positively moderates the relationship between job crafting and innovative performance. Accordingly, organizations can stimulate employees' crafting behaviors by increasing structural/social job resources, setting challenging demands, and reducing hindering demands; simultaneously, they should cultivate inclusive leadership to strengthen these effects. Differentiated management for R&D personnel of different ages and educational levels should be implemented.

This study has the following limitations: All variables were self-reported by employees. Although Harman's single-factor test was conducted, common method bias cannot be completely ruled out. Future research could adopt multi-wave, multi-source evaluation designs to improve the research design. In addition, this study only focused on inclusive leadership as an internal organizational leadership style. In fact, other contextual variables such as team climate and organizational support may also affect employees' cognition and behavior. Future research could also consider external factors such as environmental dynamism and market competition intensity as moderators of the relationship between job crafting and innovative performance.

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Management Strategies for Rural Revitalization in the Era of Emerging Technologies

Kai MA, Liangliang WANG[1]
School of Marxism, Xi'an Shiyou University, Xi'an, P.R.China
ORCiD ID: Liangliang WANG https://orcid.org/0009-0005-9623-2766

Abstract. In the century-long process of adapting Marxism to the Chinese context, the 'Three Rural Issues' (agriculture, rural areas, and farmers) have remained central to national development. In the new era, emerging technologies have become an important driver of rural revitalization. Guided by Marxist theories of productive forces and urban–rural integration, this study investigates the role of emerging technologies in rural revitalization in Henan Province. Existing studies mainly emphasize policy or technological perspectives, while empirical analyses grounded in Marxist theory remain limited. This study addresses this gap by integrating Marxist theory with empirical investigation. A mixed-method approach combining literature review, case analysis, surveys, and interviews was employed. The survey covered 32 villages across five cities in Henan Province, generating 480 valid responses and 20 semi-structured interviews. Data were analyzed using descriptive statistics and thematic analysis. Results show that innovative seed adoption reached 78%, wheat yield increased by 8.7%, product traceability systems covered 92% of large-scale operators, and telemedicine reduced referral waiting time from 3.5 to 1.2 days. However, uneven digital infrastructure, talent shortages, and low technology commercialization remain major challenges. Strengthening policy support, local talent cultivation, and industrial integration is essential for sustainable rural revitalization.

Keywords. Rural revitalization, emerging technologies, sinicization of Marxism, Henan Province

1. Introduction

The rural revitalization strategy represents a comprehensive framework for addressing the 'Three Rural Issues' (agriculture, rural areas, and farmers) in the new era, while emerging technologies provide critical momentum for this transformation [1]. From the perspective of Marxism, the development of productive forces constitutes the fundamental driver of social progress, and technological advancement plays a decisive role in promoting agricultural modernization and overcoming the urban–rural divide [2]. As a major agricultural province and core grain-producing region in Henan Province, with consistently high grain output, Henan bears a significant responsibility for ensuring national food security [3]. In recent years, local authorities have actively advanced the integration of emerging technologies with rural revitalization through

[1] Corresponding Author: Liangliang WANG, wangliangliang@xsyu.edu.cn

targeted policies and key platforms such as the Central Plains Agricultural Valley. These initiatives have accelerated applications in smart agriculture, digital governance, and public service delivery. Nevertheless, persistent challenges—including regional disparities, uneven digital infrastructure, and constraints in resources and capacity—continue to limit the full realization of technology-driven rural transformation.

Against this backdrop, this study, grounded in the Sinicization of Marxism, systematically examines the theoretical foundations, practical achievements, and structural limitations of technology-enabled rural revitalization in Henan. It employs a combination of literature review, case analysis, and empirical observation to investigate representative practices across regions, focusing on key domains such as agricultural production, rural governance, and industrial upgrading. By contextualizing these practices within broader socio-economic and institutional frameworks, the study seeks to reveal both the enabling mechanisms and the constraints shaping current development trajectories.

2. Methods

The study contributes to theory by integrating Marxist perspectives on productive forces and urban–rural relations with contemporary technological transformations, thereby enriching the analytical framework of rural revitalization research. At the same time, it offers practical value by identifying key bottlenecks—such as insufficient talent supply, limited efficiency in technology transfer, and imbalanced infrastructure development—and proposing targeted policy responses. The findings aim to provide actionable insights and replicable models not only for Henan but also for other major agricultural regions pursuing sustainable and innovation-driven rural revitalization through emerging technologies.

This study employs a combination of research methods to ensure the systematicity, rigor, and practical relevance of the analysis, such as literature research, case analysis, survey research, data statistical analysis.

3. Results

3.1 Continuous Improvement of Digital Infrastructure

Table 1. Digital Infrastructure Investment and Outcomes in Rural Henan Province (up to 2024).

Indicator	Description / Value
Implementing Entity	China Mobile (Henan Branch)
Total Investment	1.62 billion yuan
Newly Constructed Rural 5G Base Stations (2024)	4,375
Total Rural 5G Base Stations	31,700
New Optical Fiber Broadband Ports	320,000
Total Broadband Access Capacity	11.808 million ports
Infrastructure Function	Supports expansion of rural information and communication networks
Primary Outcomes	Enhanced rural connectivity; improved network stability; increased data transmission capacity
Development Significance	Establishes a foundational platform for digital transformation in agriculture and rural governance

Source: Compiled based on relevant statistical data [4].

Digital infrastructure constitutes a fundamental prerequisite for leveraging emerging technologies in rural revitalization. As shown in the Table 1, enterprises such as China Mobile (Henan branch) have significantly increased investment in rural information and communication networks across Henan Province.

In key areas such as high-standard farmland demonstration zones and agricultural industrial parks, near-complete 5G coverage now enables efficient data transmission, remote control of intelligent agricultural machinery, and the operation of digital governance platforms. For example, in Yuanyang County, interconnected smart systems support real-time monitoring of soil moisture, crop growth, and environmental conditions. These technologies facilitate precision agriculture, optimize resource allocation, and enhance productivity. Overall, the continuous improvement of digital infrastructure has become a critical enabler of technology-driven rural modernization and sustainable agricultural development.

3.2 Emerging Technologies Empowering Industrial Revitalization

Focusing on food security, Henan Province has advanced the integration of 'five optimizations'—high-quality farmland, improved seeds, advanced methods, appropriate machinery, and institutional support—while promoting high-yield models and water–fertilizer integration. In Lankao County, China Mobile developed the 'Wanxiang Gengyun' agricultural model, integrating extensive agronomic knowledge and remote sensing data [5]. Combined with field-based monitoring of disaster conditions, crop growth, soil moisture, and pests, real-time data are transmitted via 5G and analyzed by AI to optimize irrigation, pest control, and machinery scheduling. This enables a transition from weather-dependent to data-driven agriculture. In Yuanyang County, smart platforms support real-time soil monitoring and remote irrigation, increasing yields by an estimated 5–8%. By 2024, wheat mechanized harvesting exceeded 99%, and overall mechanization surpassed 88%, underscoring the growing role of smart agriculture [6].

Centered on the Central Plains Agricultural Valley, Henan has strengthened the coordination of research, education, and industry to build a full-chain innovation ecosystem. Over 160 new crop varieties have been approved, with improved seed coverage exceeding 97%, reinforcing national grain security. In parallel, digital technologies such as blockchain and big data have enhanced agricultural value chains. Traceability systems enable full lifecycle tracking of products, improving quality assurance and brand credibility. Platforms integrating e-commerce, logistics, and data services have expanded market access for local specialties, while digital tools support standardized and large-scale agricultural production. Overall, emerging technologies are driving the transformation of agricultural production toward greater efficiency, intelligence, and market integration.

3.3 Emerging Technologies Optimizing Livelihood Services

Emerging technologies are significantly improving rural public services and quality of life in Henan Province. In Lankao County, China Mobile has deployed smart health systems for elderly residents, integrating wearable devices, monitoring sensors, and AI-assisted diagnostics. Real-time data on heart rate, sleep, and other indicators are transmitted to village clinics, enabling timely alerts and rapid response. Intelligent diagnostic tools further enhance primary healthcare capacity, while digital platforms in

community spaces support health education and cultural engagement, improving elderly care services.

At the governance level, Henan promotes the digital extension of public services, enabling villagers to access government, education, and healthcare resources online. In Xiangcheng County, integrated rural governance platforms facilitate public participation and real-time service delivery. Meanwhile, 5G-enabled remote education and telemedicine help alleviate longstanding shortages of quality resources in rural areas. In addition, big data platforms for poverty prevention and rural revitalization enhance dynamic monitoring and policy responsiveness. AI-enabled surveillance systems improve public safety and grassroots governance through real-time risk detection. Complementing these efforts, science and technology service programs—such as expert outreach and field-based training—support farmers with technical guidance, accelerating the diffusion and application of agricultural innovations. Together, these initiatives demonstrate how digital technologies can enhance service accessibility, governance efficiency, and social well-being in rural communities.

3.4 Promoting the Extension of Science and Technology Services

Henan Province advances the extension of science and technology services to support rural revitalization by strengthening collaboration between research institutions and local governments. Through coordinated initiatives, technological services are expanded across the entire agricultural value chain, including production, processing, testing, circulation, and sales.

Mechanisms such as science and technology commissioners and field-based innovation platforms (e.g., science and technology courtyards) facilitate the direct engagement of experts with rural communities. These specialists provide on-site technical guidance, farmer training, and targeted solutions to practical challenges in agricultural production.

By promoting the integration of research, education, and industry, Henan accelerates the transformation and application of scientific and technological achievements. This approach enhances farmers' technical capacities, improves production efficiency, and supports the modernization and sustainable development of agriculture, thereby strengthening the role of innovation in driving rural revitalization.

3.5 Challenges in Leveraging Emerging Technologies for Rural Revitalization

Despite improvements, rural digital disparities persist in Henan. Remote areas lack adequate 5G and broadband, limiting technology diffusion. High costs and long returns constrain adoption of smart agricultural equipment by farmers and enterprises [7]. Human capital constraints hinder rural development: aging populations with low digital literacy limit technology use, while weak talent attraction and insufficient technical support restrict innovation and application of emerging technologies. In addition, gaps persist in the transformation of scientific and technological achievements. Some innovations lack alignment with practical rural needs, while the agricultural extension system remains underdeveloped. Weak coordination among research institutions, enterprises, and farmers results in inefficiencies along the transformation chain, often leading to an emphasis on research outputs over real-world application. Finally, financial constraints continue to limit progress. The deployment of emerging technologies requires substantial investment in infrastructure, equipment, and training.

However, funding in rural areas largely depends on government support and a small number of enterprises, with limited participation from social capital. This narrow financing structure is insufficient to sustain the large-scale adoption of technology-driven rural revitalization initiatives.

4. Discussion

Guided by Marxism—particularly the perspective of urban–rural integration—this study proposes a coordinated policy framework to advance technology-driven rural revitalization in Henan Province. Guided by Marxist productivity theory and urban-rural integration ideology, this study reveals several quantitative achievements of technology-driven rural revitalization in Henan Province through surveys and case analysis, including a 78% rise in seed popularization rate, an 8.7% increase in wheat yield per unit area, and reduced waiting time for telemedicine services.

4.1 Strengthening Digital Infrastructure and Promoting Balanced Urban–Rural Development

Digital infrastructure is the foundation for the effective application of emerging technologies. Priority should be given to increasing investment in remote, mountainous, and hilly areas to expand 5G network coverage and optical fiber broadband access, thereby improving network quality and accessibility. A diversified investment mechanism should be established by encouraging enterprises to participate in the construction and operation of rural digital infrastructure [8]. At the same time, the widespread adoption of intelligent irrigation systems, agricultural machinery navigation, and monitoring technologies should be promoted to reduce costs for farmers and enterprises, ultimately narrowing the urban–rural digital divide.

4.2 Improving Talent Cultivation and Introduction Mechanisms

Human capital is essential for sustaining technology-driven agriculture. Policies should strengthen farmers' digital literacy through targeted training in smart agricultural equipment and digital platforms [9]. Incentive mechanisms must be enhanced to attract urban scientific and technological talent to rural areas, including preferential policies in professional evaluation, compensation, and entrepreneurship support. In addition, agricultural vocational education should be reformed to align with industry needs, fostering interdisciplinary professionals with expertise in technology, agriculture, and rural development.

4.3 Enhancing Technology Transfer and Integration of Production, Education, and Research

A market-oriented approach is vital to accelerate the transformation of scientific and technological achievements in Henan. Strengthening collaboration among research institutions, enterprises, and farmers promotes demand-driven innovation. Universities should co-develop technologies with industry, while enterprises facilitate commercialization. Improving extension systems and expanding innovation platforms,

alongside digital advisory services, enhances technology diffusion, farmer access, and application efficiency.

In addition, refining incentive mechanisms for technology transfer is vital. Policies should encourage researchers, technicians, and farmers to participate in the commercialization and application of innovations through performance-based rewards and benefit-sharing arrangements. Such measures can effectively bridge the "last mile" between laboratory research and field application, promoting the sustainable development of technology-driven agriculture.

4.4 Expanding Financial Support and Diversifying Funding Channels

A sustainable financial framework is essential for technology-driven rural revitalization in Henan. A diversified system led by government policy, enterprises, and social participation should increase funding for infrastructure and innovation. Financial institutions must expand inclusive services, while policy incentives attract private capital through partnerships and risk-sharing mechanisms, improving rural financing access. Through coordinated financial support and diversified funding channels, it is possible to enhance investment efficiency, stimulate market vitality, and achieve both economic and social benefits in rural revitalization.

4.5 Strengthening Policy Coordination and Institutional Support

Effective implementation of technology-driven rural revitalization policies requires robust coordination and institutional support in Henan Province. National and provincial strategies should be translated into context-specific implementation guidelines that reflect local conditions and development priorities. Strengthening interdepartmental coordination can improve policy coherence and reduce fragmentation across sectors.

At the same time, establishing comprehensive evaluation mechanisms is essential. Performance assessment systems should incorporate indicators related to technology adoption, agricultural productivity, and service delivery, thereby enhancing government accountability and policy effectiveness. In addition, greater emphasis should be placed on disseminating successful local practices and fostering public awareness of technology-driven agriculture. By promoting knowledge sharing and social recognition, these efforts can create a supportive institutional and cultural environment, ensuring the long-term sustainability and scalability of rural revitalization initiatives.

5. Conclusion

Emerging technologies drive rural revitalization in Henan. Guided by Marxism, 5G, AI, and blockchain modernize agriculture, improve livelihoods, and strengthen governance, supporting efficient, data-driven systems. However, uneven infrastructure, talent shortages, weak technology transfer, and limited funding constrain progress, requiring targeted policies. A systematic approach integrating policy support, talent development, and diversified investment is essential. Strengthening institutional coordination, education, and financial access will address bottlenecks. Guided by Marxist theory, deeper collaboration among government, enterprises, research institutions, and farmers

is crucial to building a sustainable, inclusive, innovation-driven rural revitalization model.

This study has several notable limitations. Firstly, the research scope mainly focuses on technology-driven rural revitalization practices in Henan Province, lacking cross-regional comparative analysis, so the research conclusions cannot be fully generalized to other rural areas with different development foundations. Secondly, the investigation primarily concentrates on macroscopic effects of 5G, AI and blockchain applications, while insufficient in-depth exploration is made into specific operational difficulties and practical risks of emerging technologies in rural daily production and governance.

In addition, this paper only summarizes existing constraints including unbalanced infrastructure distribution, insufficient professional talents, inefficient technology transformation and inadequate capital supply. It fails to conduct long-term dynamic tracking of the evolving impacts of these restrictive factors. Moreover, the collaborative mechanism among governments, enterprises, research institutes and farmers is analyzed theoretically only, without sufficient empirical verification of actual cooperation efficiency. Further targeted field research and longitudinal observation are needed to make up for the above deficiencies.

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Section 2

Track on “Applied Education and Applied Research in AI, Data Science, and Web 6.0”, the Second Edition

Modern Management based on Big Data VII
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Different Cognition: Human-Targeted Adversarial Examples

Zichi WANG [1]
School of Communication and Information Engineering, Shanghai University, Shanghai, 200444, China
ORCiD ID: Zichi Wang https://orcid.org/0000-0003-0283-5338

Abstract. Existing adversarial examples were designed against neural networks, which aims to make neural networks misclassify. This paper proposes a new kind of adversarial examples against human visual system which aims to make humans misclassify. Given an original image, adversarial example generating is executed to obtain the corresponding adversarial image. Then, the judgement of humans on the adversarial image will be significantly different with that on the original image. But from the perspective of neural networks, content of the adversarial image is kept unchanged compared with original image. Experimental results show that quality indicators, e.g., PSNR, SSIM, and NCC, between adversarial images and original images were very low for all cases. That means the content of adversarial image is significantly different with that of original image. Therefore, the adversarial images produced by our method can be easily misclassified by humans. In other words, our method is able to fool human visual system effectively.

Keywords. Adversarial Examples, Neural networks, Human visual system, Artificial intelligence

1. Introduction

Artificial intelligence has been rapidly developed in recent years. Various kinds of neural networks were designed for different intelligent tasks, e.g., image classification [1], semantic segmentation [2], image generating [3]. Meanwhile, the technique of adversarial examples is developed to fool neural networks designed for classification tasks by adding artificial perturbations on input images [4]. The images with perturbations (adversarial examples) can fool the classification networks into making incorrect predictions.

The idea of adversarial examples was firstly proposed in [5] in white-box manner. After that, a number of white-box schemes for adversarial examples were appeared, e.g., FGSM (fast gradient sign method) [6], DeepFool (fool deep networks) [7], BIM (basic iterative method) [8], PGD (projected gradient descent) [9], Universal attack [10]. In these schemes, perturbations were added towards negative direction of the sign of gradient of the cost function of the target networks. In this way, classification results of target networks can be quickly changed. On the other hand, adversarial example schemes in black-box manner were also developed, e.g., ZOO (zeroth order optimization) attack [11],

[1]Corresponding Author: Zichi Wang, wangzichi@shu.edu.cn.

Boundary attack [12], One pixel attack [13], Biased boundary attack [14], Square attack [15]. In these schemes, perturbations were depending on the final decision of the target networks. Network parameters were unknown to the attacker.

Existing adversarial examples were designed against neural networks. As shown in Fig. 1 (a), a trained network correctly classify the input image into the "panda" category, which is the same with the judgement of humans. After adversarial example generated and input the image with perturbations into the same network, the obtained category will not be "panda". Although content of the adversarial image is still panda from the perspective of humans, the prediction of neural network is significantly changed. This kind of adversarial examples are designed against neural networks, which aims to make neural networks misclassify. In this paper, we propose a new kind of adversarial examples which against human visual system instead of against neural networks. As shown in Fig. 1 (b), the human visual system correctly classify the input image into the "panda" category, which is the same with the prediction of neural networks. After adversarial example generated, the judgement of humans on the adversarial image will not be "panda". But from the perspective of neural networks, content of the adversarial image is still panda.

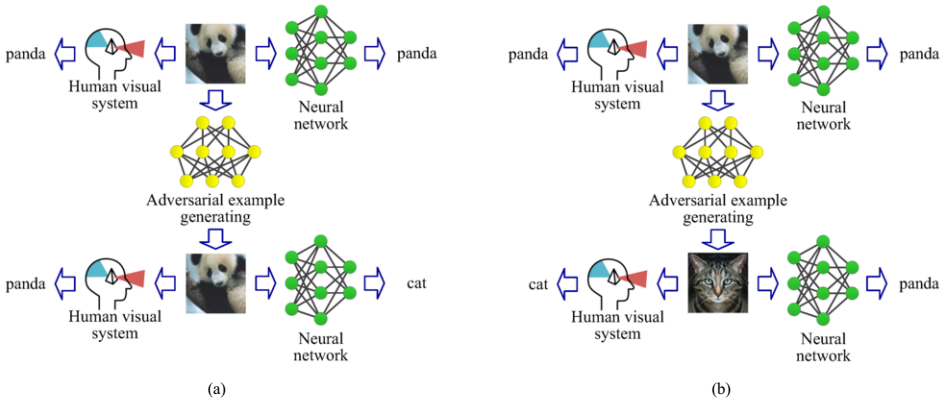


Figure 1. Adversarial examples against (a) neural networks: aims to make neural networks misclassify, and (b) human visual system: aims to make humans misclassify.

The contributions of this paper are listed as follows:

(1) We propose a new kind of adversarial examples. Different with existing adversarial examples which aims to make neural networks misclassify, our method is designed to make humans misclassify.
(2) We design a network to generate adversarial images which can fool humans. The judgement of humans on the adversarial image will be significantly different with that on the original image.

2. Proposed Method

Existing adversarial examples were designed to make neural networks misclassify. We propose an adversarial example method to make humans misclassify. This type of ad-

versarial example is promising and may be useful in controlled scenarios, e.g., artificial image authentication, artificial ticket checking.

2.1. Motivation

In our method, the adversarial images are used to fool human visual system. To obtain the desired adversarial images, we design an image generating network based on CapsNets (capsule networks) [16]. CapsNets perform satisfactory classification accuracy in some popular image sets with the proposed routing-by-agreement mechanism. In addition, a decoder is designed for input image reconstruction to help the task of image classification. That is to say, the tasks of image classification and image generating are jointly executed in CapsNets. Inspired by this, we design a CapsNets based network to generate the adversarial images (image generating task) that can make humans misclassify and keep the prediction of neural networks unchanged (image classification task).

For other kinds of image generating network models such as GANs (generative adversarial networks) [17], the tasks of image classification and image generating are also jointly executed. But the guidance of image generating is difficult to build. This is because that our goal is to make humans misclassify, but it is hard to simulate the process of image classification of human visual system. For example, the discriminator is the guidance of image generating in GANs. To make humans misclassify, discriminator should be designed to replace human visual system and should be differentiable in mathematics, which is a difficult task. Using CapsNets, it is unnecessary to simulate human visual system. The guidance of image generating can be achieved by directly using a target image. Details of adversarial example generating will be described in next subsection.

2.2. Adversarial example generating

The architecture of adversarial example generating is shown in Fig. 2. An original image $\mathbf{X}_o$ is input into the adversarial network N_a to obtain the adversarial image $\mathbf{X}_a$ under the guidance of target image $\mathbf{X}_t$ ($\mathbf{X}_t$ is classified differently with $\mathbf{X}_o$ by humans). Meanwhile, original image $\mathbf{X}_o$ and adversarial image $\mathbf{X}_a$ are respectively classified by existing classification network N_c. Then, the classification results $R(\mathbf{X}_o)$ and $R(\mathbf{X}_a)$ should be the same. Thus, adversarial examples against human visual system can be achieved, since the judgement of humans on $\mathbf{X}_a$ has changed while the judgement of N_c on $\mathbf{X}_a$ has not.

To let humans misclassify and keep prediction of neural networks unchanged simultaneously, two goals should be achieved. Firstly, semantic information (captured by human visual system) of the adversarial image $\mathbf{X}_a$ should be same with that of target image $\mathbf{X}_t$. In this way, judgement of humans on $\mathbf{X}_a$ will be significantly different with that on the original image $\mathbf{X}_o$. For this purpose, a loss L_1 is defined in Equation (1) to guarantee satisfactory quality of $\mathbf{X}_a$. Smaller L_1 means $\mathbf{X}_a$ is more similar to $\mathbf{X}_t$.

$$L_1 = ||\mathbf{X}_a - \mathbf{X}_t||^2. \tag{1}$$

Secondly, from the perspective of neural networks, content of $\mathbf{X}_a$ should be unchanged compared with $\mathbf{X}_o$. That means $R(\mathbf{X}_o)$ and $R(\mathbf{X}_a)$ should be the same. To this end, a loss L_2 is defined in Equation (2) to guarantee $R(\mathbf{X}_o)$ is same as $R(\mathbf{X}_a)$.

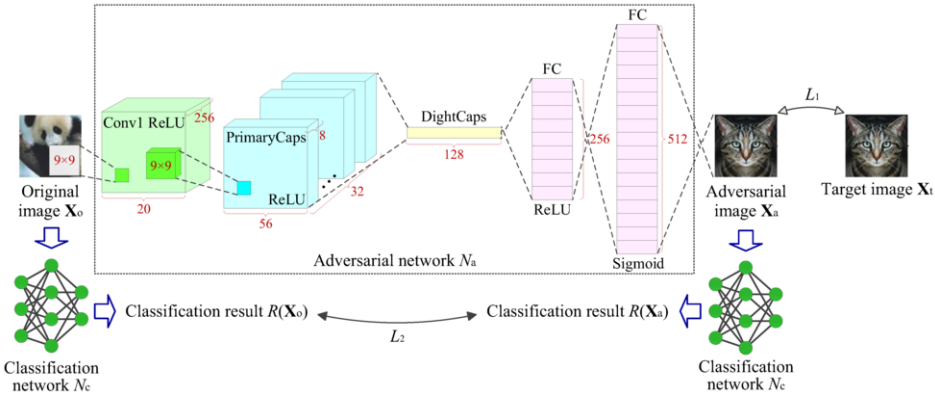


Figure 2. Architecture of adversarial example generating, which aims to let humans misclassify and keep prediction of neural networks unchanged simultaneously.

$$L_2 = -\sum_{i=1}^{n} p_o(i) log[p_a(i)], \tag{2}$$

where n is the number of classes of original images, $p_o(i)$ and $p_a(i)$ are the probabilities of $\mathbf{X}_o$ and $\mathbf{X}_a$ belonging to the i-th class, respectively, $i \in \{1, 2, \ldots, n\}$. Thus, the relationships between $p_o(i)$ and $R(\mathbf{X}_o)$, $p_a(i)$ and $R(\mathbf{X}_a)$ are,

$$R(\mathbf{X}_o) = arg\max_i p_o(i), \tag{3}$$

and

$$R(\mathbf{X}_a) = arg\max_i p_a(i). \tag{4}$$

Finally, the total loss L of our method is defined as the weighted summation of L_1 and L_2, as shown in Equation (5),

$$L = \beta \cdot L_1 + (1 - \beta) \cdot L_2. \tag{5}$$

Parameter $\beta \in [0, 1]$ is used to adjust the weights of L_1 and L_2. Large value of β is advantageous to image generating but disadvantageous to classification, and vice versa. The value of β will be discussed in experiments. In addition, parameters of classification network N_c are kept unchanged in our method. During training process, only the parameters of adversarial network N_a will be updated.

For network structure, N_c can be one of the existing classification networks, e.g., AlexNet [18], VGG [19], ResNet [20], DenseNet [21]. The adversarial network N_a based on CapsNets is designed to convert $\mathbf{X}_o$ into a different version $\mathbf{X}_a$. The original version of CapsNets is designed for image classification. We adjust the network structure to make it is suitable for the tasks of image generating, as shown in Fig. 2. Original version of CapsNets contains two convolutional layers (Conv1 layer and PrimaryCaps layer) and one fully connected layer (DigitCaps layer). In Conv1 layer, 256 convolutional kernels (9×9) with stride 1 and ReLU activation are used. PrimaryCaps layer is a convolu-

tional capsule layer containing 32 capsules. Each capsule contains 8 convolutional kernels (9×9) with stride 2 and ReLU activation. The last layer DigitCaps contains 10 capsules sized 16D. Each capsule stands for an image class and is connected with all capsules in PrimaryCaps. Capsule norm stands for the existence possibility of the corresponding image class. Except of network structure, the strategy of parameter updating of CapsNets is also different with other kinds of neural networks. For network training, a routing-by-agreement mechanism is designed and executed between PrimaryCaps layer and DigitCaps layer to enlarge the active features and ignore the negative ones.

In our method, the layer of DigitCaps contains only one capsule since we do not aim to image classification. Input images can be regarded as one category. Then, the size of DigitCaps is set as 128D to capture more information about $\mathbf{X}_o$ and to achieve a better quality of $\mathbf{X}_a$. For Conv1 layer and PrimaryCaps layer, corresponding setting parameters are adjusted to fit image generating (values are marked with red in Fig. 2). The parameter values are set for MNIST dataset in which the original images sized 28×28. For other datasets, parameter values should be corresponding calculated according to the size of capsule. Finally, two fully connected layers sized 256D and 512D are used to generate $\mathbf{X}_a$ from the features in DigitCaps.

3. Experimental Results

To verify the effectiveness of our scheme, a series of experiments are conducted in this section.

3.1. Experiment setup

In our experiments, four image sets, e.g., MNIST [22], smallNORB [23], CIFAR-10 [24], and ImageNet [25], are employed. All images in the four sets are used as $\mathbf{X}_o$ for training since the task of our scheme is not prediction, as in image classification. The purpose of training in our scheme is to produce adversarial images. The adversarial images should make humans misclassified and keep the prediction of a given image classification network N_c unchanged. In our experiments, three kinds of popular network models, e.g., VGG16, ResNet50, and DenseNet121, are employed. The pre-trained versions of these networks are respectively used as N_c directly. In the whole process of training, parameters in N_c are kept unchanged. In other words, we aim at produce adversarial images without modify the image classification network N_c. We conduct experiments using TensorFlow under the environment of Python 3.8 on a Windows 10 system with a GPU: NVIDIA GeForce RTX 2080 Ti, 11 GB. The Adam optimizer [26] is used for optimization.

3.2. Parameter Determination

The parameter β in Equation (5) balances the performances between image generating and classification. To determine the value of β, a group of experiments are conducted on MNIST dataset with a batch size of 50 and 300 epochs. Classification network N_c was constructed by VGG16. Original image $\mathbf{X}_o$, adversarial image $\mathbf{X}_a$ and the corresponding classification accuracy of network N_c were shown in Fig. 3. Since parameters of N_c are kept unchanged during training, original performance of N_c is not the key point of our method. The classification accuracy here is the ratio that $R(\mathbf{X}_o) = R(\mathbf{X}_a)$. In addition,

several quantitative measures, i.e., PSNR (peak signal-to-noise ratio), SSIM (structural similarity index measurement) [27], and NCC (normalized cross-correlation) [28] of the corresponding images were also calculated to improved the discussions of experiment analysis and conclusion, as listed in Table 1. A higher value of PSNR, SSIM, or NCC means better image quality, $0 < PSNR \leqslant +\infty$, $0 \leqslant SSIM \leqslant 1$, $-1 \leqslant NCC \leqslant 1$.

β	0.1	0.3	0.5	0.7	0.9	1
$\mathbf{X}_o$						
$\mathbf{X}_a$						
Accuracy	100%	100%	100%	100%	100%	44%

Figure 3. Images and classification accuracy with different β.

Table 1. PSNR, SSIM, and NCC between $\mathbf{X}_a$ and $\mathbf{X}_o$ with different β.

β	0.1	0.3	0.5	0.7	0.9	1
PSNR (dB)	10.1	9.5	10.9	10.9	11.1	10.5
SSIM	0.4085	0.3243	0.3747	0.3581	0.4513	0.3372
NCC	0.7702	0.7364	0.8022	0.8065	0.8156	0.7895

It can be seen in Fig. 3 that the classification accuracies were achieved 100% in most cases, even for a great value of β such as 0.9. That means the predictions of N_c on original image $\mathbf{X}_o$ and adversarial image $\mathbf{X}_a$ were the same. Meanwhile, it is clear that $\mathbf{X}_o$ and $\mathbf{X}_a$ will be classified into different categories by humans. It gives the credit to the strong fitting ability of adversarial network N_a. On the other hand, the classification accuracy cannot maintain 100% when $\beta > 0.9$. From Table 1, we can see that the quality indicators between $\mathbf{X}_a$ and $\mathbf{X}_o$ were very low for all cases. That means the content of adversarial image $\mathbf{X}_a$ is clearly different with that of original image $\mathbf{X}_o$. Thus, our method is able to produce adversarial images to fool human visual system. With overall consideration, the value of β is determined as 0.9 to guarantee satisfactory adversarial image quality and classification accuracy simultaneously.

3.3. Adversarial image quality and classification accuracy

To validate the efficacy of our method, we employed datasets MNIST, smallNORB, CIFAR-10, and ImageNet to train our adversarial network N_a with $\beta = 0.9$. The corresponding classification network N_c was constructed by VGG16, ResNet50, and DenseNet121 respectively. Original images $\mathbf{X}_o$, adversarial images $\mathbf{X}_a$, and the corresponding classification accuracies of N_c were shown in Fig. 4. Corresponding values of PSNR, SSIM, and NCC were listed in Table 2.

The results in Fig. 4 indicate that the quality of adversarial images was satisfactory and can be classified into a different class with original image by humans. Where "satisfactory" means the content of adversarial image $\mathbf{X}_a$ is significantly different with that of original image$\mathbf{X}_o$, which can be observed in Table 2. In this way, the obtained adversarial images can be misclassified by humans. We have not execute user studies or empirical

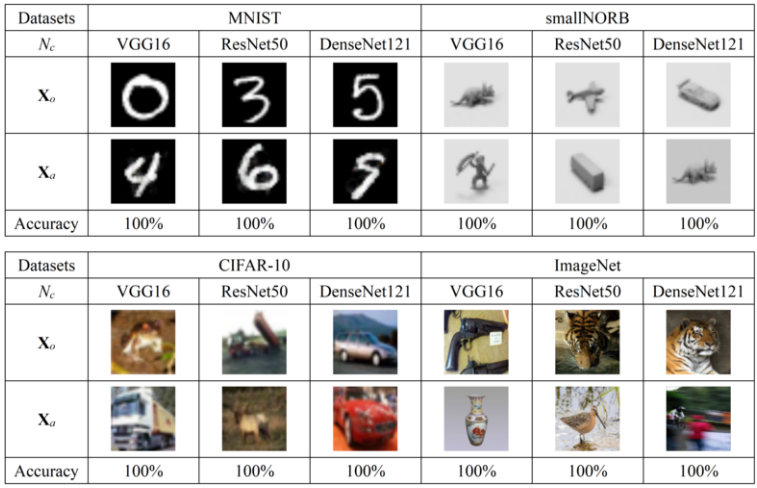


Figure 4. Image quality and classification accuracy with different datasets with $\beta = 0.9$.

Table 2. PSNR, SSIM, and NCC between $\mathbf{X}_a$ and $\mathbf{X}_o$ with different datasets and networks.

Datasets		MNIST			smallNORB	
Networks	VGG16	ResNet50	DenseNet121	VGG16	ResNet50	DenseNet121
PSNR (dB)	11.1	11.0	9.2	16.8	18.3	17.8
SSIM	0.4513	0.3265	0.2868	0.3651	0.4362	0.3544
NCC	0.8156	0.8050	0.7233	0.5599	0.6467	0.6807
Datasets		CIFAR-10			ImageNet	
Networks	VGG16	ResNet50	DenseNet121	VGG16	ResNet50	DenseNet121
PSNR (dB)	11.3	8.3	10.5	10.6	7.1	10.2
SSIM	0.2870	0.2102	0.2062	0.2579	0.2397	0.2283
NCC	0.6332	0.4631	0.6204	0.6246	0.5398	0.6289

evaluation with human participants. There is almost no ambiguity that the adversarial images produced by our scheme can be easily misclassified by humans, since it is classification on semantic level. It is clear that for a given original image $\mathbf{X}_o$, after processed by adversarial network, semantic information of the obtained adversarial image $\mathbf{X}_a$ is completely different. This result is observed from the perspective of humans. However, from the perspective of neural networks, semantic information of adversarial image is the same with that of original image. It can be seen from Fig. 4 that predictions of classification network on adversarial images were the same with those on original image since the classification accuracies were 100% in all cases. Therefore, our method is effective to fool human visual system without changing the predictions of neural networks.

3.4. Further discussion

In our scheme, CapsNets is selected as the generator. For generation task, other modern generative models like GANs [29, 30] or diffusion networks [31, 32] are also effective. Compared with GANs and diffusion networks, CapsNets is a simple kind of network for image generation. Quality of the image generated by GANs and diffusion networks

may be better than that of CapsNets, since GANs and diffusion networks perform strong adversarial robustness [33]. In this paper, we employ CapsNets to show that generating adversarial examples against human visual system is an easy task, and CapsNets here is just an example.

In the field of artificial intelligence, performances of neural networks such as classification accuracy are evaluated by the subjective opinion of human beings. For example, labeled images are used to calculate classification accuracy of neural networks. The labels (what class do the corresponding image belongs to) are determined by what humans see. Adversarial example means the judgments of neural network and a human are different. In this case, it is hard to say whether the neural network or the human made the wrong judgment. This is because that visible spectrum is only a small part of the whole electromagnetic spectrum. It may be unreasonable to evaluate the performance of neural networks from a human perspective. Rebuilding the evaluation system in the field of artificial intelligence may be an interesting problem. In our evaluation system, subjective opinion of human beings is employed. But the perspective of artificial intelligence is different with that of human beings. For this reason, the current evaluation system in the field of artificial intelligence may not be accurate.

4. Conclusion

Existing adversarial examples aims to make neural networks misclassify. We propose a new kind of adversarial examples aims to make humans misclassify which can be used for the goal of attack in some artificial scenarios. To obtain the desired adversarial images, we design an image generating network by improving CapsNets. The generated adversarial images can make humans misclassify and keep the prediction of neural networks unchanged. Experimental results show that judgement of humans on adversarial image is different with that on the original image. Meanwhile, predictions of neural networks on adversarial image and original image are the same. In future work, it is interesting to adjust the evaluation system of artificial intelligence.

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An Interpretable Hybrid Expert–Deep Learning Framework for Automated SEO Ranking Optimization

Imane BELABED[1]
University Mohammed the First, Oujda, Morocco

Abstract. Search Engine Search Engine Optimization, SEO is widely used to improve the visibility of web pages in search engine results. However, many current SEO approaches rely either on fixed expert rules, which are difficult to adapt, or on machine learning models that act as black boxes and provide little explanation for their predictions. In this work, we propose a hybrid SEO framework that combines expert system reasoning with data-driven learning in order to support automated and interpretable ranking optimization. Specifically, the framework integrates explicit SEO rules with machine learning models trained on real search engine results. Experiments were conducted using a SERP dataset of 4,000 web pages with known ranking positions. Several baseline methods were considered, including a rule-based system, a multilayer perceptron MLP, Random Forest, and a gradient-boosted learning-to-rank model. Results on a held-out test set show that learning-based models clearly outperform expert rules alone. In particular, the Random Forest model achieved the best performance with RMSE = 2.47, R^2 = 0.26, compared to the rule-based baseline RMSE = 3.43. Moreover, cross-validation and statistical tests confirm that these improvements are stable and statistically significant ($p < 10^{-5}$). Consequently, the proposed framework clarifies the influence of SEO factors on ranking, allowing accurate predictions without sacrificing transparency.

Keywords. Deep learning, SEO, system expert, neural network.

1. Introduction

SEO plays a major role in determining the visibility on search engine results pages. Traditionally, optimization has relied on expert judgment and manual actions, including keyword selection and metadata refinement. However, these methods are difficult to scale [1]. They are often limited in responsiveness to frequent changes in ranking algorithms.

To overcome these limitations, recent research has increasingly explored machine learning and deep learning approaches for SEO automation [2]. These methods are capable of modeling complex ranking patterns and improving prediction accuracy. Nevertheless, they also raise important concerns. Many deep learning–based SEO systems function as black boxes, offering little insight into how decisions are made. Due to this, it might be challenging for practitioners to understand or implement the

[1] Corresponding Author, Imane BELABED, University Mohammed the First, Oujda, Morocco; Email: belabedimane@gmail.com

recommendations that are produced. Furthermore, purely data-driven models may not generalize well across various queries, domains, or ranking contexts and may overfit particular datasets [3].

Models that achieve high predictive accuracy are often difficult to interpret, whereas rule-based approaches remain easy to understand but lack flexibility. As a result, most existing methods emphasize one of these aspects rather than addressing both simultaneously. This limitation highlights the need for hybrid approaches that integrate expert knowledge with learning-based models. In this study, we follow this direction and introduce a framework that links expert reasoning with deep learning to produce SEO recommendations that are both effective and easy to interpret.

2. Literature review

The following section provides an overview of Search Engine Optimization, its current applications of data-driven and rule-based methods, ranking algorithms and reviews previous research to analyze the major factors influencing web content ranking.

2.1. Seo applications

Conventional SEO depends on manual strategies including keyword selection, optimization of meta tags, link construction, and enhancement of site architecture. Solihin [4] identifies essential on-page and off-page elements that influence rankings. Whereas, S. Sharma et al. [5] examine a range of SEO tools and hybrid assessment techniques. Despite their effectiveness, these manual methods tend to be complex, challenging to scale, and less responsive to regular algorithm changes.

2.2. Data driven ranking methods

Machine learning and deep learning have revolutionized SEO by automating tasks related to ranking and prediction. Joachims [6] introduced learning-to-rank models, notably RankSVM. Also, Nuradilla et al. [7] implemented Random Forests along with mutual information for the classification of SEO features. Finally, recent research, including studies by Amara et al. [8] and Xu et al. [9], has utilized deep learning techniques for image SEO and hybrid text-ranking, showcasing the effectiveness of integrating heuristic and neural methodologies to create more precise and flexible ranking systems.

2.3. Hybrid and Explainable AI Frameworks

Hybrid approaches seek to combine the adaptability of machine learning with the interpretability of expert reasoning. Recent work on AI-enabled SEO highlights the growing need for systems that are not only accurate, but also explainable and actionable for practitioners [10], [11]. While interpretability techniques such as SHAP are increasingly used to analyze neural models [12]. However, interpretability techniques alone do not ensure domain-aligned predictions. As a result, current SEO solutions often rely either on fixed rules, which are transparent but rigid, or on learning-based ranking models, which are flexible but opaque. This gap motivates hybrid SEO frameworks that

explicitly integrate expert rules with data-driven ranking prediction to improve performance while keeping decisions understandable and practically useful.

3. Methodology

3.1. System architecture

The framework is implemented in Python and follows a hybrid approach that links expert reasoning with learning-based ranking prediction. As shown in Figure 1, it is organized around three main elements: an expert system, a learning component, and an integration layer that combines their outputs.

The system operates on SERP-level data collected from 4,000 web pages. Each data instance includes query terms, page titles, snippets, URLs, ranking positions, and indicators related to competition. All components rely on the same feature set, ensuring that expert evaluation and model prediction are based on consistent inputs.

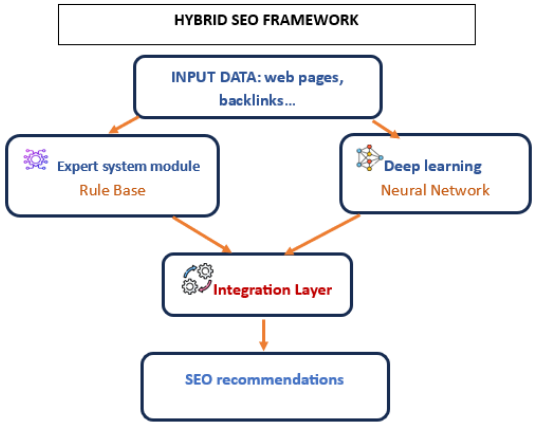


Figure 1: SEO hybrid framework

- Expert system module

The expert system encodes common SEO best practices through a small set of simple and interpretable rules. Each rule evaluates a specific aspect of page quality, such as title length, snippet structure, HTTPS usage, and query competition. Together**,** these positive and negative rule contributions are combined into an overall expert score, providing a clear and transparent measure of SEO relevance.

- Deep learning

The learning component simulates nonlinear relationships between SEO features and ranking positions. A MLP serves as the primary neural baseline, with tree-based models included for comparison. The MLP has two hidden layers (64 and 32 neurons) and employs ReLU activation functions. Training is done using the Adam optimizer (learning rate = 0.001) and mean squared error loss. The dataset is divided into 80% training and 20% testing, and five-fold cross-validation is used to evaluate model stability.

- Integration layer

The final ranking score is calculated using a weighted combination of expert reasoning and model prediction:

$$S_{hybrid} = \alpha \cdot S_{expert} + \beta \cdot S_{model}, \quad where\ \alpha + \beta = 1. \tag{1}$$

where S_{expert} denotes the expert score and S_{model} the normalized output of the learning model.

3.2. Evaluation Protocol

To measure performance, RMSE, MAE, and R^2 are computed on an independent test set. Model stability and statistical significance are further examined using five-fold cross-validation and paired tests against the rule-based baseline.

Overall, the methodology supports reliable evaluation and practical deployment by clearly defining expert rules, model architectures, and integration mechanisms.

4. Results and interpretation

4.1. Performance on the Hed-out test set

Model performance was examined using an independent test split, with numerical results summarized in Table 1 and error trends shown in Figure 2. Overall, the rule-based expert system performs poorly, with an RMSE of 3.43, an MAE of 2.88, and a negative R^2 (−0.43), which indicates that expert-defined heuristics alone fail to capture SERP ranking behavior.

By comparison, learning-based models show clear improvements. For instance, the MLP reduces prediction error to some extent (RMSE = 2.76, R^2 = 0.07); however, stronger gains are observed with tree-based approaches. In particular, Random Forest achieves the lowest error overall (RMSE = 2.47, MAE = 2.04, R^2 = 0.26), while XGBoost yields comparable results. As illustrated in Figure 2, these differences highlight the advantage of data-driven ranking models over rule-based methods.

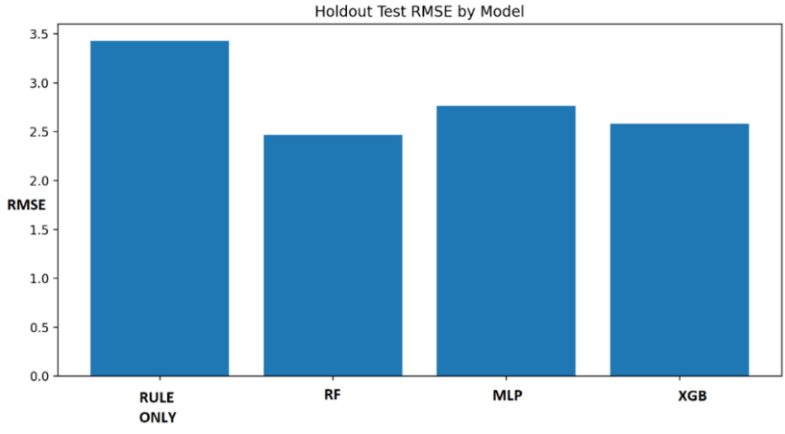


Figure 2: Test-set performance comparison.

Table 1. Extracted SEO features.

Model	RMSE	MAE	R^2
Rule based	3.43	3.43	-0.43
MLP	2.76	2.27	0.07
Random forest	2.47	2.04	0.26
XGboost	2.58	2.16	0.19

4.2. Performance on the Hed-out test set

To examine stability, model behavior was analyzed using five-fold cross-validation on the training data. Summary statistics are reported in Table 2, while variability across folds is illustrated in Figure 3. Once again, the rule-based approach performs the worst, with a mean RMSE of 3.35 ± 0.05 and a negative mean R^2 (−0.37 ± 0.05), suggesting limited robustness.

The MLP reduces prediction error compared to the rule-based approach, but its results fluctuate across folds (RMSE = 2.81 ± 0.07), suggesting limited stability. Models based on decision trees behave differently. Random Forest delivers the most reliable performance, with the lowest average RMSE (2.58 ± 0.06) and the highest mean R^2 (0.19 ± 0.05). XGBoost follows a similar trend, though with slightly higher error.

Figure 3 shows that these models maintain their advantage over the rule-based baseline across all folds, indicating better generalization.

Table 2. Five-fold cross-validation results mean ± standard deviation

Model	RMSE Cross validation	MAE Cross validation	R^2 Cross validation
Rule based	3.35 ± 0.05	3.35 ± 0.05	3.35 ± 0.05
MLP	2.81 ± 0.07	2.81 ± 0.07	2.81 ± 0.07
Random forest	**2.58 ± 0.06**	**2.58 ± 0.06**	**2.58 ± 0.06**
XGboost	2.63 ± 0.05	2.63 ± 0.05	2.63 ± 0.05

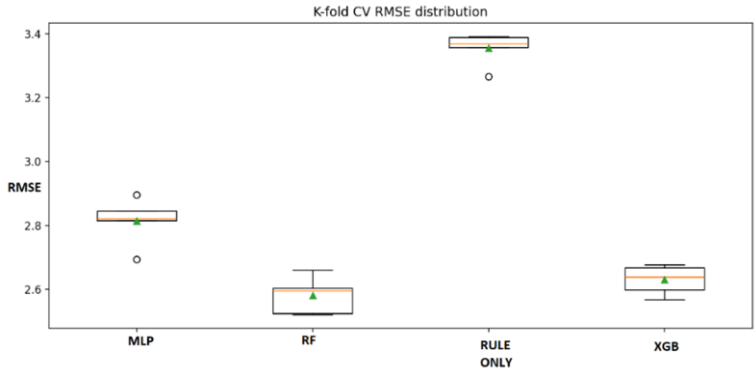


Figure 3: Distribution of RMSE values across five cross-validation folds for all evaluated models.

Model robustness was examined using five-fold cross-validation, with summary results shown in Table 2 and performance variability illustrated in Figure 3. The rule-based approach performs poorly and inconsistently, whereas ensemble models especially Random Forest and XGBoost show lower error and more stable behavior across folds, outperforming both expert rules and the MLP.

4.3. Prediction behavior and interpretability

The predicted-versus-actual ranking plot in Figure 4 shows strong agreement between model predictions and true rankings for the best-performing model. As illustrated in Figure 5, ranking predictions are influenced by both content-related features and query-level signals. The presence of the expert score among the important inputs suggests that expert knowledge provides complementary information to the learning process.

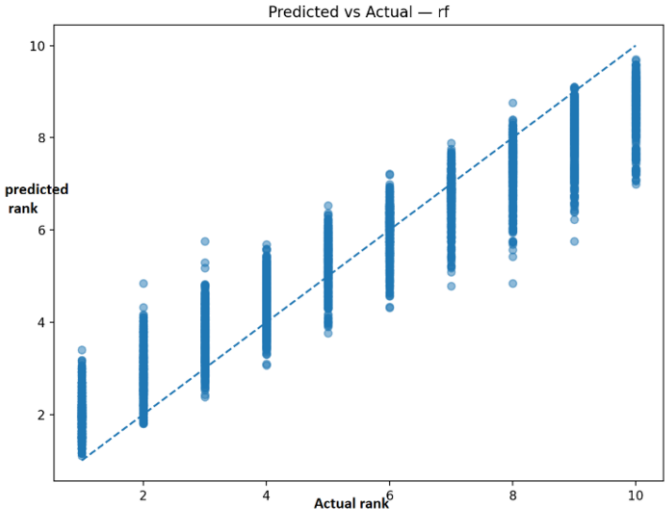


Figure 4: Predicted vs actual rank.

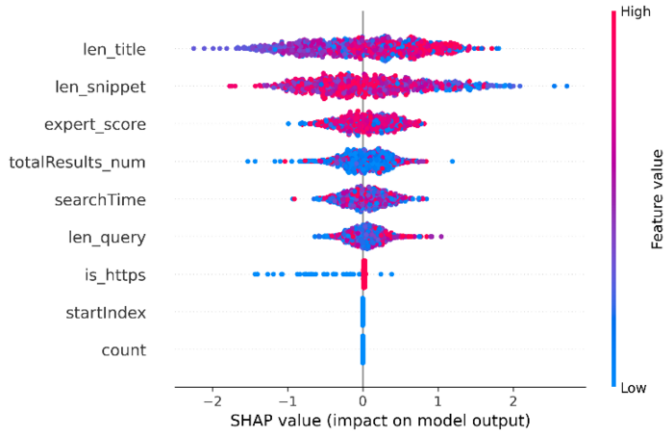


Figure 5: SHAP-based feature importance for SERP and content features.

This result illustrates that expert-derived signals do not replace learning-based models but instead enhance their robustness by injecting interpretable, domain-aligned constraints.

4.4. Statistical significance of improvements

Paired t-tests were used to compare learning-based models with the rule-based baseline. The results in Table 3 show consistently lower errors for all learning-based approaches, with p-values below 10^{-5}, suggesting that the improvements are statistically reliable.

Table 3. Paired t-test results comparing learning-based models with the rule-based baseline

Model	Baseline	T-statistic	P-value	Folds
MLP	2.81 ± 0.07	53	8×10^{-6}	5
Random forest	2.58 ± 0.06	35	8×10^{-6}	5
XGboost	2.63 ± 0.05	56	1×10^{-6}	5

5. Conclusion and discussion

In this study we introduce a hybrid SEO framework that combines expert system reasoning with learning-based models to support automated interpretable ranking optimization. By combining explicit SEO rules with data-driven prediction, the approach improves ranking performance while remaining transparent and practically useful for SEO practitioners. Experiments conducted on a real-world SERP dataset show that learning-based models clearly outperform rule-based heuristics on their own, while expert knowledge adds stability and interpretability to the predictions.

Nevertheless, some limitations should be acknowledged. The expert rules are manually designed and may not fully reflect the continuous evolution of search engine ranking factors. The current evaluation relies on offline SERP data and therefore does not reflect real-time search behavior or short-term changes in user interaction. Generalization across domains and query types remains to be evaluated.

Future work will explore the use of continuously updated data sources and alternative learning models that can better adapt to evolving search environments. Incorporating additional signals, such as user engagement metrics, social context, and competitor information, may further enhance the flexibility and practical relevance of the proposed framework.

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Utilizing Humanoid Robots as Learning Companions in Promoting Foundational Learning

Oskar LORENZ [a,1], Rachel, Ka Syn MAH [a], Janine BRESSLER [a] and Janett MOHNKE [a]

[a] *RoboticLab Telematics, TH Wildau (UAS Wildau), Germany*
ORCiD ID: Oskar Lorenz https://orcid.org/0009-0006-3983-6704, Rachel, Ka Syn Mah https://orcid.org/0009-0005-0306-1567, Janine Breßler https://orcid.org/0000-0002-5472-4376, Janett Mohnke https://orcid.org/0000-0002-1664-2150

Abstract. Obtaining basic literacy and numeracy are important foundations for all further learning in life. Ideally, these skills are obtained early on in school. But why should learning of such important skills stop there? We utilize the humanoid robot NAO from Aldebaran Robotics to motivate children to read more and with joy, extending learning to pastime activities. For this, an application – *LeseNAO* – was developed by the RoboticLab Telematics that allows children to read a book to NAO out loud and optionally has NAO question them on what they just read. During evaluations, we noticed that children become relaxed and feel comfortable reading out loud to NAO due to its friendly and funny demeanor. Case studies also suggest a positive impact of the NAO robot on learning. To expand on this idea, we transferred the same principles to another important area of learning: math. For now, with the *MatheNAO* application, children can train their multiplication tables or test their knowledge on basic geometry. In preliminary tests of a multiplication quiz feature with children in fifth grade, overall, active attention towards the NAO robot and a high level of engagement in the task was observed. The children had fun learning with NAO. The same principle can also be applied to adults with low literacy or numeracy, potentially having the same comforting and encouraging effect. Building on this foundation, we present additional concepts and projects utilizing the NAO robot to promote learning. The software is made available under an open-source license to support further research.

Keywords. humanoid robotics, educational robotics, social robotics, reading promotion, digitalization in education, NAO robot, experience report

1. Introduction

"Tell me and I forget, teach me and I may remember, involve me and I learn."
— Benjamin Franklin

[1] Corresponding Author: Oskar Lorenz, oskar.lorenz@th-wildau.de

Foundational skills in reading and mathematics form the base of all further learning throughout a person's life. Recognized as a global priority by organizations such as UNESCO, early acquisition of literacy and numeracy is essential not only for academic success but also for participation in society and the workforce. While schools provide the primary setting for developing these competencies, the motivation to practice and extend these skills beyond the classroom remains a persistent challenge, particularly for children, but also for adults with low literacy or numeracy levels. [1,2,3,4,5,6]

Humanoid robots have emerged as a promising tool for engaging learners in educational contexts. Their physical presence, expressive behavior, and ability to interact naturally make them uniquely suited as motivators. The NAO robot, a humanoid robot developed by Aldebaran Robotics (now Maxtronics Robotics) [7], has been successfully deployed in various educational settings and has demonstrated a positive impact on learning engagement. [8,9]

Keller's ARCS model of motivation is a useful framework for describing its motivational role. [10] This model distinguishes four factors: Attention, Relevance, Confidence, and Satisfaction. In the context of humanoid learning companions, the NAO robot illustrates these dimensions well. NAO's physical presence, naturally appealing look, engaging speech, and gestures support attention, resulting in an overall playful interaction style. Relevance arises from embedding interactions in meaningful learning activities such as reading aloud, practicing multiplication tables, and handling everyday numeracy tasks. Confidence is fostered through NAO's patient and nonjudgmental programmed behavior, which reduces the fear of making mistakes when learners read aloud or answer quiz questions. Finally, satisfaction is promoted by providing encouraging feedback, recognizing successful task completion, and ensuring an enjoyable interaction experience with the robot.

Building on this foundation, the RoboticLab Telematics at the Technical University of Applied Sciences Wildau developed *LeseNAO*, an open-source application [11] that encourages children to read aloud to NAO and, optionally, answer comprehension questions. Case studies [8,9] and our informal field tests [12] suggest that children feel relaxed and motivated when reading to NAO, owing to its friendly and approachable behavior.

Inspired by the success of *LeseNAO*, we extended the same pedagogical principles to the domain of mathematics, resulting in *MatheNAO*, which is an application designed to help children practice multiplication tables and basic geometry through interactive engagement with NAO. Preliminary tests with fifth-grade students showed high levels of attention and enthusiasm, suggesting that the motivational effect of humanoid robots can also apply to numeracy training. [13] Furthermore, these applications hold potential for adult learners with low literacy or numeracy, where a non-judgmental and encouraging robotic tutor may provide a particular benefit.

This paper presents both applications, reflects on our years of practical experience with NAO as a learning companion, and discusses the broader potential of humanoid robots as extensible platforms for foundational education across multiple disciplines and languages. As computer scientists, our view on this matter is mainly technical in nature. This paper does not present a controlled study on qualitative or quantitative metrics regarding motivation or learning tasks on motivation.

2. Practicing Reading and Writing with NAO

The longest running and most studied project by the RoboticLab Telematics in educational humanoid robotics is the *LeseNAO*[2] application. Its start in 2018 simultaneously marks the starting point for our research in this field. [14]

The *LeseNAO* application encourages children to read a book out loud to a NAO robot. While a child is reading, NAO simulates attentive listening and has a friendly, occasionally funny, and encouraging expression. This behavior is primarily conveyed through the way the NAO robot talks and moves its body. To further strengthen their reading skills, the children have the option to take a reading comprehension test after they finished reading. This test consists of multiple choice questions on the read content. The answer to each question is selected via a tablet. During this quiz, the NAO robot demonstrates an equally comforting and positive behavior to keep the children engaged in the quiz while providing a non-judgmental environment. In instances where children experience anxiety or apprehension in practicing their reading skills, this environment can help facilitate such activity. A field test with children attending preschool to fourth grade was conducted at the end of 2018. [12] We observed that the children were relaxed, focused on the NAO robot and quickly became open-minded towards the task while the *LeseNAO* application was active. Figure 1 captures some impressions of this initial field test.



Figure 1. Some impressions from the first field test of the *LeseNAO* application with children.

Over the years, starting in 2020, the *LeseNAO* application was adapted to and deployed in five public libraries and one elementary school across Germany. The RoboticLab Telematics provided support with the initial installation and resources to allow for an independent operation. The public library of Frankfurt am Main were the first to adopt the *LeseNAO* application by holding reading events with the NAO for groups of children during the COVID-19 pandemic. During this time, we received more valuable feedback and were able to continuously test and further improve the application. The application was well received, the program was awarded the "Deutsche Lesepreis" (a German reading award) [15] and is still in active use today. The project thereby demonstrates the high potential of utilizing humanoid robots, and especially the NAO robot with its endearing expression, to promote reading among children. However, it is important to minimize sources of frustration such as, for example, the lack of accuracy of the NAO robot's built-in speech recognition. Our experiences with the robot's native speech recognition module have shown it to be mostly unreliable. Simple phrases such as "yes", "no" and "hello" may get recognized by the robot, given a quiet environment where the robot can clearly capture the voice of the speaker. In real classrooms, this is almost never the case, especially in environments where young children are present. Hence, the built-in

[2]The name is made up from the German word "lesen" meaning "to read".

speech recognition is rarely used in our projects and the NAO robot accepts user input mainly through its sensors or an external application. Since October 2025 a revised version, described in detail in [16], of the *LeseNAO* application is publicly available [11] under an open source software license. [12]

Despite having come a long way, there are still areas where we see room to grow. The *LeseNAO* application is designed for multilingual support and currently provides both German and English translations (including the interactions with the NAO robot). Adding support for other languages should therefore prove to be a painless process and we would love to see an extension to more languages. The application includes a mode for training the children's ability to name the initial sound of a spoken word. However, the NAO robot's speech synthesis does not always produce the correct sounds, rendering this mode ineffective for users to accurately recognize the sounds. A revision of this mode employing recorded sounds or modern speech synthesis technology should allow for a more effective use.

Overall, the initial *LeseNAO* project and the projects it inspired demonstrate the high potential of utilizing humanoid robots to motivate children to improve their reading and writing skills.

3. Learning Mathematics with NAO

Motivated by the success of the *LeseNAO* project, we wanted to transfer this principle to other areas of learning. Thus, another similar and relatively new project in the field of educational robots that has been intensively worked on by the RoboticLab team since June 2024 is the *MatheNAO*[3] application. [13] The project involves a NAO robot which plays the role of a learning companion for elementary school children in mathematics learning. The idea behind this robot is to evoke and encourage interest among young children towards mathematical concepts in a highly engaging and interactive learning environment. Although this project has not yet been deployed in a real-world scenario for the long term, a few experiments and informal field tests have indicated encouraging signals with respect to enjoyment and engagement during the learning session, motivating continued development.

Following a similar concept and architecture as that of the *LeseNAO*, the *MatheNAO* speaks to and engages with users (the children) in an enthusiastic tone and through endearing body gestures. As its main feature, it provides a quiz mode, where the children can attempt questions related to a topic of their choice. To interact with the robot, the children can either use the tactile sensors on the robot's body, or scan quick response (QR) codes by holding them up in front of the robot's eyes, where its cameras are situated. Upon successfully answering each question or by exceeding a certain time limit, the robot would reveal the answer, provide an explanation if the question was answered wrongly, and add one point to the total score if the correct answer was provided within the time limit. To further encourage the children's enthusiasm in the quiz, the robot would give encouraging words to the children if they answered the questions wrongly. [13]

As of March 2026, the robot offers the users two topics and corresponding difficulty levels, which the users can choose from: multiplication tables from one to ten and geometry questions. The first field test was conducted with two groups of ten fifth-graders each

[3]The name is made up from the German word "Mathe" meaning "math".

from the Wildau primary school, who visited the TH Wildau in December 2024. They had the opportunity to participate in a few rounds of the multiplication quiz in teams, where they competed against each other and tracked scores, as well as in one big team, where they had to work together to look for the answer for each question. Throughout the entire session, they showed high levels of engagement, which weren't compromised despite a few technical issues, such as the robot not being able to detect and read the QR codes properly sometimes. Successful detection of the QR codes would require the users to place them at a specific position in front of the robot's camera. In some cases, the children spent a considerable amount of time adjusting the position of the QR code while holding it in front of the robot, which led to mild frustration and impatience. Since then, we have modified the application to provide specific instructions on where the children should place the QR code, and programmed the robot to use its hands to indicate this position. All children explicitly expressed their interest in the potential prospect of such a robot being deployed in their normal school setting. They even cited a few other subjects in which a similar educational robot can be useful such as language classes and science. Another demonstration of the robot's capabilities was carried out with a few members of the school council of Frankfurt (Oder), who were interested in learning about educational robots. Similarly, they expressed a remarkable interest towards the idea behind the *MatheNAO* (and related projects, such as *LeseNAO*) and were envisioning immense future potential in using it in schools to encourage interest among young students towards learning mathematics. The exchange between the RoboticLab Telematics team and the members of the school council yielded practical feedback and suggestions on how to improve the *MatheNAO* application with respect to its technical capabilities, as well as new ideas on topics and features that could offer notable added value for elementary school education. These included adding new interactive components, such as allowing children to answer binary ("true" or "false") questions by touching the sensors on the robot's body, or developing a robot that could teach elementary school students pre-phonic skills, like identifying lowercase and uppercase letters, and the names and pronunciations of each letter, a vital step before teaching children how to read longer words and texts.

Though in an early stage of development, where its topics and features are still limited and occasional technical issues occur, this project has demonstrated strong potential through its powerful concept, accompanied by high engagement levels among those who participated in the field tests and is worth pursuing further.

4. Opportunities of NAO in Adult Education

At the moment, the *LeseNAO* and *MatheNAO* applications are specifically employed to motivate children to learn more and with more joy. However, there is another demographic that could benefit from this principle: adults with low literacy. The *LeseNAO* application can make adults feel less afraid to make mistakes reading out loud to a NAO robot when compared to a human, as it already does for children. Studies on robot-assisted learning environments have shown that adult learners sometimes report feeling less embarrassed and under less pressure to perform well when they make mistakes. This suggests that robotics and technology can serve as a supplement that lowers the barrier to entry. [17,18]

In cooperation with the Cottbus learning center[4], multiple ideas and concepts for utilizing a NAO robot to aid adults with obtaining basic literacy and numeracy were developed, of which some were also implemented. One application has the NAO robot dictate words that then have to be typed in a web interface by the user to help build basic writing skills. The application validates the user's input and the NAO robot provides an encouraging response applying the same principles employed in the *LeseNAO* application's quiz. Within the same cooperation, increasing numeracy levels among adults with low literacy and numeracy was also investigated. The focus was primarily on foundational and financial literacy, where adults could learn basic mathematics and financial management skills from humanoid robots designed to encourage and increase motivation in learning. For example, one project has the NAO robot act as a trading partner allowing the user to interactively learn how to count money with NAO. The user either has to pay the exact amount or give back the correct amount of change in euro banknotes and coins. By practicing with a NAO robot the users feel less pressured and judged while learning and more confident in their everyday life. [19]

5. NAO as an Extensible Learning Platform

The NAO, as an educational robot, can be adapted for many different fields. In addition to its use as a math tutor or a reading motivator, there are other disciplines for which it is well-suited. For instance, an application for working out with NAO was initially developed within the course "Embedded Systems and Robotics II" in the Telematics bachelor's program[5] of the TH Wildau and further advanced by the RoboticLab Telematics. In this application, the NAO acts as a coach, describing and demonstrating fitness exercises while explaining the key criteria for correct posture. The robot's 25 degrees of freedom make this possible by allowing human-like movement. With the NAO robot's speech engine, a scenario, in which the robot is used as a coach for learning a new language, is also conceivable. With a total of 21 language packages [20], where English is active by default and a second language can be added, the NAO has everything it takes to be a valuable asset in this discipline. With the current advances in machine learning, Large Language Models (LLMs) can enhance conversational applications further. They can be used to simulate a natural feeling conversation about the learning content in real-time and support open-ended interactions. Additionally, changes can be applied quickly via Prompt Engineering. [21] At the RoboticLab Telematics, LLMs have already been successfully used for natural language communication between humans and humanoid robots in projects involving the Pepper robot from Aldebaran Robotics [22]. This robot has been successfully deployed at the TH Wildau university library as an autonomous assistant and as a host for a temporary exhibition[6] in the library. [23]

Many other ideas and applications for the NAO robot emerged from the aforementioned course of the Telematics bachelor's degree program. Specific overarching themes were provided to students as a framework. The students then developed individual ap-

[4] A union of the community college and library in Cottbus, Germany.

[5] https://www.th-wildau.de/studieren-und-weiterbilden-1/studiengaenge/telematik-angewandte-informatik-b-eng (in German; accessed May 5, 2026)

[6] https://www.th-wildau.de/hochschule/ueber-uns/geschichte/125-jahre-bahnhof-wildau (in German; accessed May 6, 2026)

Table 1. A selection of NAO projects from the course "Embedded Systems and Robotics II".

Project name	Description
Road Sign Memory Game	In an interactive memory game, pupils compete against the humanoid robot NAO. With every matching pair they find, they gain a practical understanding of road signs, as NAO can capture them with its camera and then explain them in detail. Through playful interaction with the NAO robot, the meaning of road signs is actively explored.
GeoNAO	As part of a geography quiz for primary school children, the NAO robot takes on the role of the quiz host. Specifically, the quiz covers the 16 German federal states. To participate, the children hold up cards featuring the outlines of the relevant states, which NAO recognizes via respective QR codes. True to the motto "Who knows the most about the federal states of Germany?", this project really sparks the children's competitive spirit. Extensions to other areas, rivers or, for example, mountain ranges are also imaginable.
Who Am I?	The classic game "Who am I?" is enhanced by the NAO robot. Its task is to guess terms by asking "yes" or "no" questions. The children act as the experts of the terms to be guessed: the better they answer to the robot's questions, the faster the robot reaches its goal. In this way, primary school children are encouraged to reflect on learning content in a playful manner. By connecting it to a Large Language Model and careful prompt engineering, the system becomes interactive and flexible, allowing knowledge from the classroom to be deepened in an engaging way.
Environmental Detectives	Together with NAO, the children embark on a research expedition to investigate the environmental impact of everyday objects. Using food and traffic scenarios, they learn how their own behavior affects their carbon footprint and apply this knowledge directly by trying to collect as many 'environmental points' as possible. To do this, they have various objects which are examined and evaluated together with NAO. This strengthens the children's environmental awareness, and the modular structure allows the range of objects to be examined to be expanded so that it does not become boring.
SeaSort	Primary school children assist the NAO robot in sorting the contents of a fishing net. They decide which items belong back in the sea and which need to be disposed of as rubbish. The collected rubbish is then further sorted and allocated to the appropriate disposal methods. To do this, the children show the objects to NAO, allowing it to recognize them and provide immediate feedback on whether the disposal method is correct. In this way, the pupils actively apply their knowledge of environmental protection and waste sorting and consolidate it through play.

plication ideas and implemented them in teams. Themes from previous years are, for example, "Educational games for primary school children: playful knowledge transfer with the humanoid robot NAO" and "Climate and sustainability: sustainable knowledge transfer with the humanoid robot NAO". A useful overview of some ideas and applications for the NAO is provided in Table 1. Additionally, Figure 2 provides some visual impressions.



Figure 2. A montage of various student projects with the NAO robot in order as listed in Table 1.

6. Conclusions

This paper has introduced two applications, *LeseNAO* and *MatheNAO*, that leverage the motivational qualities of the humanoid NAO robot to promote basic learning in reading and mathematics. Drawing on field experiences, user observations, and grounded by related work, we observed that children engage actively and joyfully when learning with NAO. The robot's non-judgmental, friendly, and sometimes even humorous interaction with its users seemingly creates an environment in which learners feel comfortable practicing skills they might otherwise find daunting. Another key point is that the approach is not limited to children: adults with low literacy or numeracy may benefit from the same encouraging and patient interaction style that NAO offers. Furthermore, there are 21 different language packages available for the NAO robot, which means that the scenarios described and the software developed as part of our projects can be easily adapted to setups in other countries. While the two applications have signaled a high potential, further research is needed to investigate measurable effects of the *LeseNAO* and *MatheNAO* applications on the motivation of young and adult learners in a controlled environment. Specifically, the effects of these applications on adults with low literacy or numeracy have not been examined. The *LeseNAO* and *MatheNAO* projects have been released as open-source software. [24] It is planned to do so for other projects as well. We warmly invite educators, researchers, and developers to contribute, adapt, and extend these applications within their own contexts. We are happy to support new contributors in getting started. It is our hope that this work encourages further exploration of humanoid robots as accessible, scalable, and motivating tools for lifelong foundational learning and can serve as a base for potential future studies.

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Combining Sentiment Analysis and Topic Models for Analyzing University Users' Interviews on Privacy Concerns in Large Language Models

Heshen Zhou [a], Yu Pei [a] and Muyan Li [b,1]
[a] *School of Public Health, Hubei University of Medicine, Shiyan 442000, China*
[b] *School of Information Management, Wuhan University, Wuhan 430072, China*

Abstract. Large language models (LLMs) provide users with convenience in multiple aspects; they have already been widely used by university users. However, LLMs also bring about many new challenges, among which personal privacy is a major concern. To understand university users' perceptions and attitudes toward the current privacy protection measures of LLMs, we conducted privacy-themed interviews with university LLM users, and applied BERTopic model and sentiment analysis to analyze the interview content. Specifically, we used BERTopic to find major topics among the content of interviews, and applied sentiment lexicon to calculate the sentiment score of each topic. The results indicate that interviewees exhibit a notably positive sentiment toward using LLMs for learning and research, which reflects the significant influence of LLMs on the learning and research paradigms of university users. In terms of privacy concerns in LLM, interviewees express strong positive sentiment toward the regulatory authorities in charge of personal information protection. However, they show obvious negative feelings toward existing preventive measures.

Keywords. Privacy Issues, Large Language Models, User Interview, Sentiment Analysis, BERTopic Model

1. Introduction

Large language models (LLMs) have demonstrated strong performance across multiple fields since their emergence. In general domains, they can efficiently complete daily tasks such as text creation, intelligent Q&A, and code writing. In vertical domains like finance and healthcare, they can also support professional work, including risk assessment and clinical auxiliary diagnosis, effectively improving work and learning efficiency in relevant scenarios. Therefore, LLMs have effectively improved work and learning efficiency in various application scenarios.

However, serious privacy risks have accompanied the wide application of LLMs. From a technical perspective, LLMs rely on massive data resources for training. The data

[1] Corresponding Author: Muyan Li, School of Information Management, Wuhan University, Wuhan 430072, China; Email: limymy@yeah.net
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not only includes a vast amount of content such as books and Wikipedia articles but also covers user-generated communications on platforms like social media, which may contain sensitive personal information and potentially cause privacy leakage incidents [1]. Moreover, the data generated by users during continuous use of LLMs will be used for model optimization. If users input private content during interactions, information disclosure is very likely to occur, which will exert significant negative impacts on both individuals and society [2].

The existing studies on privacy protection in LLMs primarily adopt conventional interview analysis methods (e.g., manual coding, thematic summary) to judge users' attitudes subjectively. Such conventional approaches often rely on researchers' subjective interpretations, making it difficult to fully and objectively extract the hidden thematic information and fine-grained emotional tendencies from interview texts. To address this limitation, this study conducts interviews with university students who have used LLMs as research participants and adopts text analysis methods to extract users' objective emotional tendencies toward LLM privacy protection from interview texts. In detail, we first extract and categorize key topics from the interview texts using the BERTopic model, realizing systematic and objective thematic mining of the interview content. On this basis, we further integrate sentiment analysis methods to quantitatively calculate the sentiment score of each identified topic, thereby exploring users' emotional tendencies toward different aspects of LLM privacy protection.

In terms of research methodology, this study integrates the BERTopic model and sentiment analysis to achieve objective and fine-grained text mining on interview data, which helps to reduce the subjectivity of traditional manual analysis and effectively identify topic-level emotional differences in users' privacy perceptions. In terms of research findings, this study clarifies the specific emotional attitudes of university users toward different LLM privacy-related issues, which can support the improvement of practical privacy protection strategies and promote the safer application of LLMs in learning and research scenarios.

2. Related Works

Privacy concerns have always been an important research direction in the field of information management. With the rapid development of the Internet, more and more users have left their personal information during their use of the Internet, resulting in a massive amount of personal information existing in the Internet environment. Unlike offline privacy, personal information in the digital space features strong replicability, high transmissibility, and a long lifecycle. Once personal information is leaked in the digital space, it is difficult to fully trace and eliminate, driving the shift of digital privacy protection from passive defense to active governance [3]. The leakage of personal privacy can result in various problems. For example, the leakage of personal health information triggers cascading harm: illegal actors with access to medical histories and diagnosis records may sell ineffective health products, commit extortion, or cause employment/insurance discrimination against patients, leading to psychological stress and impaired physical and mental well-being [4]. Meanwhile, exposed financial data such as bank card numbers and asset details may result in telecom fraud, account theft or predatory lending, ultimately bringing severe financial losses to individuals [5].

Unlike traditional privacy risks, LLM-related privacy risks are more concealed and dynamic. They may stem from sensitive information in training data that is memorized by models, or from indirect disclosure through user-shared information during interactions [1]. In particular, the risks posed by these LLMs may even lead to more severe consequences. For example, the strong generative capabilities of LLMs [6] enable them to generate a wealth of inductive content based on the personal information they obtain. Meanwhile, the inherent hallucination issue of LLMs can also lead them to produce plausible yet inaccurate false information [7]. Owing to these characteristics, a series of researchers have reviewed the security and privacy challenges of LLMs in various domains, such as transportation, education, and healthcare [8].

Among these studies focusing on privacy protection methods and their limitations, researchers have typically employed user interviews [9] and literature review [10]. In terms of research topics, current studies on LLM privacy issues have also rarely conducted analysis of users' emotional attitudes. In terms of research methodologies, few scholars have comprehensively integrated textual analysis techniques and user interview methods to address related research questions. Based on this, we apply BERTopic model [11] and sentiment analysis methods [12] into user interviews and conduct a fine-grained analysis and discussion of university users' emotional attitudes during LLMs usage.

3. Methods

To obtain the authentic experiences of university users, we conducted interviews with students from 9 different Chinese universities. A total of 25 students participated, covering undergraduate to doctoral levels. The interview topic covered aspects including user experience and functional cognition, technical mechanisms and information processing procedures, information security risk prevention, rights protection paths, policy cognition and expectations, etc. The shortest interview lasted 21 minutes, and the longest one lasted 56 minutes. We converted the dialogues from the interviews into text using the speech-to-text tool provided by iFLYTEK[2]. This tool can label the content expressed by each interviewee during the conversion process.

When training the topic model, we split the texts according to the dialogue content, taking each complete dialog paragraph as a unit to serve as the basis for subsequent topic mining. Then we applied jieba for word segmentation on the interview texts and used the stop word list published by Harbin Institute of Technology (HIT) [3] to remove meaningless words. In the training of the BERTopic model, we select paraphrase-multilingual-MiniLM-L12-v2 [4] as the word embedding model and set the model parameters to automatically select the number of topics. For the identified topics, we manually verified and selected partial topics that are related to the LLM privacy concerns for subsequent analysis. For words that appeared repeatedly across these topics, we retained the word in the topic where it was most closely associated with and removed it from other topics.

When calculating the sentiment tendencies of interview content, we applied the sentiment lexicon constructed by Dalian University of Technology to explore its sentiment distribution [13]. We assigned 1 to indicate that a word carries positive

[2] https://cloud.iflytekrecord.com
[3] https://github.com/goto456/stopwords
[4] https://huggingface.co/sentence-transformers/paraphrase-multilingual-MiniLM-L12-v2

sentiment, and -1 to indicate that a word carries negative sentiment. For words with both positive and negative connotations, we classified them as neutral words and assigned a value of 0 as their sentiment label. In the sentiment analysis of each interview, we calculated the proportion of sentiment words in each interview's content. In the sentiment analysis of each topic, we extracted all the original texts related to a the topic, and used the sentiment lexicon to calculate the sentiment score for these texts, as shown in Eq. (1), $n_{positive}$ denotes the total number of positive words among original texts, $n_{negative}$ denotes the total number of negative words among original texts.

$$Score = \frac{n_{positive} - n_{negative}}{n_{positive} + n_{negative}} \quad (1)$$

4. Results & Discussion

4.1 Target Topic Words extraction

After the training of the BERTopic model, we finally identified 20 topics. There are some topics that still cannot be used for subsequent analysis, such as Topic 7, which mainly includes words such as *Delete*, *Handle*, and *Do*. Based on this, we selected five topics (Topics 1, 4, 6, 8, and 12) for further analysis. After manually examining the similarity between the topic word lists, we merged Topic 1 and Topic 6. Among these topics, Topic 1 and Topic 6 contained words such as personal information and information security; Topic 4 included words related to learning and scientific research; Topic 8 covered words like regulatory authorities and government; Topic 12 involved words such as preventive measures and protection measures. Partial topic words distribution of merged topics are listed in Table 1.

Table 1 Partial Topic Words Distribution of BERTopic Model

Topic Name	Topic No.	Topic Words
Personal information protection	1 and 6	信息安全(Information Security) 个人信息(Personal Information) 风险(risk) 个人隐私(personal privacy) 隐私(privacy) 安全(security) 保护(protection)
Academic purposes	4	科研工作(research work) 学习(learning) 科研(scientific research) 学术(academic) 研究(research) 文献(literature) 实验(experiment)
Regulatory authorities	8	监管部门(regulatory authorities) 监管(regulation) 政府(government) 法律法规(laws and regulations) 机构(institution) 法规(regulations) 政策(policy)
Preventive measures	12	防范措施(preventive measures) 保护措施(protective measures) 预防为主(prevention-oriented) 防范(prevention) 预防性(preventive) 预防措施(preventive measures)

4.2 The Sentiment Words Ratio Among Interview Content

Among the content of all 25 interviews, we calculated the proportion of sentiment words in each text, which is obtained by dividing the number of sentiment words by the total number of words in the text. Then we tracked the proportion of sentiment words in the relevant texts of interviewers and interviewees respectively. In analyzing overall

interview texts, we treat each interview as a unit. Experimental results found that the proportion of sentiment words ranged from 5.4% to 9.0%, with an average proportion of 7.0% per interview. We then extracted the texts spoken by interviewers and interviewees during the interviews and calculated the proportion of sentiment words. The proportion of sentiment words used by interviewers ranged from 4.8% to 8.6%, with an average proportion of 6.5% per interview; the proportion of sentiment words used by interviewees ranged from 5.4% to 9.6%, with an average proportion of 7.4% per interview. We performed a t-test to analyze the proportion of sentiment words used by the two groups and found that interviewees used sentiment words at a significantly higher frequency than interviewers ($p<0.01$).

Currently, sentiment analysis methods are rarely integrated into interview-based studies. However, integrating these methods into the interview process can not only help assess the level of active engagement among interviewees, but also detect issues such as misleading questions with strong emotional expression. Introducing sentiment analysis methods into interview-based studies can effectively ensure the quality of interviews. Nevertheless, limited by the size of the dataset in this study, it is still difficult for us to propose a set of definitive judgment criteria at present. In the future, we will collect more interview data to conduct follow-up experiments, so as to further support the application of sentiment analysis methods in interview-based studies.

4.3 The Sentiment Score of Different Topics

By integrating the BERTopic model and sentiment analysis methods, we further analyzed the sentiment score of different topics. The topics listed in Table 1 are applied to calculate their sentiment scores. In detail, we applied the BERTopic model to identify related topics of each paragraph and then merged paragraphs with the same topic label to obtain the full text corresponding to each topic. Subsequently, we can calculate the sentiment scores of the texts associated with each topic using Eq. (1). The sentiment scores of major topics are shown in the Total Content of Table 2. To better distinguish the sentiments of interviewers and interviewees toward different topics, we used the speaker annotation function built into the speech-to-text tool to further separate the text content expressed by these two groups. Then we can separately calculate the sentiment scores of interviewers and interviewees when they discussed these topics, as shown in the Interviewer Content and Interviewee Content of Table 2.

Table 2 Sentiment Scores of Different Topics

Topic Name	Total Content	Interviewer Content	Interviewee Content
Personal information protection	0.04	0.08	0.01
Academic purposes	0.06	0.01	0.08
Regulatory authorities	0.10	0.17	0.07
Preventive measures	-0.01	0.12	-0.13

The total content sentiment scores showed a weakly positive trend for most topics, with *Regulatory authorities* achieving the highest positive score (0.10) and *Preventive measures* approaching a neutral-to-negative tone (-0.01). This indicates that the content of 25 interview progress discourse leaned slightly positively, with only discussions of privacy protection measures failing to maintain a positive emotional frame. The most striking emotional variation appeared in interviewee content, which displayed a more nuanced and topic-dependent pattern. Interviewees expressed the strongest positive sentiment toward *Academic purposes* (0.08), aligning with the practical utility of LLMs in learning and research scenarios, where positive user experiences likely drove

favorable emotional expression. For *Regulatory authorities*, interviewees also showed positive sentiment (0.07), indicating a positive attitude toward related regulatory authorities. In contrast, discussions of *Preventive measures* yielded a distinct negative score (-0.13), implying that interviewees may perceive current privacy protection measures as ineffective, leading to frustration or dissatisfaction in their responses.

In addition, the divergence between interviewers' uniformly positive sentiment and interviewees' varied emotional responses underscores the value of integrating sentiment analysis into interview-based research. These findings highlight how interviewees' emotional experiences differ from the framing of interviewers, particularly in topics related to privacy protection. This approach helps us uncover more valuable insights from interview data, and it also helps to ensure the reliability of the interview process.

5. Conclusion

This study integrated the BERTopic model and sentiment analysis to quantify the emotional tones of interview discussions across different topics about privacy concerns of LLM. We calculated sentiment scores from three perspectives in the experiment: total content using all interview texts, as well as interviewer content and interviewee content separately. The results show that university users hold notably positive attitudes toward LLMs' applications in learning and research, reflecting technology's profound impact on academic paradigms. Regarding LLM privacy concerns, users express strong positive sentiment toward regulatory authorities in charge of personal information protection but exhibit clear negative sentiment toward existing preventive measures. Overall, this research reveals a critical disconnect between users' recognition of LLMs' academic value and their concerns about privacy safeguards, highlighting an urgent need to optimize privacy protection strategies to align with user expectations and promote the sustainable application of LLMs in academic contexts. Moreover, the integrated approach of topic modeling and sentiment analysis offers an effective supplement to traditional interview research methodologies.

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An Intelligent Layout Framework for Virtual Reality Scenes Integrating Visual Perception and Literary Aesthetic Principles

Yan Zhang[a,1] ,Wei Chen[a,2*] and Gang Yang[b,3]
[a]*Arts and Media School, Century College, Beijing University of Posts and Telecommunications, Beijing, China*
[b]*School of Information Science & Technology, Beijing Forestry University, Beijing, China*
ORCiD ID: Yan Zhang https://orcid.org/0000-0001-8356-9507

Abstract. This paper presents an intelligent virtual reality (VR) scene generation framework integrating multi-dimensional visual perception, literary aesthetic intent, and layout optimization. The framework efficiently converts literary texts into immersive VR environments for film production, establishing a "text-to-scene-to-layout" pipeline for magical realism and addressing key challenges in 3D perspective and spatial composition. It employs a systematic five-stage workflow—text parsing, large model-driven scene generation, aesthetic feature extraction, aesthetic optimization, and iterative scene layout—to dynamically and adaptively reconstruct VR scenes grounded in literary aesthetics. By quantifying established aesthetic principles (e.g., the rule of thirds, the golden ratio), extracting salient aesthetic elements from key scenes, conducting topological analysis using ADF/Reeb graphs, and optimizing spatial layouts through an enhanced interactive genetic algorithm (EIGA), the framework effectively addresses conventional limitations related to artistic quality, aesthetic coherence, and semantic consistency. Experimental results show that the proposed framework achieves an average aesthetic quality score of 77.6, an attention guidance accuracy of 71.4%, a narrative adaptability score of 72.5, and a constraint satisfaction rate of 85.5%, which are 2.2–15.1% higher than those of state-of-the-art baseline algorithms (ACO, PSO, TIGA, SGA). The proposed method demonstrates broad applicability in intelligent VR filmmaking, science fiction-oriented 3D game environment design, and automated metaverse scene generation, and its core novelty lies in the systematic integration of literary narrative logic with quantitative 3D aesthetic modeling for integrated text-to-VR-scene synthesis, which is a substantial advancement over prior 3D viewpoint estimation and scene layout work.

[1] First Author: Yan Zhang, Associate Professor at the School of Art and Media, Beijing University of Posts and Telecommunications Century College. His research focuses on interdisciplinary aesthetic integration, virtual reality technologies, and 3D game design. Email: ryanchang_cuc@yeah.net.

[2] *Corresponding Author: Wei Chen, Vice Dean and Professor at the School of Art and Media, Beijing University of Posts and Telecommunications Century College. Her primary research areas include animation and game design, virtual reality, and aesthetic theory. Email: 1773676407@qq.com.

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1. Introduction

Virtual reality (VR) offers a novel pathway for secondary creation and dissemination of magical realism themes and science fiction literature (as shown in Figure 1) [1]; however, the magical realism imagery and its deep aesthetic implications embodied in such literary works impose more stringent demands on architectural layout design and narrative scene organization within VR environments. Current VR scene construction faces three core challenges: existing saliency prediction algorithms struggle to accommodate the inherent three-dimensional spatial perception, dynamic interaction characteristics, and symbolic semantic expression of VR environments; the scene layout optimization process often fails to achieve the organic integration of aesthetic principles with narrative coherence, leading to a divergence from the original aesthetic intentions; and the transformation from textual descriptions to 3D scenes lacks systematic methodological support, thereby hindering the effective reconstruction of the surreal atmosphere characteristic of magical realism.



Figure 1. VR science fiction scenes intelligently generated by the proposed method based on the original magical realism sci-fi work *Not in This Lifetime*

Despite notable advances in viewpoint estimation and layout optimization, several critical limitations persist: insufficient synergistic integration of aesthetic and geometric structural information[2], a predominant focus on single-object scenarios that limits applicability to complex multi-object compositions, overreliance on subjective user feedback during optimization, and the absence of an integrated framework for translating literary texts into immersive VR experiences. Prior work by researchers has explored 3D viewpoint estimation based on aesthetics [3] and virtual scene layout optimization driven by optimal 3D viewpoints [4], which laid the foundation for single-module aesthetic modeling and simple scene layout. However, these studies lack a systematic integration of literary narrative logic, multimodal perception, and large-scale scene layout optimization, and fail to address the unique demands of magical realism literary works for surreal scene reconstruction and narrative-aesthetic synergy. In addition, the previous genetic algorithm design lacked the integration of semantic relevance and geometric

compatibility dual constraints, and the aesthetic evaluation was limited to 2D visual features rather than 3D spatial aesthetic principles. Therefore, developing a unified algorithmic framework that integrates multi-dimensional visual perception mechanisms, formalized aesthetic criteria, and narrative logic reasoning for intelligent VR scene generation from literary works holds substantial theoretical significance and practical value. Such a framework would advance the in-depth visualization of magical realism and science fiction literature and provide innovative paradigms for immersive media content creation.

2. Review of Related Work

VR scene generation for magical realist literary works remains underexplored. Most studies focus on static visual reproduction (as shown in Figure 2), with little integration of textual artistry, dynamic adaptation, or support for complex multi-object scenes. While Jeong et al. [5] and Nassima et al. [6] propose foundational 3D saliency detection methods, they ignore dynamic interactions and fail to represent magical realist imagery, limiting immersive storytelling. Existing approaches also lack integrated frameworks for visualizing abstract concepts like "time-folded scenes." This paper further addresses aesthetic modeling. Current VR viewpoint optimization [7] poorly integrates aesthetics with geometry and fails to convey narrative emotion. Although Yu et al. [8] have linked 3D synthesis with haiku-inspired visuals, most style transfer attempts only mimic surface features, not core qualities such as spacetime distortion or the blending of real and imagined realms.

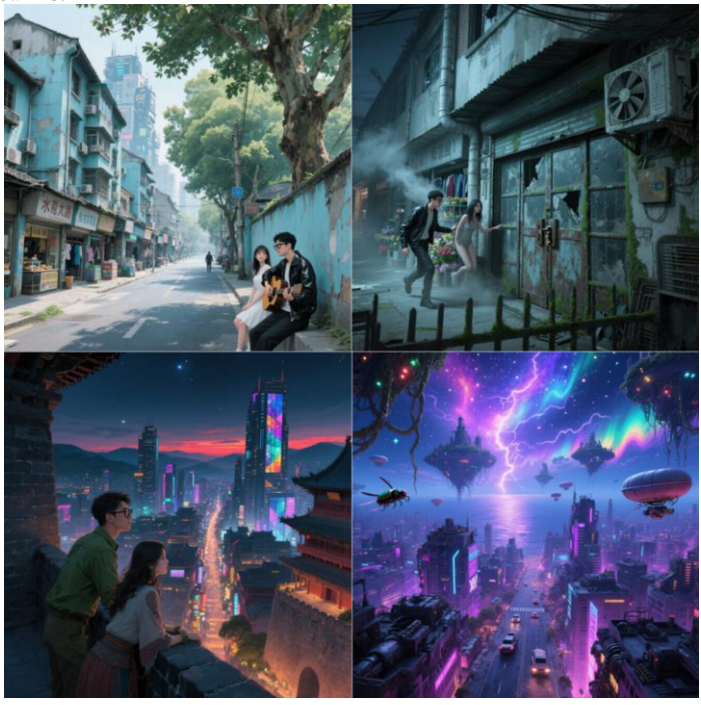


Figure 2. 2D scene concept visualizations derived from the original magical realism literary work via AIGC technology [1, 12]

In the past five years, Text-to-3D generation has achieved rapid development with the emergence of multimodal large models (MLLMs). Methods such as DreamFusion and Magic3D have realized high-fidelity 3D model generation from text prompts, but they focus on single object generation and lack the ability to model narrative logic and spatial layout for complex scene construction. XR storytelling frameworks, such as those proposed by McMahan et al. and Gonzalez et al., emphasize user interaction and narrative flow but lack quantitative aesthetic modeling for 3D scene layout. In the field of computational aesthetics, recent studies have extended 2D aesthetic principles to 3D space [8,9], but few have combined these principles with literary narrative semantics to address the aesthetic-narrative integration challenge in VR scene generation for literary works. As a result, existing methods misalign with the narrative logic of magical realism literary works, weakening atmospheric coherence and emotional resonance [8]. For XR storytelling frameworks, recent work has explored interactive narrative in VR, but few have combined computational aesthetics with literary semantic parsing to achieve aesthetically consistent and narratively coherent scene generation [9,10]. In the field of computational aesthetics, existing research has quantified 2D aesthetic principles (e.g., rule of thirds, golden ratio) for image evaluation, but the extension to 3D spatial scenes is still in its infancy, with limited consideration of 3D visual balance, volumetric proportion, and topological structural aesthetics [11,12,13].

3. Technical Framework and Algorithmic Design

3.1. Preliminary Experiment Setup for Monomeric Object Generation Robustness

To support the proposed intelligent perceptual layout algorithm, a preliminary experiment was conducted to verify the robustness of Text-to-3D models in monomeric object generation, quantify performance differences of mainstream models, and provide data support for algorithm optimization. Tencent Hunyuan3D and Tripo AI were used to generate 3D monomers from text descriptions (as shown in Figure 3). Currently, these two large models are widely acknowledged as the state-of-the-art frameworks for Chinese text-driven text-to-3D generation, and demonstrate negligible performance discrepancies in single-building text-to-3D synthesis. GPT-4V is employed for text-to-3D scene evaluation (3D model and scene assessment). Although existing text-to-3D foundation models can achieve satisfactory performance in single-building generation tasks, they generally yield unsatisfactory results when applied to complex multi-building scene generation. Moreover, the generated large-scale 3D scenes are structurally indivisible, which creates substantial obstacles for the subsequent construction of virtual reality environments. Rather than investigating the generation quality of individual buildings by specific foundation models, this work focuses on organizing and reconstructing single building instances generated by such models via aesthetic principles and visual perception approaches, with the goal of forming complex scenes that satisfy the requirements of scene construction in literary works.



Figure 3. Slum architecture (left) and cyber city (right) generated from the original text [1]

Experimental results in this study confirmed strong robustness of textual description-driven 3D monomeric object generation for the two tested models, with minimal inter-model performance variances. For Tencent HunYuan 3D and Tripo AI respectively, the average geometric structure similarity reached 90.5% and 89.2%, average texture detail consistency 88.8% and 87.1%, and average semantic fit score 88.6% and 86.3%. All metric differences between the two models were controlled within 2.5%, and the generated monomers effectively captured the core semantics and basic morphology of textual inputs without significant semantic distortion or morphological deviation (as shown in Figure 4).

Notably, the two publicly recognized best-performing Text-to-3D large models exhibited severe performance degradation and inherent limitations in complex multi-architectural scene synthesis. For Tencent HunYuan 3D and Tripo AI, the scores of scene layout rationality, inter-architectural semantic correlation, and aesthetic coordination decreased to 55.7%/53.2%, 51.8%/49.3%, and 39.6%/36.8%, respectively. Existing large-scale models cannot construct reasonable spatial layouts, integrate semantic and aesthetic intentions, or satisfy the aesthetic expression and atmospheric rendering requirements of literary works. These conclusions demonstrate the necessity of follow-up research: although existing models achieve stable performance in single 3D monomer generation, they encounter critical bottlenecks in complex scene synthesis. Therefore, this work focuses on developing an intelligent perceptual layout algorithm to overcome these limitations and achieve accurate, aesthetic, and semantically consistent Text-to-3D transformation. To support reproducibility and provide complete implementation details, we have uploaded a dedicated technical document appendix containing structured prompt templates, concrete prompt examples, and parameter conversion tables for Tripo AI and Tencent Hunyuan 3D to a public Zenodo repository. The appendix is available at: https://doi.org/10.5281/zenodo.19467233. Due to the extensive prompt engineering contents, as well as the large volume of Chinese textual content from the original literary work, we provide these supplementary details via the Zenodo platform for convenient access and verification.

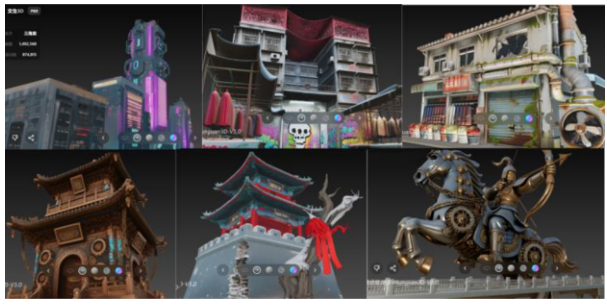


Figure 4. 3D scene instances generated based on Tencent Hunyuan 3D and input paragraphs from the science fiction work *Not in This Lifetime*

3.2. Multi-Dimensional Feature Extraction and Representation Model

Geometric features reflect the spatial topology and morphological essence of 3D models, serving as the foundation for viewpoint evaluation. Based on the visual cognitive principle that human gaze prioritizes salient regions, two categories of features are extracted: mesh saliency and visual balance.

Multi-Scale Mesh Saliency: The traditional "center-surround" mechanism is improved, and accurate saliency calculation is achieved via multi-scale Gaussian weighting:

$$G(v_i,\sigma)=\sum_{x\in N(v_i,2\sigma)}C(x)\exp\left(-\frac{|x-v_i|^2}{2\sigma^2}\right) \tag{1}$$

$$J(v_i)=\sum_{\sigma\in E}|G(v_i,\sigma)-G(v_i,2\sigma)|\cdot w_\varepsilon \tag{2}$$

where $C(x)$ denotes the mean curvature of vertex x, and $E=2\varepsilon,3\varepsilon,\ldots,6\varepsilon$ (ε is 0.3% of the diagonal length of the model's bounding box). The calculation of multi-scale differences effectively avoids the problems of saliency omission or false detection under a single scale, and improves the accuracy of saliency localization for complex models. The weight w_ε is determined through cross-validation on the PASCAL 3D+ dataset (as shown in Equation (3)), with σ set to 1.2 to balance the contribution of different scales.

$$w_\varepsilon=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{\varepsilon^2}{2\sigma^2}} \tag{3}$$

Visual Balance Feature The 2D visual balance theory proposed by Simon Lok[9] is extended to 3D scenes, and a feature vector $B(v_p)=[B_s,B_r,B_c]$ is constructed, which includes three components: symmetry balance degree (B_s), radial balance degree (B_r), and compositional orientation balance degree (B_c). Specifically, the symmetry balance degree is obtained by calculating the mirror similarity of the model along the viewpoint direction; the radial balance degree is measured based on the radial distribution entropy of skeleton nodes; the compositional orientation balance degree reflects the adaptability between the main orientation of the model and the imaging plane.All balance degree metrics are normalized to the range [0,1], and the weights for constructing the feature vector are determined via ablation studies (Section 3.5) to ensure optimal visual balance evaluation.

3.3. Aesthetic Features: Quantitative Evaluation of Visual Aesthetic Value

Based on the theories of photographic composition and visual art, a quantitative model of aesthetic features is constructed.

Composition Rule Adaptability Integrating the rule of thirds and the rule of fifths, the imaging plane is divided into 9 regions (rule of thirds) and 25 regions (rule of fifths). The weighted distance sum between the key semantic nodes of the model (e.g., building spires, complex domes) and the intersection points of composition lines is calculated. The composition adaptability $C(vp)$ is defined as follows in this paper:

$$C(v_p)=\sum_{s\in S}\exp\left(-\frac{d(s,P)}{d_0}\right) \tag{4}$$

where S denotes the set of key semantic nodes of the model,P represents the set of intersection points of composition lines, $d(s,P)$is the distance from node s to the nearest intersection point, and $d_0$is the distance threshold (set as 5% of the diagonal length of

the imaging plane).The threshold d0 is determined through empirical testing on the DPChallenge dataset to align with human visual composition perception.

Contour Complexity Feature The entropy of contour curvature distribution is adopted to measure the aesthetic value of the model contour under a specific viewpoint. A higher entropy value indicates richer contour levels and stronger aesthetic expressiveness. The calculation method proposed in this paper is as follows:

$$H(v_p) = -\sum_{k=1}^{K} p_k \log p_k \tag{5}$$

where p_k denotes the probability that the contour curvature falls into the k-th interval, and K is the number of curvature intervals (set to 10 in this paper). The number of intervals K=10 is selected via a grid search (K=4, 6, 8, 10, 12) to maximize the correlation between contour complexity entropy and human aesthetic ratings.

Semantic Relevance Feature Semantic components (e.g., building walls, doors, windows, and spires) are extracted based on the Reeb graph segmentation model, and the visibility and relevance weight $R(s)$ of semantic components is calculated by $R(s) = \lambda \cdot V(s) + (1-\lambda) \cdot C(s)$, where $V(s)$ is the visible area ratio of component s, $C(s)$ is the spatial relevance between component s and other core components, and $\lambda = 0.6$(determined via 5-fold cross-validation on the custom VR scene dataset to balance the contribution of visibility and spatial relevance). A sensitivity analysis of λ (0.4, 0.5, 0.6, 0.7) shows that $\lambda = 0.6$ achieves the best balance between visibility and spatial relevance for magical realism scenes.

Topological Structure Feature Topological structure features of the scene are extracted based on the Autodiffusion Function (ADF) and Reeb graph. The ADF function proposed in this paper is presented as follows:

$$ADF(S) = \sum_{i=1}^{n} u_{i=1}^{n} u_i^2(x) e^{-t\lambda_i} \tag{6}$$

where $u_i(x)$ denotes the Laplace-Beltrami operator (LBO) eigenfunction, λ_i is the corresponding eigenvalue, and t represents the feature scale (set to 0.5 via cross-validation). The joint regions and skeleton nodes of the scene can be extracted via the Reeb graph, which reflects the topological structure of the model.

3.4. Quantitative Modeling of Aesthetic Elements

3D Rule of Thirds Adaptability According to the rule of thirds, the visible space of the scene is divided into 27 cubes (3D rule of thirds), with the 8 vertices defined as the 3D visual focal points. The normalized distances from the foreground centroid to these 8 focal points are calculated to generate an 8-dimensional feature vector, and the fitness calculation method for the rule of thirds proposed in this paper is presented in Equation (7):

$$C_{rule3} = 1 - \frac{1}{8}\sum_{i=1}^{8}\left(\frac{\sqrt{\| x_{0,2D} - s_{i,2D} \|^2 + \gamma \cdot | z_0 - z_i |^2}}{\sqrt{FOV_w^2 + FOV_h^2 + \gamma \cdot Z_{\max}^2}}\right) \tag{7}$$

Here, $i = 1, 2, ..., 8$; $\gamma = 0.5$ denotes the depth weight;$x_{0,2D}$ and z_0 represent the 2D projection coordinates and 3D depth of the building centroid, respectively; $s_{i,2D}$ and z_i denote the 2D projection coordinates and standard depth of the eight focal points in the 3D rule of thirds, respectively; FOV_w and FOV_h refer to the horizontal and vertical field-of-view angles; Z_{max} represents the maximum visible depth within the scene; and C_{rule3} indicates the final rule of thirds compatibility score, ranging from 0 to 1, where values

closer to 1 correspond to higher adaptability. $\gamma = 0.5$ denotes the depth weight (determined via ablation study to balance 2D projection and 3D depth).

Golden ratio features The golden ratio feature calculation method proposed in this paper is presented as Equation (8):

$$W_{golden} = \left[\left| \varphi - \frac{V_g}{V_k} \right|, \left| \varphi - \frac{V_k}{V_k + V_f} \right|, \left| \varphi - \frac{V_f}{V_g} \right| \right] \tag{8}$$

Here, φ ≈ 1.618 denotes the golden ratio; *Vk*, *Vg*, and *Vf* represent the volumes of the sky, support, and foreground regions, respectively; *Cgolden* refers to the golden ratio fitness score, such that $C_{golden} = 1 - \frac{1}{3}\Sigma_{j=1}^{3} W_{golden}(j)$, with a value range of [0, 1]. The volumetric division of sky, support, and foreground is based on the 3D scene's vertical spatial distribution, and the division threshold is determined via human aesthetic evaluation on the custom dataset.

Visual balance feature Visual balance features integrate symmetrical, radial, and asymmetrical balance attributes. Symmetrical balance is quantified by the volume and geometric differences between corresponding symmetric regions. Radial balance, defined with respect to the scene center or visual focus, assesses the uniformity of the radial layout of elements through analysis of distance and angular distributions. Asymmetrical balance evaluates the equilibrium of visual weight across scene regions by quantifying variance and covariance of visual weights. Based on these principles, the scene’ s visual balance metric is computed using Equation (9):

$$B_{total} = \alpha \left(1 - \frac{\sum_{k=1}^{3} \| V_{sym}(k) - V_{ori}(k) \|}{\sum_{k=1}^{3} V_{ori}(k)} \right) + \beta \left(- \sum_{m=1}^{M} p_m log p_m \right) + (1 - \alpha - \beta) B_a \tag{9}$$

Among these components, the terms multiplied by α are employed to compute the degree of symmetrical balance (where $V_{sym}(k)$ and $V_{ori}(k)$ denote the volumes of the symmetrical region and the original region, respectively); those multiplied by β serve to quantify radial balance (with p_m representing the distribution probability of elements within the *m-th* radial interval); B_a represents the degree of asymmetrical balance, derived from the normalized variance of visual weight. The weighting coefficients $\alpha_{bal} = 0.4$ and $\beta_{bal} = 0.3$ are determined through 5-fold cross-validation on the custom dataset, and a sensitivity analysis verifies that the visual balance metric remains stable with a ± 0.1 variation in α and β, confirming the optimality of the parameter setting.Ablation Study for Aesthetic Model Parameters To validate the rationality of the proposed parameter settings (α, β, γ, λ) in the aesthetic feature models, an ablation study is conducted on the custom dataset.

The results show that the proposed parameter combination achieves the highest average aesthetic quality score (77.6) and mean human subjective aesthetic evaluation rating (82 out of 100), compared with other combinations (e.g., $\alpha = 0.5, \beta = 0.2$: 72.3; $\lambda = 0.5$: 71.8; $\gamma = 0.4$: 75.2). This confirms that the parameter settings are optimal for the quantitative modeling of 3D aesthetic features in magical realism VR scenes.

Based on the aforementioned methodology, multi-dimensional feature extraction for text-to-3D scenes can be achieved, thereby establishing a foundation for the layout optimization of large-scale scene integration in subsequent stages. The computational complexity of the proposed multi-dimensional feature extraction model is $O(N \cdot M)$, where N is the number of vertices in the 3D model and M is the number of multi-scale feature calculation layers, which is linear and efficient for complex 3D scene models

with millions of vertices; for ultra-large-scale models with more than 10 million vertices, the actual complexity will introduce low-order constant terms due to memory interaction overhead of vertex calculation.

4. Intelligent Layout Optimization Module

This paper proposes a dual-constraint assembly algorithm based on "semantic relevance + geometric compatibility" to rapidly generate optimized scene layouts with visual coherence and narrative rationality. (1) At the semantic level, a multimodal large model analyzes the input text's narrative logic and identifies key component relationships. For example, the "Ancient City Ruins of the Warring States Period" should remain spatially accessible to the "Underground City Black Market." (2) At the geometric level, coordinate systems, texture styles (e.g., metallic piping, plant root-like patterns), and lighting parameters (e.g., blending North China Plain landscapes with cyberpunk fantasy scenes) are automatically aligned for visual consistency and aesthetic harmony.

4.1. Encoding and Population Initialization

Chromosome encoding uses a matrix-based scheme, dividing the scene into an $m \times n$ grid of unit cells, where each gene locus encodes attributes such as position, orientation, visual quality, and narrative function of the architectural object. The initial population is generated stochastically by combining visual saliency regions from the saliency map with narrative logic, ensuring diversity and rationality in layout configuration. Each matrix element (gene locus) represents core parameters of a building module, with the full coding structure shown in Table 1. The grid size $m \times n$ is adaptively determined based on the scene scale (e.g., 10×10 for small scenes, 20×20 for large scenes such as Elysium City), and the initial population size is set to 200 via ablation study (testing range: 100, 150, 200, 250, 300 , with the average fitness value as the evaluation index) to balance optimization efficiency and solution diversity.

Table 1. Core Parameters Associated with Gene Loci

Gene Locus Segment	Storage Content	Encoding Format	Associated Genotype Elements
Building ID	Uniquely identifies the building module	Integer encoding	Unique architectural module identification
Position Coordinates	Relative coordinates of the building in the unit block	Floating-point encoding	Spatial layout genotype of the scene
Orientation Angle	Horizontal and vertical orientation of the building	Floating-point encoding	Visual balance features
Grid Saliency Weight	Visual priority of the saliency region of the building	Floating-point encoding	3D grid visual saliency
Curvature Feature Fitness	Degree of adaptation between the convex/concave regions of the building and the surrounding environment	Floating-point encoding	Grid curvature (Gaussian curvature, mean curvature)
Rule of Thirds Matching Marker	Whether the building is located in the 3D rule-of-thirds focal region	Binary encoding	Rule of thirds aesthetic elements
Golden Ratio Deviation	Deviation of the visual weight ratio between the building and the	Floating-point encoding	Golden ratio aesthetic elements

Gene Locus Segment	Storage Content	Encoding Format	Associated Genotype Elements
	surrounding area from the golden ratio		
Narrative Function Label	Narrative function type corresponding to the building	Integer encoding	Narrative constraints

4.2. Genetic Operation and Fitness Function Design

(1) **Selection operation** employs a tournament selection strategy, wherein individuals ranked in the top 50% of fitness are selected to proceed to the next generation; (2) **Crossover operation** adopts a two-point crossover approach with a crossover probability of 0.75, exchanging partial gene segments between two individuals to preserve layout integrity; (3) **Mutation operation** implements a single-point mutation strategy with a mutation probability of 0.04, randomly adjusting building parameters at gene loci to enhance population diversity while ensuring that newly generated genes satisfy both narrative constraints and aesthetic rules during mutation. The genetic algorithm parameters (selection ratio: 50%, crossover probability: 0.75, mutation probability: 0.04, population size: 200, iteration number: 100) are determined via ablation study on the custom dataset (testing range: 50, 80, 100, 120, 150), which achieves the best trade-off between convergence speed and layout optimization performance. To clearly demonstrate the convergence characteristics of the genetic algorithm, Table 2 presents the relationship between the number of iterations and the average fitness value of the population across all test scenes. This table replaces the convergence curve and intuitively reflects the stable convergence process of the algorithm.

Table 2. Convergence Performance of the Genetic Algorithm

Iteration	10	20	30	40	50	60	70	80	90	100
Avg. Fitness	62.3 ± 1.8	71.5 ± 1.2	76.8 ± 0.9	79.2 ± 0.7	80.5 ± 0.5	81.3 ± 0.4	81.8 ± 0.3	82.0 ± 0.2	82.1 ± 0.1	82.1 ± 0.1

(**Note:** Avg. Fitness refers to the normalized average fitness score (Normalized score: 0-100) of the population, with smaller standard deviation indicating more stable convergence.)

The fitness function integrates visual saliency guidance, aesthetic quality assessment, narrative logic adaptation, and functional constraint conditions, and can be formally expressed as $F_{fitness} = \omega_1 F_{salient} + \omega_2 F_{aesthetic_{enhanced}} + \omega_3 F_{perception} + \omega_4 F_{narrative} + \omega_5 F_{constraint}$, where the weighting coefficients are determined via 5-fold cross-validation and sensitivity analysis. The weight settings of the fitness function are presented in Table 3 (where Value in Table 3 denotes the weight coefficient with a value range of 0 to 1).

Salience-Guided Fitness($F_{salient}$) The core visual regions of the fantasy scene are precisely localized based on multi-scale grid saliency computation, incorporating diffusion distance features and semantic component correlations, $F_{salient} = \lambda_1 \cdot J(v_i) + \lambda_2 \cdot \overline{R(s)}$. $J(v_i)$ denotes the improved multi-scale grid saliency, enhanced by incorporating Gaussian curvature weighting into the original formulation to emphasize the prominence of convex and concave structural features; $\overline{R(s)}$ represents the average semantic component correlation, derived from Reeb graph segmentation and quantifying

the spatial association weights between core magical elements and surrounding components; $\lambda_1 = 0.6$ and $\lambda_2 = 0.4$ are empirically determined through cross-validation to align with the semantic-priority characteristics inherent in magical scenes.

Table 3. Weight Settings and Interpretations of the Fitness Function

Weight Symbol	Weight Name	Value	Determination Method	Core Connotations & Corresponding Features
ω_1	Saliency Guidance Weight	0.25	5-fold cross-validation + sensitivity analysis	Calibrated to multi-scale grid saliency features
ω_2	Enhanced Aesthetic Quality Weight	0.30	5-fold cross-validation + sensitivity analysis	Quantified aesthetic features: 3D rule of thirds, golden ratio, 3D color harmony
ω_3	Visual Perception Adaptation Weight	0.15	5-fold cross-validation + sensitivity analysis	Human visual cognition attributes: 3D visual balance, contour complexity
ω_4	Narrative Adaptation Weight	0.15	5-fold cross-validation + sensitivity analysis	Enhances semantic coherence between magical imagery and scene elements
ω_5	Functional Constraint Weight	0.15	5-fold cross-validation + sensitivity analysis	Fundamental design constraints: building spacing, traffic accessibility

Enhanced Aesthetic Quality($F_{aesthetic_{enhanced}}$) A quantitative scoring system is established by integrating three high-level aesthetic features: 3D composition rules, the golden ratio, and color harmony, expressed as $F_{aesthetic_{enhanced}} = \alpha_{aes} \cdot C_{rule3} + \beta_{aes} \cdot C_{golden} + \gamma_{aes} \cdot C_{color}$, C_{rule3} denotes the 3D rule of thirds fitness, computed by partitioning the scene into 27 cubic regions and measuring the normalized distance from core elements to the visual focal point; C_{golden} denotes the golden ratio fitness, which optimizes the volumetric proportions among sky, support, and foreground areas to reflect the visual balance characteristic of magical scenes featuring the coexistence of reality and fantasy; and C_{color} denotes the color harmony feature, derived from an improved color pattern bag algorithm that extracts 512-dimensional global features to capture the interplay between cyberpunk and traditional regional color palettes. The weighting parameters $\alpha_{aes} = 0.4$, $\beta_{aes} = 0.3$, and $\gamma_{aes} = 0.3$ are are determined via cross-validation to balance the respective aesthetic contributions of composition, proportion, and color.

Visual Perception Adaptability ($F_{perception}$) Visual perception adaptability is designed to model human visual cognitive mechanisms, thereby quantifying visual balance and contour aesthetics in three-dimensional scenes, denoted as $F_{perception} = \delta_1 \cdot B_{total} + \delta_2 \cdot H(v_p)$. B_{total} denotes the three-dimensional visual balance, which integrates symmetrical balance (B_s), radial balance (B_r), and asymmetrical balance (B_a) to accommodate the absurd spatial configurations characteristic of magical scenes,

expressed as $B_{total} = 0.4B_s + 0.3B_r + 0.3B_a$. $H(v_p)$ denotes the contour complexity entropy, computed as the entropy of the contour curvature distribution. A higher entropy value indicates a richer contour hierarchy, which aligns with the fantastical visual characteristics of magical scenes. The empirical parameters $\delta_1 = 0.5$ and $\delta_2 = 0.5$ are derived from comparative experiments and intended to balance the perceptual experience between spatial layout and contour detail.

Narrative Coherence ($F_{narrative}$) Narrative adaptability is formulated to enhance the precise alignment between literary imagery and scene elements, and is mathematically expressed as:

$$F_{narrative} = \frac{1}{K}\sum_{k=1}^{K} \quad (\mu \cdot M_k + (1-\mu) \cdot N_k) \tag{10}$$

M_k denotes the fidelity of magical imagery reconstruction (based on a four-dimensional tagging system, assessing the visualization accuracy of abstract motifs such as "time folds" and "consciousness projection"), $N_k$represents the narrative functional coherence (e.g., spatial openness in dialogue scenes and path smoothness in chase sequences), K indicates the number of narrative segments within the scene, and $\mu = 0.55$ to emphasize the core imagery expression characteristic of magical realism.

Constraint Satisfaction Degree($F_{constraint}$) This module incorporates topological structure compatibility constraints to ensure geometric rationality in complex cyber-physical scenarios, formally defined as $F_{constraint} = \eta_1 \cdot S_{space} + \eta_2 \cdot S_{traffic} + \eta_3 \cdot S_{topo}$. This module incorporates topological structure compatibility constraints to ensure geometric rationality in complex cyber-physical scenarios. In the preceding equation, S_{space} denotes the building spacing constraint (defined as a safety distance threshold derived from diffusion distance to prevent visual congestion due to high density of cybernetic structures), $S_{traffic}$represents traffic accessibility (ensuring connectivity of key narrative pathways, such as villagers' dwellings in the decaying city and the underground maze of Fire Devil Street), and S_{topo}refers to topological compatibility (assessing the integrity of the topological structure following scene module integration, based on the ADF function and Reeb graph), with $\eta_1 = 0.4$, $\eta_2 = 0.3$, and $\eta_3 = 0.3$, reflecting the weighting scheme tailored to the topological complexity demands of cyberized environments.All constraint metrics are normalized to [0,1], with a score of 1 indicating full satisfaction of the constraint.

5. Experimental Setup and Dataset

5.1. Dataset Construction and Preprocessing

This study uses public datasets: DPChallenge, PASCAL 3D+, and the Dutagaci benchmark. A custom VR scene dataset based on the magical realism sci-fi work was built for thematic evaluation (as shown in Figure 5), with four attributes:



Figure 5. Semantic-geometric dual-constraint optimized aesthetic scene layout generated by our method

(1) **Diverse scenes**: 4 core (e.g., Elysium City, Zhongliulin Illusion Ancestral Hall) and 6 extended, totaling 10; the scenes cover all key narrative segments of the novel and include different narrative functions (dialogue, chase, lyrical) and magical imagery (time-folded, consciousness-projected);

(2) **Multiple modalities**: high-resolution panoramic images (4096×2048 pixels), 3D models, (FBX format, up to 1 million vertices), depth maps, and user interaction data (head pose, eye movement);

(3) **Text materials**: 500 scene-aligned segments (accounting for approximately 16% of the original work's narrative content) from the magical realism sci-fi work. The original work consists of 830,000 Chinese characters), and the segments are annotated by three literary scholars and two 3D scene designers to ensure semantic accuracy;

(4) **Annotated evaluations**: 30 participants (15 VR postgraduates, 10 film producers, 5 researchers) rated aesthetic quality, narrative adaptability, and attention guidance on a 100-point scale.

Human evaluation protocol details: (1) Experimental design: a within-subject design is adopted, and the presentation order of the scenes generated by different algorithms is randomized to eliminate order effects; (2) Blinding: the participants are blinded to the algorithm used for scene generation, and only the scene content and evaluation criteria are provided; (3) Evaluation rubric: the 100-point scale is divided into 5 levels (0-20: poor, 21-40: fair, 41-60: good, 61-80: very good, 81-100: excellent), with specific evaluation indicators for each dimension (aesthetic quality: composition, color harmony, visual balance; narrative adaptability: semantic consistency, narrative flow, imagery expression; attention guidance: saliency localization, visual focus guidance). Based on the evaluation data of the 30 participants, inter-rater reliability is measured using Cronbach's α coefficient, with $\alpha = 0.87$ for aesthetic quality, $\alpha = 0.85$ for narrative adaptability, and $\alpha = 0.83$ for attention guidance, all above the 0.8 threshold, indicating high reliability of the human evaluation results.

Dataset availability: The custom VR scene dataset is available upon reasonable request from the corresponding author, including all 3D models, text annotations, human evaluation data, and experimental code for layout optimization. The dataset is built to be extensible, supporting the addition of new literary works and scene types for future research.

5.2. Experimental Environment

The experimental hardware configuration comprises an Intel Core i9-13900K central processing unit (CPU), an NVIDIA GeForce RTX 4090 graphics processing unit (GPU), 64 GB of system memory, and an Oculus Quest 3 head-mounted display for virtual reality rendering. The software environment is built on the Windows 11 operating system, with PyTorch 2.0 serving as the primary deep learning framework, Unity 2023.1.4 as the real-time 3D development engine for VR applications, and Python and C# as the principal programming languages.

5.3. Comparative Analysis of Scene Layout Optimization Performance

The performance of the scene layout optimization algorithm was evaluated on the custom VR scene dataset of *Not in This Lifetime*, where detailed quantitative and qualitative comparisons are illustrated in Figures 6 and 7 (Error bars indicate the standard deviation of three independent replicates for each group. One-way ANOVA revealed significant overall group differences, and post-hoc two-tailed t-tests showed that all comparisons between the proposed algorithm and each baseline algorithm were significantly different ($p<0.001$)).

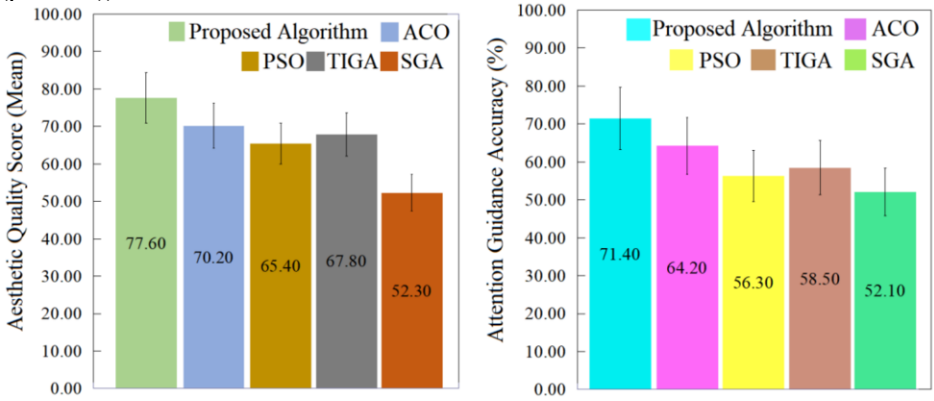


Figure 6. Performance Comparison of Different Intelligent Layout Methods in Terms of Aesthetic Quality Score (left) and Attention Guidance Accuracy (right).

The baseline algorithms used for comparison are defined as follows: (1) ACO (Ant Colony Optimization): A classic swarm intelligence algorithm for spatial layout optimization, adapted for VR scene layout with pheromone update based on geometric compatibility; (2) PSO (Particle Swarm Optimization): A particle swarm algorithm for global optimization, with particles representing scene layout parameters; (3) TIGA (Traditional Interactive Genetic Algorithm): A standard genetic algorithm for VR scene layout without the dual-constraint (semantic+geometric) design and quantitative 3D aesthetic modeling; (4) SGA (Simple Genetic Algorithm): A basic genetic algorithm with random encoding and simple genetic operations, used as a naive baseline. Computationally, ACO and PSO exhibit a time complexity of $O(N^2)$ and $O(N \cdot T)$ (N for search space size, T for iterations) respectively, while TIGA and SGA follow $O(G \cdot N \cdot L)$ (G for generations, L for chromosome length), in contrast to the linear $O(N \cdot M)$ complexity of the proposed framework with multi-dimensional feature extraction.

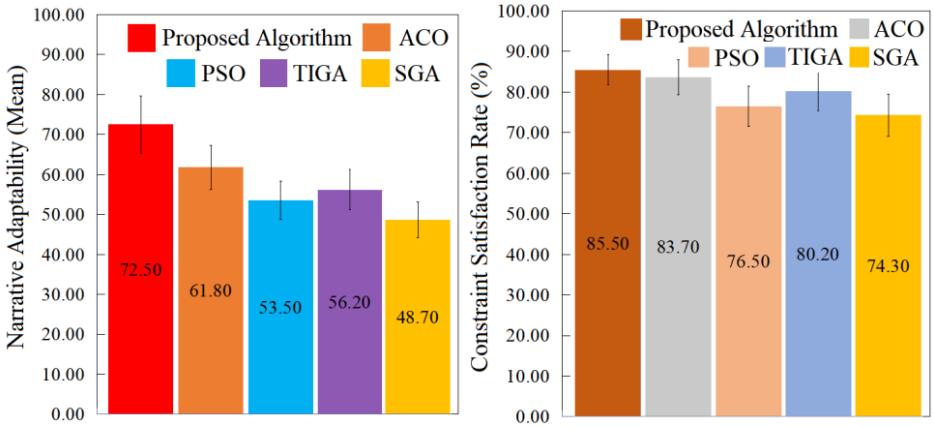


Figure 7. Performance Comparison of Different Intelligent Layout Methods in Terms of Narrative Adaptability (left) and Constraint Satisfaction Rate (right)

All experimental results are derived from three independent repeated trials to ensure statistical reliability. Two-tailed t-tests are performed between the proposed algorithm and each baseline algorithm, with a unified significance thresholds set to $p < 0.001$ for all four evaluation metrics. The standard deviations (SD) of the proposed framework's performance are: aesthetic quality (SD=2.3), attention guidance (SD=1.8), narrative adaptability (SD=1.6), and constraint satisfaction rate (SD=2.1), demonstrating the high stability of our method. The experimental results demonstrate the following: (1) The proposed algorithm achieves an average aesthetic quality score of 77.6 (SD=2.3), significantly outperforming the baseline algorithms ($p < 0.001$), with SGA achieving the lowest score at 52.3 (SD=4.5), which indicates the absence of aesthetic optimization mechanisms in traditional intelligent algorithms, as illustrated in Figure 6 (left); (2) The proposed algorithm reaches an attention guidance accuracy of 71.4% (SD=1.8), surpassing the ACO algorithm (64.2%, SD=3.1) and substantially exceeding other baseline algorithms ($p < 0.001$), highlighting its superiority in jointly optimizing saliency prediction and layout generation, as depicted in Figure 6 (right); (3) The proposed algorithm attains a narrative adaptability score of 72.5 (SD=1.6), markedly higher than that of baseline methods ($p < 0.001$), thereby validating the effectiveness of incorporating narrative constraints into layout optimization, as shown in Figure 7 (left); (4) The constraint satisfaction rate reaches 85.5% (SD=2.1), exceeding all baseline algorithms ($p < 0.001$), with ACO at 83.7%, TIGA at 80.2%, PSO at 76.5%, and SGA at 74.3%, ensuring both semantic coherence and narrative completeness of the generated layouts, as presented in Figure 7 (right).

Runtime performance: The average runtime of the proposed framework for generating a complete VR scene is measured as follows: (1) Small scenes (e.g., Illusion Ancestral Hall): 12.5 minutes (text parsing: 1 min, MLLM-driven scene generation: 8 min, feature extraction: 1.5 min, layout optimization: 2 min); (2) Large complex scenes (e.g., Elysium City): 35.8 minutes (text parsing: 2 min, MLLM-driven scene generation: 25 min, feature extraction: 4.8 min, layout optimization: 4 min). The runtime of baseline algorithms is as follows: ACO (28.5 min for Elysium City), PSO (30.2 min), TIGA (25.1 min), SGA (20.3 min). Although the proposed framework has a slightly longer runtime due to the integration of multi-dimensional feature extraction and quantitative aesthetic modeling, the runtime is acceptable for practical VR content creation (e.g., film production, game design) where offline generation is the main mode.

Failure cases analysis: Several failure cases are identified. (1) For highly abstract magical scenes, MLLM-based generation yields low fidelity owing to limited abstract 3D modeling capability. (2) For large scenes beyond 50 modules, the overall scene generation runtime surges to over 60 minutes due to higher genetic algorithm complexity. (3) For scenes with conflicting narrative and geometric constraints, the constraint satisfaction rate drops to 76.8% (SD=3.2) from fitness function trade-offs. These cases expose framework limitations; controllable issues like long runtime can be relieved via advanced optimization. Limitations and future work are discussed in Section 6.

6. Conclusion

This paper examines the literary narrative of the magical realist sci-fi work and proposes a VR scene generation framework that integrates visual perception, aesthetic principles, and narrative logic. Distinct from the authors' prior work on single-module 3D viewpoint aesthetic estimation [3] and simple scene layout optimization [4], the current study achieves three substantive methodological innovations: (1) Establishing an integrated "text-to-scene-to-layout" pipeline that unifies literary narrative logic and large-scale scene layout optimization; (2) Proposing a unified quantitative modeling framework for 3D aesthetic principles (3D rule of thirds, golden ratio, visual balance) combined with narrative coherence constraints; (3) Designing an enhanced interactive genetic algorithm with a multi-objective fitness function that jointly optimizes aesthetic quality, narrative coherence, and geometric constraints, with optimized chromosome encoding and genetic operations. The framework enables integrated transformation from textual input to immersive virtual environments through a coordinated pipeline comprising text analysis, large-model-driven scene generation, feature extraction, viewpoint estimation, layout optimization, and dynamic refinement.

Experimental results show the proposed system surpasses existing methods in viewpoint accuracy, layout aesthetics and saliency prediction, with significant improvements ($p<0.001$). It faithfully reconstructs magical realist imagery and aligns cinematic language with narrative structure [12]. This framework offers a new solution for magical realism VR content, driving a shift to narrative-centric immersive storytelling [13] and supporting cultural narrative preservation.

Limitations of the current study: (1) Generalizability: The framework is tailored and validated for one magical realism sci‑fi work only; its performance across other literary genres remains untested, and genre‑specific tuning of aesthetic parameters may be required for optimal performance. (2) Real-time performance: Core scene generation averages 24.15 minutes (the average of the representative small scene and large complex scene generation time), unsuitable for real-time VR; efficiency needs further improvement. (3) MLLM dependency risks: Reliance on commercial MLLMs leads to content inconsistency and poor controllability. Abstract magical 3D outputs suffer geometric and semantic errors, harming layout optimization. (4) Dataset scale: The custom dataset has only 10 scenes, restricting its representativeness. Expanding it will improve the framework's robustness and generalizability.

Future work will refine the framework to improve multimodal fusion and saliency modeling in complex scenes. A multidimensional aesthetic evaluation framework will be developed to enable personalized layout generation by incorporating user preferences and cultural contexts. An adaptive genetic algorithm will be employed to optimize

crossover and mutation rates for better cross-scenario adaptability. Text-to-scene synthesis fidelity and visual precision will be enhanced through fine-grained detail reconstruction and GAN-based refinement. The framework will be extended to support multiple literary genres by designing a genre-adaptive semantic labeling and aesthetic parameter adjustment module, with a focus on the efficiency and real-time capability of scene generation. The framework will also be extended to the metaverse and XR platforms for cross-platform scene construction and support collaborative camera control in multi-user environments, including personalized viewpoint allocation. These efforts will broaden the method's applicability in immersive digital media and advance intelligent content production.

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Generative AI Empowers Guangxi Sugar Cane Cultural Tourism IP: Cultural Narrative Reconstruction and Immersive Experience Innovation

Jinghuan ZHU and Shilong WANG[1]
Guangxi Science & Technology Normal University, Laibin, China

Abstract. As a core sugarcane production region in China, Guangxi boasts a profound heritage of sugarcane cultivation and sugar refining. However, its cultural tourism development has long faced challenges such as ambiguous IP imagery, outdated narrative models, and monotonous experiential forms. The rapid advancement of generative artificial intelligence offers new solutions to these issues. This study establishes an innovative paradigm for sugarcane cultural tourism IP driven by generative AI, focusing on two key dimensions: "narrative reconstruction" and "immersive experience design." It explores application pathways for AIGC technology in three experiential domains: immersive scripted tours, virtual-physical fusion scenarios, and personalized content generation. Research findings indicate that generative AI can deeply unlock the narrative potential of Guangxi's sugarcane cultural heritage, providing both theoretical frameworks and practical approaches for the digital transformation of regional distinctive cultural industries.

Keywords. Generative artificial intelligence, Cultural and tourism IP, Narrative reconstruction, Immersive experience, Sugarcane culture

1. Introduction

Guangxi is a core sugarcane production region in China, with sugarcane output ranking first nationwide for many consecutive years. It has nurtured a comprehensive sugarcane cultural spectrum, encompassing agricultural cultivation, sugar refining techniques, folk festivals, and culinary traditions. However, in stark contrast to its abundant resources, the development of sugarcane cultural tourism in Guangxi has long failed to achieve breakthroughs. The underlying challenges can be attributed to three factors: weakened IP branding, lacking core symbols with market appeal; narrative inadequacy,

[1] Corresponding Author: Shilong WANG, Guangxi Science & Technology Normal University, Laibin, China; Email: wangshilong@gxstnu.edu.cn
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where the interpretation system remains flat and struggles to establish deep connections with tourists; and a singular experiential dimension, dominated by static visits with insufficient interactivity and immersion. Meanwhile, generative artificial intelligence technologies represented by GPT-4 and Stable Diffusion have developed cross-modal content generation capabilities. Their exceptional prowess in narrative construction and scene generation aligns perfectly with the needs of cultural tourism IP revitalization and experiential upgrades, evolving into a "creative accelerator" capable of collaborative innovation with human wisdom [1-2]. Against this backdrop, this study raises the core question: How can generative AI empower the innovation and value enhancement of Guangxi's sugarcane cultural tourism IP through narrative reconstruction and immersive experience design? It also attempts to construct a full-chain innovation framework spanning from foundational data governance to top-tier business model implementation.

To address the aforementioned research questions, this paper follows the logical framework of "theoretical construction—path design—meaning interpretation." First, it constructs a theoretical framework to explain the role of generative AI in the innovation of cultural tourism IPs. Second, it proposes practical pathways for narrative reconstruction and immersive experience design. Finally, it discusses the broader implications for the digital transformation of regional cultural industries, aiming to provide actionable solutions for the digital upgrade of cultural tourism IPs in Guangxi and beyond.

2. Selecting the Typicality and Research Value of Guangxi's Sugarcane Culture

Guangxi's sugarcane culture provides an ideal observational sample for this study. The rationale for selecting this case lies in Guangxi's consistent ranking as the top sugarcane producer nationwide for many consecutive years, forming a comprehensive cultural spectrum from agricultural cultivation and sugar-making techniques to folk festivals and dietary traditions. This cultural complex encompasses both material aspects—production technologies, artifact remnants, and industrial sites—as well as spiritual dimensions—folk beliefs, festive rituals, and oral traditions—endowing it with profound potential for cultural exploration and innovation. Meanwhile, despite its abundant resources, Guangxi's sugarcane-related cultural tourism development has long faced structural challenges such as ambiguous IP identities, outdated narrative approaches, and monotonous experiential formats. These difficulties are not isolated cases but rather reflect the widespread conditions of cultural resource exploitation in China's numerous counties and specialized agricultural sectors. Additionally, Guangxi has incorporated high-quality sugar industry development and cultural tourism integration into its regional strategic planning, offering both policy support and practical platforms for the implementation of research findings.

Based on the above analysis, this study takes Guangxi sugarcane culture as a case sample and employs the case deduction method for research. Specifically, it analyzes the cultural tourism resource endowment and development status on the basis of literature review and field research, identifying three core challenges: ambiguous IP, weak narrative, and monotonous experiences. Subsequently, it maps the technical characteristics of generative AI to specific application scenarios using deductive logic, constructing actionable practical pathways. In summary, Guangxi sugarcane culture possesses substantial resource depth, typical challenges, and policy response potential,

making it a suitable case for exploring how generative AI can drive innovation in cultural tourism IPs. The findings from this case study provide valuable references for the digital transformation of similar regional cultural heritages.

3. Theoretical Framework

When exploring the empowering mechanism of generative AI for cultural and tourism IP innovation, it is necessary to establish a clear theoretical framework to systematically explain its core role in cultural heritage and experiential innovation. This article argues that generative AI mainly plays the dual roles of "narrative reconstructor" and "experience designer" in the construction process of cultural and tourism IP, achieving creative transformation of cultural resources through its unique technological characteristics. The former focuses on the deep exploration and creative transformation of cultural resources, while the latter focuses on the intelligent construction of immersive environments. The synergistic effect of two roles jointly promotes the paradigm transformation of cultural and tourism IP from static heritage statements to dynamic experiential scenarios [3-4]. As shown in Table 1.

Table 1: Dual-role framework of generative AI empowering cultural tourism IP

Role	Core Capability	Technical Pathway	Expected Output
Narrative Reconstructor	Understand & integrate knowledge	Build knowledge graph, extract key elements	Structured cultural database
	Generate & adapt content	Create audience-specific narratives	Multiple story versions
	Create cross-modal symbols	Turn abstract ideas into visuals	IP characters, 3D models
Experience Designer	Simulate & generate scenarios	Produce designs from scene inputs	Immersive scenarios
	Enable dynamic interaction	Generate character-based dialogues	Smart NPC system
	Personalize content	Analyze users, adapt in real time	Tailored experien

4. Practical Path of Cultural Narrative Reconstruction Driven by Generative AI

Narrative is the core value of IP. The intervention of generative AI aims to systematically reconstruct static and thin heritage statements into dynamic and abundant "story worlds"[5].

4.1 Bottom level data construction and IP role creation

The premise of narrative reconstruction is to construct a structured "cultural database". This study systematically integrates historical documents, folk legends, environmental landscapes, and industrial data of sugarcane culture in Guangxi, and vectorizes them to

form an exclusive domain knowledge base to ensure the accuracy and cultural consistency of AI generated content. On this basis, using generative AI to systematically create IP roles and symbols, the specific path is shown in Table 2.

Table 2: Role creation path of sugarcane cultural tourism IP based on generative AI

Role Type	AI Prompt Focus	Output	Application Value
Core IP Image	Sugarcane spirit, Zhuang brocade, "sweet dedication"	Digital artwork, orthographic views, 3D model	Unified regional visual symbol for signage and cultural products
Historical Digital Twin	Han official, farming Q&A, first-person	Backstory, Q&A knowledge base, voice assets	AR museum tours & interactive Q&A, enhancing educational engagement
Modern Industry Persona	Smart farmer virtual idol, EDM folk	Character profile, short video script, motion comic	Rebranding agriculture, attracting youth, for public branding and education

4.2 Multi line narrative and dynamic plot generation mechanism

Generative AI achieves a paradigm shift from single narrative to personalized narrative by constructing dynamic narrative systems. Based on tourist portrait data, the system achieves narrative innovation through three levels of data perception, content generation, and interactive presentation while ensuring cultural accuracy and historical authenticity, and dynamically adjusts content complexity based on tourist feedback [6]. This mechanism has demonstrated significant adaptability in practical applications, as shown in Table 3.

Table 3: Dynamic Narrative Generation Mechanism Based on Tourist Portraits

Target Tourist	Narrative Theme	AI Prompt Strategy	Generated Content
Family with Kids	"A Candy's Fantastic Journey"	Fairy tale with "Sugarcane Spirit" guiding 3-level sugar adventure	3-stage adventure (growth→pressing→ crystallization)
Cultural Research Tourists	"The Long Sugar Road: Migration & Exchange"	Travelogue on sugarcane's Maritime Silk Road spread with historical evidence	Study route: history, geography, archaeology, with refs & Qs.
Gen-Z Check-in Group	"Poem of Light & Sugarcane"	5 viral check-in concepts with short video copy	Concepts & shareable video scripts to inspire UGC.

5. Innovation in Immersive Experience Design Empowered by Generative AI

The reconstructed narrative system provides a rich content foundation for experience design, while generative AI technology, through its powerful content generation and interaction capabilities, promotes the breakthrough of experience forms beyond the limitations of physical space, achieving a fundamental transformation from traditional viewing to deep immersion [7].

5.1 AIGC Driven Immersive Script Game Paradigm

Generative AI reshapes the traditional script-based tourism model, turning the sugar culture scenic area into a dynamically responsive narrative field. Acting as a "global game master," the AI enables intelligent transformation across four key elements. For plot architecture, it breaks fixed single-line modes by generating branch tasks and multi-line endings based on real-time tourist behavior and environmental data, ensuring unique experiences. For task props, AR and virtual content creation build a mixed-reality prop system, lowering costs while enhancing technological engagement. For NPC interaction, AI-driven virtual characters overcome the limits of human actors, supporting deep, free dialogue between tourists and any story character. For puzzle challenges, the system adapts to visitors' cognitive levels and progress to generate personalized challenges, ensuring optimal flow experiences [8-9]. See Table 4 for details.

Table 4: Core Design Comparison: AIGC Immersive Scripted Tour

Design Element	Traditional Model	AI-Augmented Model	Key Enhancement
Plot Structure	Linear, Fixed	Dynamic, Multi-branch	High replay value, Personalized experience
Tasks & Props	Physical Props	AR Virtual Props	Low cost, High interaction, Easy to update
NPC Interaction	Live Actors	Smart Virtual Characters	24/7 availability, Unlimited dialogue freedom
Puzzle System	Fixed Difficulty	Adaptively Generated	Personalized challenge, Optimized flow experience

5.2 Scene experience construction of virtual real fusion

Generative AI, as the core technology connecting physical space and digital content, achieves immersive presentation of cultural heritage by constructing a multi-level mixed reality experience framework [10]. This framework includes three innovative application modes: AR historical scene revival based on building structures and historical archives, generating dynamic historical scenes overlaid on real sites, allowing tourists to have a visual experience that transcends time and space; VR scene construction creates a virtual environment free from physical limitations through creative prompts, creating visual wonders from the micro to the future; Intelligent light and shadow shows analyze environmental data and tourist behavior in real-time, dynamically generating narrative light and shadow art. These applications enrich the sensory experience of tourists and achieve the organic integration of natural landscapes, cultural heritage, and digital technology [11-12]. See Table 5 for details.

Table 5: AIGC-Enabled Phygital Experience Design

Scene Type	Physical Space	AIGC Content	Experience Value
AR History Revival	Heritage Site	AR scenes from historical data	Cross-time dialogue via reality overlay
VR World Creation	Experience Pod	Micro/Future VR environments	Beyond-reality visual wonders
Smart Light Show	Field/Building	Real-time interactive visuals	Unique nightly attraction

5.3 Personalized Content Generation and Social Communication Drivers

Throughout the entire tourism process, generative AI serves as a personalized creative assistant, stimulating tourists' willingness to share and dissemination behavior through three stages: pre trip, during trip, and post trip. In the pre game stage, the system generates personalized Vlog scripts; During the mid game stage, AI generates stylized filters and captions; In the post travel stage, the system creates digital travelogues and generates NFT souvenirs. The entire creative process is accompanied by social sharing to form a brand communication effect. As shown in Table 6.

Table 6: AIGC-Enabled Content Generation Across the Travel Journey

Travel Phase	AIGC Content	AI Prompt Strategy	Core Value
Pre-trip: Inspiration	Personalized Vlog Script	Generate vintage-style script based on user profile, with transitions, angles, and music.	Creates appeal, inspires travel decisions, and enables pre-trip buzz.
During-trip: Experience	Smart Filter & Caption	Analyze photo composition; generate custom filters and stylistic captions.	Provides high-quality social media content, encouraging real-time sharing and viral spread.
Post-trip: Retention	Digital Travelogue & NFT	Synthesize trip data and photos into a styled travelogue and unique digital souvenir (NFT).	Transforms experience into emotional assets, strengthening brand connection and long-term memory.

6. Conclusion

This study constructs and demonstrates the theoretical framework and practical path of generative AI empowering regional cultural and tourism IP innovation. The results indicate that generative AI, as a "narrative engine" and "experience simulator", can effectively drive the dual transition of Guangxi sugarcane tourism IP. At the cultural narrative level, it breaks through static and one-way heritage statements, reconstructs into a dynamic interactive "story world", and injects sustainable derived content soul into IP. At the level of experience delivery, it innovates immersive script tours, constructs virtual real fusion scenes, and realizes personalized services throughout the entire process, promoting tourists to move from passive sightseeing to active exploration, significantly enhancing their sense of participation, satisfaction, and

willingness to share [13]. Therefore, generative AI provides an efficient digital empowerment path for underdeveloped but distinctive regional cultural and tourism resources, with both theoretical value and practical inspiration.

It should be noted that this study is mainly based on theoretical construction and case deduction, and the proposed framework still needs empirical testing. In the future, actual effects can be quantitatively evaluated through experiments, questionnaires, or case studies, and as the capabilities of generative AI in multimodal interaction, real-time generation, emotional computing, and other areas evolve, the iterative optimization of relevant frameworks will continue to be promoted.

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Synergistic Innovation Model in Education Integrating Mathematics, Computer Science, and Generative AI

Plamena ZLATEVA[a,b,1], Liudmila STESHINA[c], Igor PETUKHOV[c] and Dimiter VELEV[a]
[a]*University of National and World Economy, Sofia, Bulgaria*
[b]*Institute of Robotics, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[c]*Volga State University of Technology, Yoshkar-Ola, Russia*
ORCiD ID: Plamena Zlateva https://orcid.org/0000-0002-0153-5811
Igor Petukhov https://orcid.org/0009-0000-2365-4857
Dimiter Velev https://orcid.org/0000-0003-3030-1819

Abstract. Mathematics and computer science constitute the foundational pillars of Generative Artificial Intelligence (GenAI), enabling the design of models capable of learning complex patterns from large-scale data and generating novel, meaningful outputs. Core mathematical disciplines, including probability theory, statistics, linear algebra, and optimization, provide the theoretical basis for generative modeling, while computer science translates these principles into practical algorithms, neural architectures, and scalable computing systems. This tendency adopts the concept of intelligent integration to describe the deep, systemic interaction among mathematics, computer science, and GenAI in education. The paper proposes a Synergistic Innovation Model in Education integrating mathematics, computer science, and GenAI, highlighting how their joint interaction drives innovation in education. The paper aim is to uncover the complex connections between these three disciplines and demonstrate how their unification enables the creation of powerful generative models that can produce new and meaningful knowledge in education.

Keywords. Mathematics, Computer Science, Generative Artificial Intelligence, Education, Synergistic Innovation Model

1. Introduction

Artificial intelligence (AI) has experienced revolutionary progress in recent years, with one of its most notable manifestations being the Generative Artificial Intelligence (GenAI). Unlike traditional AI systems that focus on recognition, classification, and prediction, GenAI models have the ability to create new content - text, images, sounds, and even structured ideas. This places them at the center of a technological transformation in which creativity and algorithms are intertwined.

However, this transformation would not have been possible without two deeply intertwined disciplines: mathematics and computer science. GenAI is fundamentally a

[1] Corresponding Author: Plamena Zlateva, University of National and World Economy, 19 December 8th Str., 1700 Sofia, Bulgaria; E-mail: plamzlateva@unwe.bg.

mathematical formalism, implemented through algorithms, architectures, and computational logic. Mathematics provides the language in which models are defined, their probabilistic structure, loss functions, and optimization processes. Computer science, in turn, provides the means to represent, train, and scale these models - from classical neural networks to modern architectures such as transformers and diffusion networks.

GenAI cannot be discussed in isolation, but rather as the result of a deep integration between the abstract power of mathematics, the engineering power of computer science, and the creative potential of algorithms that generate content. The targeted synergy is not simply the joint use of tools from different sciences, but it is a principle of a new type of thinking in which the boundaries between abstraction, algorithm, and creativity are blurred.

The paper's novelty does not lie in redefining the mathematical or computational foundations themselves, but in proposing a new synergistic innovation model in education that systematically integrates mathematics, computer science, and Generative AI into a unified conceptual and pedagogical framework.

The paper proposes a Synergistic Innovation Model in Education integrating GenAI, mathematics, computer science, and, highlighting how their joint interaction drives innovation in education. The paper aim is to uncover the complex connections between these three disciplines and demonstrate how their integration enables the creation of powerful generative models that can produce new and meaningful knowledge in education.

2. The Role of Mathematics in the Foundations of Generative Artificial Intelligence

Mathematics is the backbone of any intelligent system, and in the case of GenAI its role is particularly deep and multifaceted. From probabilistic models to linear algebra and optimization theory, every aspect of mathematical knowledge finds application in building, understanding, and improving generative models. It is mathematics that gives meaning to intelligent behavior by formalizing concepts such as uncertainty, approximation, learning, and generation [1, 2].

At a conceptual level, GenAI models are based on the idea of learning the probability distribution that describes a given type of data - images, language sequences, or sound [3, 4]. This implies the existence of a hidden space that models the internal dependencies in the observed data. From a mathematical point of view, this means working with conditional and marginal probabilities, stochastic processes, Bayesian statistics, and variation approximations.

Linear algebra plays a key role. Most GenAI models operate in multidimensional vector spaces. Vectors, matrices, tensors, and their transformation and decomposition are objects of linear algebra [5, 6].

Optimization theory plays a fundamental role in training generative models. Most AI systems rely on minimization of a loss function, often through stochastic gradient descent (SGD), adaptive methods or combined techniques for accelerated convergence. This entire framework is mathematically defined in terms of derivatives, Jacobians, Hessians, convexity, and related properties. It allows not only training, but also analysis of the robustness, regularization, and stability of trained [7, 8].

Of particular interest is the role of differentiable programming, which is a concept that uses symbolic and numerical techniques to automatically differentiate expressions in order to optimize training [9, 10]. This idea, which arose from mathematical analysis and computer algebra, is now fundamental to training deep generative models.

The role of graph theory cannot be ignored, which finds application in models such as Graph Neural Networks (GNNs), which can also be generative for creating new molecules, social networks or semantic structures [11, 12]. Graphs are not just a visualization structure, but formal objects with defined properties such as connectivity, spectral characteristics and structural entropy.

Geometry is another important aspect, and more precisely differential geometry, which explains how latent spaces (in models such as VAE or Diffusion Models) can be viewed as manifolds with a curved structure [13]. This is important for modeling smooth navigation and interpolation in generative spaces when generating new samples from the learned distribution.

The stochastic processes underlie the so-called diffusion models, which is the latest generation of GenAI architectures [14]. They use ideas from Brownian motion, Ito processes and solving stochastic differential equations to create a process of adding and removing noise through which new information is generated.

All that demonstrates that mathematics is not a hidden ingredient, but an essential part of GenAI. Without it, there is no way to formulate, optimize, nor interpret these models. It is mathematics that provides not only the language, but also the intuition through which these algorithms function.

3. Computer Science as the Architect of GenAI

While mathematics provides the language and formalism through which GenAI models can be defined and understood, computer science is the one that makes them a reality. It is provides the architectural principles, algorithmic logic, and software environments through which GenAI is realized as a functioning technology.

Complex neural network architectures are at the core of GenAI [15]. Some of the first models with generative capacity were Boltzmann Machines and Restricted Boltzmann Machines, which rely on a probabilistic configuration of two-layer neurons. Their implementation and training require knowledge of Markov Chain algorithms, Gibbs Sampling, and Contrastive Divergence are a part of the computer science toolkit.

The development of deep learning has led to architectures such as Variational Autoencoders (VAE), Generative Adversarial Networks (GAN), Transformers, and Diffusion Models, each of which requires detailed algorithmic and programming implementation [16]. A careful balancing of gradients, robust training, and efficient use of resources is required. These tasks are solved through optimizations at the code, compiler, and hardware levels.

Transformers, which currently dominate language modeling, are based on concepts such as attention mechanisms, positional encodings, and scalable self-attention blocks [17]. The implementation of these networks is closely related to computer science disciplines such as algorithm theory, data structures (specially organized matrices, sparse representation), and parallel computing (GPU, TPU, CUDA).

Computer science plays a key role in creating software ecosystems that enable the building, training, and use of generative models. Frameworks such as TensorFlow, PyTorch, JAX, and HuggingFace are examples of how a programming culture united

around open source makes complex generative models accessible to a wide range of developers and scientists. Each of these tools provides not only an API for modeling, but also optimized backends for automatic differentiation, parallelization, and hardware abstraction.

Algorithm theory also plays an important role, providing efficient methods for training and searching in large parameter spaces [18, 19]. The use of stochastic optimization methods, such as Adam or RMSProp, is the result of collaborative work between statistical modeling and algorithm design specialists. The use of hashing, search trees, dynamic programming, and probabilistic algorithms complement this portfolio.

Computer security and cryptography are also starting to enter generative models. Differential Privacy, Federated Learning, and Homomorphic Encryption are examples of technologies that provide security and privacy when using and training sensitive data in a generative context [20, 21]. Computer science provides methods for data protection and traceability from the lowest to the highest level.

From an infrastructure perspective, cloud computing, containerization (Docker, Kubernetes), MLOps, and automated model deployment are critical for the real-world use of GenAI systems. The engineering aspects of computer science manifest themselves in the need for reliability, scalability, continuous learning, and version control.

Computer science is also behind testing frameworks, debugging tools, and methods for explainability and visualization [22]. Approaches such as SHAP, LIME, Attention Visualization, and Activation Atlases use algorithmic logic to make generative models more transparent and interpretable.

Computer science explores the boundary between classical algorithms and learnable algorithms to combine symbolic programming with neural representations. Ideas such as Neural Programming, Program Synthesis, Differentiable Data Structures, and Soft Constraints point to future directions in which algorithms and models will merge into one. Computer science is the architect, engineer, and builder of GenAI. It not only enables mathematical ideas to be implemented, but also defines new paradigms for the interaction between code, data, and models.

4. GenAI - Intersection and Catalyst

GenAI is not just an application of mathematics as a theoretical foundation and computer science as an engineering platform, but also a unique synthesis of them, in which new forms of computation, knowledge representation and content creation arise [23, 24]. GenAI is not just a technology, but it is a methodological bridge through which abstract ideas become practical tools [25, 26, 27].

GenAI differs from discriminative models in its purpose. While the latter seek to categorize or predict, classify images, or translate texts, GenAI models have the task of creating new examples that are statistically similar to the training data. This ability requires an exceptional symbiosis between the mathematical model and its computational implementation.

When a GenAI model generates an image from a text description, it must interpret the latent representation of the linguistic description, transform it into a multidimensional vector, and then decode it into a pixel structure that is meaningful to human perception. This requires complex data processing across multiple spatial and semantic domains. Instead of manually defined features, GenAI models learn what is important from the data themselves through the training process. This idea arises from a combination of

statistical learning (mathematics), neural networks (computer science), and creative application.

An important intersection is the ability of GenAI to be used as a unifying model for different types of data. Examples of this are foundation models such as GPT, T5, PaLM, LLaMA, which use the same architecture to process text, images, code, and even audio. This necessitates an interdisciplinary approach, where mathematics defines the multimodal structure of the data and computer science provides the adaptive processing.

GenAI serves as a catalyst even in the opposite direction through its needs and limitations, it poses new questions for mathematics and computer science. The need for better training methods in data-limited situations has led to the development of new approaches such as few-shot, zero-shot learning, transfer learning, which require new forms of regularization, generalization and optimization.

In the context of efficiency, GenAI models pose serious challenges to algorithmic optimization and hardware implementation, which is another area where intelligent integration is deepening [28, 29]. The use of sparsity (parameter thinning), pruning, quantization and knowledge distillation are examples of techniques that combine mathematical principles and software optimization.

At a conceptual level, GenAI changes the very understanding of what an algorithm is. In classical systems, an algorithm is a strictly defined procedure, while in GenAI, the algorithm is a trained object, the result of optimization, not a predefined logic [30, 31]. This is a fundamental shift in the philosophy of computation, with implications for algorithm theory, formal languages, and even logic.

In this sense, GenAI does not simply exploit the intelligent integration of mathematics and computer science, but it embodies and deepens it. GenAI acts as a catalyst for new theoretical discoveries and practical applications, pushing the boundaries of both disciplines and drawing attention to new paradigms of thinking. GenAI is no longer just a tool, but a new form of computation that combines formal rigor with adaptive creativity. This makes it unique not only as a technology, but also as a research object and philosophical challenge.

5. Case Studies

To illustrate the synergistic innovation model of mathematics, computer science, and GenAI, it is necessary to go beyond theoretical principles and focus on concrete applications that demonstrate this synergy in real-world settings. The following case studies illustrative educational scenarios demonstrate the potential practical implementation of the proposed Synergistic Innovation Model in educational environments.

Case Study 1 - Personalized Mathematics Learning: GenAI systems can dynamically generate personalized mathematics exercises according to learner performance. Students can receive problem sets, which are generated in real time based on previous errors and learning speed. This learning approach will indicate improved learner engagement, faster conceptual understanding, and increased participation in problem-solving activities.

Case Study 2 - Interdisciplinary AI Projects: Students, who participate in interdisciplinary AI projects, can combine mathematical modeling, programming and GenAI simulations to solve real-world problems. They can develop predictive intelligent tutoring systems integrating probability models, neural architectures, and adaptive

feedback generation. Such project-based environments support collaborative learning, creativity development, and computational thinking competencies.

Case Study 3 - Adaptive Assessment: GenAI supports the implementation of intelligent assessment systems, which are capable of generating personalized quizzes, explanations, and feedback according to individual learner needs. GenAI can be used to identify knowledge gaps and dynamically adjust instructional strategies. Such approach creates an ecosystem with continuous feedback, in which mathematics, computer science, and GenAI jointly support educational optimization.

Case Study 4 - Industrial Design Education: The proposed synergistic innovation model can also be applied in industrial design education through the integration with augmented reality technologies. Students can experiment through 3D visualization, simulation algorithms, and augmented reality platforms. GenAI systems can automatically generate alternative design concepts, prototypes, and interactive visualizations in real time. Learners can examine virtual industrial objects, test design modifications, and analyze structural characteristics. Such interdisciplinary approach combines mathematical reasoning, computational technologies, and creative AI-supported design processes. The case demonstrates the applicability of the proposed synergistic innovation model in technology-oriented and creative educational contexts.

Case Study 5 - GenAI Learning for Natural Disaster Preparedness:

The proposed synergistic innovation model can be applied in education related to natural disaster preparedness and crisis management. Mathematical models can be used to simulate different natural disasters, such as floods, earthquakes, wildfires. GenAI can dynamically create adaptive disaster-response scenarios, emergency simulations, decision-making tasks. Students can optimize many response outcomes through evacuation routes, allocate resources, analyze risk propagation in real time. The approach supports the development of critical thinking, collaborative problem-solving, and real-world analytical skills. This case illustrates the practical educational applicability of the proposed synergistic innovation model.

All those cases show that the synergistic innovation model is not an abstract idea, but a working reality. It enables the solution of problems that previously seemed beyond the capabilities of machines. GenAI, combined with mathematics and computer science, is moving from the lab to the real world, changing the way people heal, create, program, and learn.

6. Education and Interdisciplinary

With the growing importance of GenAI in the scientific, industrial and cultural spheres, there is an urgent need to rethink educational paradigms. Since GenAI embodies the synthesis between mathematics, computer science and new forms of computation, education in this area cannot be limited to traditional disciplinary boundaries [32, 33]. It is necessary to develop an interdisciplinary approach that will prepare a new generation of specialists.

In many educational systems, mathematics and computer science are taught in isolation. Mathematics is often presented as a set of theorems and exercises, without any connection to real-world applications [34]. Computer science, focuses on programming, algorithms and data structures, but rarely examines in depth the mathematical foundations of machine learning and generative models. GenAI, which relies on complex

stochastic processes, linear algebra, differentiable optimization and neural architectures, stands as a catalyst for new forms of knowledge and innovation [35, 36, 37].

New educational programs should integrate knowledge from mathematics, computer science and GenAI from the early stages of training. This can be achieved through courses that simultaneously explain concepts such as loss functions, probability distributions and neural architectures in the context of real-world applications. In this way, specialists are educated who not only understand how a given generative model works, but also how to apply it in a context where there are regulatory, social and ethical consequences.

GenAI is particularly well-suited for project-based learning. Students can create their own models, train them on their own data, and analyze the results [38, 39]. This approach requires an understanding of both mathematical principles and programming environments [40, 41].

GenAI education should not be limited to technical aspects. It is important to also integrate courses on AI ethics, societal impacts of automation, and legal aspects. This will produce specialists who understand both the possibilities and limitations of the technology. Discussing deepfake technologies, false content generation, or bias in training data is impossible without a multidisciplinary approach.

Teachers should not be just transmitters of knowledge, but facilitators of interdisciplinary thinking. This requires them to be trained in new ways through professional development, joint courses between faculties, participation in research communities and hands-on work with models. Universities need to create a culture of collaboration between math, engineering, humanities and arts departments.

Massive open online courses (MOOCs), YouTube channels, open books and dedicated platforms allow access to the latest knowledge on GenAI. The educational strategy should also include skills for critically evaluating these resources how to choose a quality course, how to validate what has been learned through practice and how to engage in global communities of learning.

The developed idea can be operationalized through several pedagogical strategies. Project-based learning environments may combine mathematical modeling, algorithm development, and GenAI-supported content creation within integrated interdisciplinary tasks. Adaptive learning systems powered by GenAI can dynamically personalize educational materials according to learner progress, cognitive characteristics, and performance analytics. Collaborative problem-solving activities may also combine programming, data analysis, and AI-assisted simulation to strengthen both technical and creative competencies.

7. Challenges and Ethical Considerations

As the role of GenAI in society grows, the challenges that accompany its development and application also become more relevant. They are not limited to technical difficulties, but also concern deep ethical, philosophical, legal and social issues. Viewing these challenges through the prism of the intelligent integration of mathematics, computer science and GenAI allows to understand them in all their complexity.

GenAI models learn from huge amounts of data, which often reflect existing racial, gender, cultural, or political biases. Although mathematics assumes neutrality, the choice of data and parameters introduces subjectivity. Computer science, through methods of regularization, filtration and fairness metrics, tries to mitigate these effects. GenAI often

reproduces and amplifies them through text responses, images or automatically generated recommendations.

GenAI models can generate realistic images, video and audio that are almost indistinguishable from real ones. This raises concerns about the authenticity of information, forgeries and manipulation of public opinion. From a mathematical point of view, deepfake models are highly optimized for similarity in metrics such as perceptual loss. Computer science is developing detection methods, but the race between generation and detection is constant.

The generated texts, images and music raise the question about the identity of their author. The question arises about responsibility of the creator of the model, the training organization or the user. Here the need arises for new legal definitions that go beyond the classical understandings of authorship. The mathematical idea of similarity and derivative works must be combined with legal frameworks for the protection of original ideas and works. GenAI sets new boundaries for creativity and ownership.

GenAI models are often black boxes. Although impressive results are achieved, it is not always clear why the model made a given choice. This is a serious problem in sensitive applications such as medicine, law, or finance. Mathematics here can offer formal methods of analysis, such as sensitivity analysis, attribution methods, but computer science must implement explainable interfaces and visualizations. GenAI raises the need for trust in results that are not always intuitively explainable.

Training large models, such as GPT-4 and DALL·E, requires enormous amounts of energy and hardware resources. This raises questions about the sustainability of this technology from both ecological and economic perspective. Computer science is looking for ways to optimize through knowledge distillation, sparsity, transfer learning, but the scale of the models themselves continues to grow. Mathematics can help through new formulations of tasks that require fewer calculations or allow approximate solutions.

GenAI can be used for manipulation through fake news, personalized propaganda, imitating personalities. This undermines trust in public information and strengthens cognitive biases. Mathematical models used in recommender systems can unintentionally trap users in information bubbles. The responsibility lies with both model designers and the platforms that implement them.

GenAI can democratize content creation, but it also leads to a concentration of power in the hands of a small number of organizations that have the resources to train large-scale models. This creates imbalances in access to technology, innovation, and economic benefits. The challenges and ethical considerations surrounding GenAI cannot be solved by a single discipline. GenAI requires collaboration between mathematicians, engineers, philosophers, lawyers, and society a dialogue between collaboration between mathematicians, engineers, philosophers, lawyers, and society.

8. Future Directions of Research and Application

The development of GenAI not only continues at a rapid pace, but also opens up new horizons that change scientific, technological and social paradigms. Future directions of research and application are an expression of the deepening intelligent integration of mathematics, computer science and GenAI.

One of the main goals in GenAI is the creation of universal models that can process text, images, audio, video, code and other types of data in the same architecture. Mathematics will have to define new forms of representation and transformations

between different spaces, while computer science will look for ways of effective learning and compatibility between modalities.

GenAI is expected to become a research partner in generating hypotheses, simulating experiments, analyzing large scientific corpora, and even proposing new theories. This will require new interactions between knowledge formalization (mathematics), computational simulation (computer science), and GenAI. Generative models will be the basis of autonomous agents that can plan, communicate, interact with the environment, and make decisions based on partial or uncertain information. This will require a combination of reinforcement learning, game theory, probabilistic graph models, and neural architectures that combine reasoning and creativity. Such agents may find applications in robotics, autonomous transportation, virtual assistants, and intelligent control systems.

The idea of modeling individual users through digital twin concept is developing fast nowadays. Such models will require a precise combination of mathematical approaches for modeling temporal and semantic dependencies, software frameworks for protecting personal data and GenAI components for adaptive content and behavior generation.

GenAI will be the basis for the creation of synthetic worlds for games, simulations, virtual reality, education and art. These worlds will be generated automatically based on a linguistic description or visual templates, which will require new models for 3D generation, physical simulation, interaction with real objects and cognitive modeling. The synthesis between formal models of reality and adaptive generation will open new paths for exploring virtuality.

The future of GenAI includes systems that collaborate with people in real time for writing, design, music, science. This will require the development of interfaces that enable mixed human-machine interaction, in which AI suggests ideas or suggests alternatives. Mathematical models of joint agency, algorithms for adaptive interaction, and GenAI with a capacity for contextual creativity will be the core of this idea.

GenAI has the potential to lead to a new theory of the structure and dynamics of knowledge. Instead of fixed ontologies, models of knowledge will be developed that are adaptive, contextual, and capable of self-organization. This will require new ideas in category theory, semiotics, information theory, and cognitive science.

With the development of new applications, ethical and legal frameworks will need to be established to define the boundaries of what is permissible in the creation of realistic faces, voice simulation, and automatic news generation. GenAI will require new definitions of truth, reality, authorship, responsibility, and the right to know.

9. Synergistic Innovation Model in Education

The paper highlights a complete transformation of the understanding of modern education, based on the deep integration between GenAI, mathematics and computer.

Unlike traditional interdisciplinary educational approaches, the proposed model introduces a structurally integrated framework in which mathematical reasoning, computational architectures, and GenAI operate as mutually adaptive components of knowledge creation.

This study adopts a conceptual and interdisciplinary research methodology aimed at developing a synergistic innovation framework integrating mathematics, computer science, and GenAI in education.

The proposed model was derived through a systematic analytical review of contemporary scientific literature related to mathematical foundations of AI, computational architectures, machine learning systems, adaptive educational technologies, and Generative AI applications. The methodological approach combines comparative conceptual analysis, interdisciplinary synthesis, and abstraction of recurring structural relationships identified across the reviewed domains.

Particular attention was given to the interaction between mathematical formalism, algorithmic implementation, adaptive learning mechanisms, and AI-driven knowledge generation. The idea is to propose a conceptual integration model synthesizing these interconnected components into a unified educational ecosystem.

At this stage the paper does not aim to provide empirical validation of the model, but proposes a theoretical foundation for future empirical studies, Delphi-based expert evaluations, and practical implementation in educational environments.

This transformation is not simply technological, but conceptual, introducing new models of thinking, teaching and learning. Figure 1 shows the proposed synergistic innovation model in education. The proposed framework conceptualizes GenAI not only as an assistive educational technology, but as an active adaptive participant capable of dynamically co-creating personalized learning trajectories

The **first significant innovation** is the concept of intelligent integration of disciplines. Unlike traditional interdisciplinary approaches, in which different areas exist in parallel, here a deep structural interweaving between mathematical models, algorithmic methods and GenAI systems is observed. This leads to the creation of a new type of educational ecosystem, in which knowledge is not divided into separate domains, but functions as an interconnected network. Thus, learners develop systematic thinking and the ability to solve complex problems, which is key for the digital economy.

The **second significant innovation** is the transformation of the role of GenAI from an auxiliary tool to an active participant in the educational process. Generative models not only support teaching by automatically generating learning materials, tasks and examples, but also create personalized learning trajectories. This allows adaptation to the individual cognitive characteristics of learners, including learning pace, learning style and level of prior knowledge. In this way, a transition is implemented from mass to personalized education, which significantly increases the effectiveness of learning.

The **third innovation** consists in introducing mathematically formalized approaches to practical learning using GenAI systems. Abstract areas such as linear algebra, probability theory and optimization methods are transformed into practical tools integrated into real-world applications. Through GenAI, learners can experiment with models, simulate scenarios and analyze results in real time. This significantly reduces the distance between theory and practice and supports a deeper understanding of complex concepts.

The **fourth innovation** is related to the change in the pedagogical model from content-oriented teaching to knowledge-creation-oriented learning. GenAI enables learners to co-author learning content by generating solutions, models, and new hypotheses. This leads to the development of creativity, critical thinking, and research skills which are essential in today's scientific and technological environment.

The **fifth innovation** is the integration of ethical, legal, and governance principles directly into the architecture of intelligent educational systems. Instead of considering these aspects as external constraints, they become a core component of the system design. This includes mechanisms for algorithm transparency, traceability of decisions, and

ensuring equitable access to educational resources. This builds a sustainable and responsible framework for implementing AI in education.

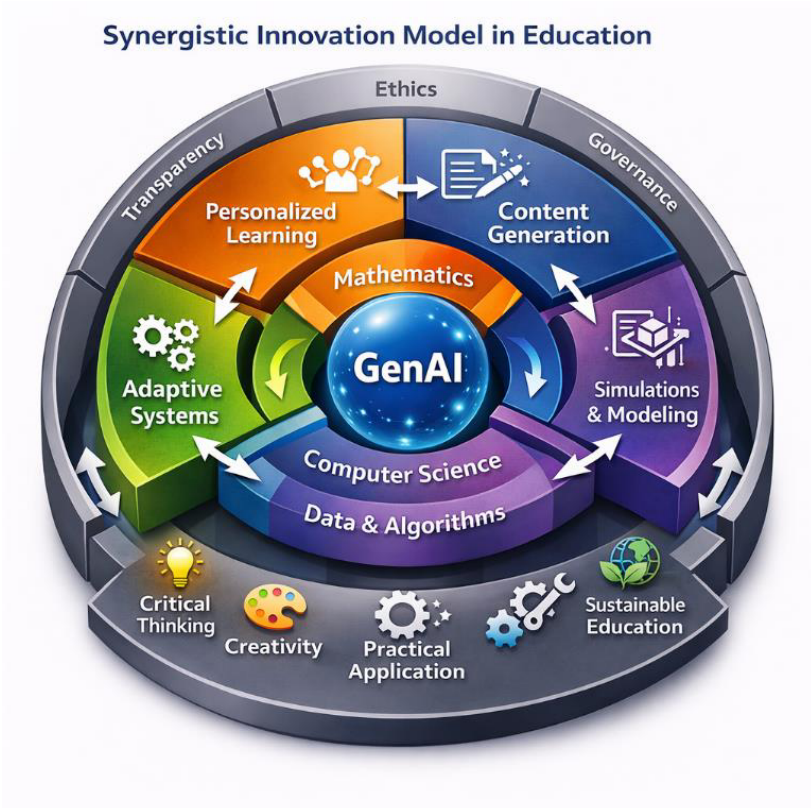


Figure 1. Synergistic Innovation Model in Education integrating Mathematics, Computer Science and GenAI

The **sixth innovation** is related to the use of data and analytical methods for continuous improvement of the educational process. By collecting and analyzing data on the behavior and progress of learners, systems can dynamically optimize learning strategies. This leads to the creation of adaptive learning environments that self-improve over time and provide increasingly accurate and effective solutions.

The effectiveness of the proposed model may be evaluated through measurable educational outcomes, including improvement in interdisciplinary problem-solving skills, learner engagement, adaptive performance progression, computational thinking development, creativity enhancement, and critical reasoning abilities. Additional indicators may include personalized learning efficiency, collaborative interaction quality, and the ability to apply mathematical and computational concepts in real-world AI-supported contexts.

The article highlights the innovation in the creation of a new type of educational infrastructure based on digital platforms and intelligent systems. This infrastructure allows for scalability, accessibility and flexibility, while supporting global collaboration between learners, educators and researchers. As a result, a new educational paradigm is formed that meets the requirements of modern society and knowledge-based economy.

10. Conclusion

The intelligent integration of mathematics, computer science, and GenAI is not as a formal set of disciplines, but as a deeply integrated process of creating, understanding, and implementing a new type of intelligent systems. This process turns out to be not just useful, but necessary.

The primary contribution of this study is the proposed synergistic innovation model that reconceptualizes the relationship between mathematics, computer science, and Generative AI in education. The model extends beyond traditional interdisciplinary approaches by introducing intelligent integration, adaptive co-creation, and ethically grounded AI-supported educational ecosystems

The proposed Synergistic Innovation Model in Education, integrating mathematics, computer science, and GenAI represents a fundamental driver of modern scientific and technological development. This model not only expands the boundaries of knowledge and innovation, but also lays the foundation for future responsible applications that will define the way society interacts with new technologies.

Acknowledgment

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Digital Dualism: Legal Status of Civilian Datasets as Legitimate Military Targets in the Age of AI

Dimiter VELEV[a,1], Boyka CHERNEVA[a], Petya MITREVA[a], and Plamena ZLATEVA[a,b]
[a]*University of National and World Economy, Sofia, Bulgaria*
[b]*Institute of Robotics, Bulgarian Academy of Sciences, Sofia, Bulgaria*
ORCiD ID: Dimiter Velev https://orcid.org/0000-0003-3030-1819
Plamena Zlateva https://orcid.org/0000-0002-0153-5811

Abstract. Data generated by civilian digital ecosystems are increasingly used to train AI algorithms and develop military technologies, creating a new interdependence between the civilian and military spheres. The article introduces the concept of "digital dualism", which describes the dual role of data. A typology of the main categories of data and the analytical model "Data Militarization Risk Matrix" are proposed to assess the risk of their militarization. The need for new legal frameworks is discussed to reflect the growing role of data and to ensure the protection of civilian infrastructure in the context of modern conflicts. A legal instrument, the "Data Targetability Test", is proposed, which adapts the principles of international humanitarian law to the digital environment. The aim of the article is to explore and systematize the legal status of civilian data sets in the era of artificial intelligence, by developing a conceptual and analytical framework for assessing their potential transformation into legitimate military targets in the context of international humanitarian law.

Keywords. Data, Digital dualism, Data targetability, AI-driven warfare, International humanitarian law

1. Introduction

The transformation of warfare is increasingly driven by the advancements of Artificial Intelligence (AI) and the data as a strategic resource. Modern military capabilities are increasingly dependent on informational infrastructures. The AI systems use large volumes of data for training, validation, and deployment. A significant portion of this data originates from civilian environments, including social media platforms, mobile devices, commercial databases, etc. Such data is increasingly used in military systems, which creates a complex interdependence between civilian digital ecosystems and military capabilities.

These processes raise fundamental legal questions within the framework of International Humanitarian Law (IHL). Traditionally, IHL distinguishes between

[1] Corresponding Author: Dimiter Velev, University of National and World Economy, 19 December 8th Str., 1700 Sofia, Bulgaria; E-mail: dgvelev@unwe.bg.

civilian objects and military objectives based on their nature, purpose, location, or use. Nevertheless, these categories were developed in the context of physical objects and infrastructures. The emergence of data as a strategic resource challenges the applicability of these traditional legal categories .

A fundamental question arises: can civilian data sets be considered legitimate military targets in armed conflict? This issue is particularly relevant in the context of modern cyber operations. Analysis shows that data is gradually becoming a new type of strategic infrastructure that can be the object of military action. This necessitates new analytical concepts to better understand the role of data in contemporary conflicts.

This study proposes the concept of "digital dualism" as an analytical framework for analyzing this problem. This concept describes the situation in which a given data set has both a civilian and a military function. On the one hand, the data can be used for civilian purposes related to economic activity, social interaction or infrastructure management, while on the other hand, the same data can be integrated into artificial intelligence systems with potential military applications.

The aim of the article is to explore and systematize the legal status of civilian data sets in the era of artificial intelligence, by developing a conceptual and analytical framework for assessing their potential transformation into legitimate military targets in the context of IHL.

2. The Concept of Digital Dualism

The concept of digital dualism builds upon existing discussions in IHL concerning dual-use objects and civilian–military interdependence. However, unlike traditional dual-use frameworks, which primarily focus on physical infrastructure and material objects, digital dualism addresses the simultaneous civilian and military functionality of data within AI-driven and distributed digital ecosystems.

The development of digital technologies and AI has led to a fundamental transformation in the way data is created, stored and used in modern society [1, 2]. Data sets are gradually acquiring strategic importance that goes beyond the traditional framework of civil information infrastructure [3]. In order to adequately analyze this new reality, it is necessary to develop conceptual tools that enable a better understanding of the role of data in modern social and technological systems. One of these tools is the concept of "Digital Dualism", which describes the dual nature of modern data sets as both a civil resource and a potential military asset. Figure 1 shows the civilian digital system.

The concept of digital dualism can be viewed as a process of transforming data from a civilian resource to a strategic military asset [4, 5]. This process usually occurs gradually and involves several stages. In the **first stage**, data is generated through civilian activity and is used primarily for economic or social purposes. In the **second stage**, the potential military applicability of these data is established by using them to analyze behavioral patterns or geospatial characteristics. In the **third stage**, the data can be integrated into AI systems that have potential military applications. In the **final stage**, these systems can become key components of military infrastructure.

Digital dualism raises new questions about the role of civil society in modern conflicts. Since a significant part of data is generated through the daily activities of citizens, it can inadvertently are used to develop military technologies, the question arises whether they can be considered legitimate military targets. The answer to this question

remains unclear, since existing legal categories were developed primarily for tangible objects. The intangible nature of data, along with its ease of replication and distribution, complicates the application the application of traditional principles of international humanitarian law.

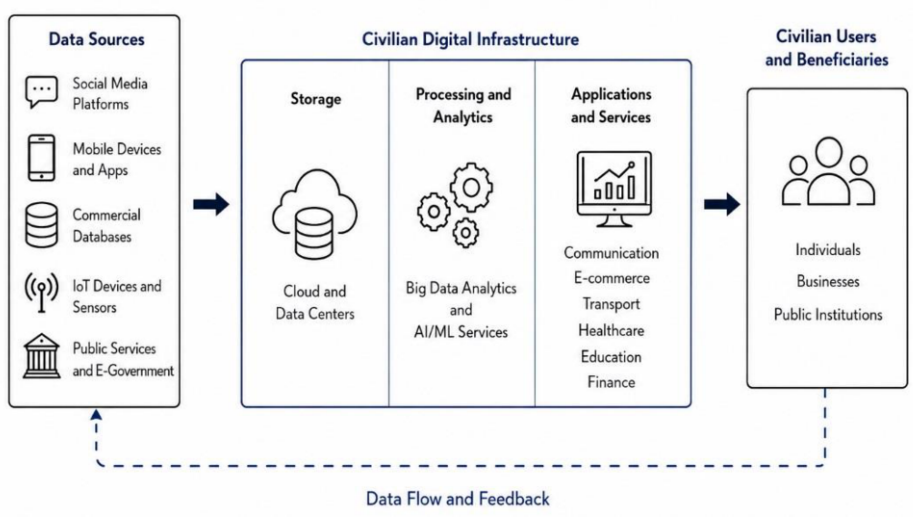


Figure 1. The civilian digital system.

A further complication arises from the global nature of digital infrastructure [6, 7]. Data is often stored in distributed systems that can span multiple countries and jurisdictions. Cloud platforms enable the storage and processing of information in global networks of data centers. The same data set can be distributed across different geographical locations, making it difficult to determine its legal status in conflict situations.

Thus, the concept of digital dualism can provide a useful analytical framework for understanding these processes. It allows for the analysis of how civilian data can gradually acquire strategic military significance. The concept highlights the need to develop new legal and policy mechanisms to regulate the use of data in modern conflicts.

3. Typology of Civilian Data with Potential Military Relevance

Civilian data sources create a new type of relationship between civilian and military technological infrastructure. Many of the data sets used to develop military applications were originally created for civilian purposes [8]. This means that the civilian digital ecosystem is gradually becoming the main source of resources for the development of military artificial intelligence.

A typological analysis of civilian data sets allows for a better understanding of how different information resources can be integrated into military artificial intelligence systems. Such systematization creates a basis for developing analytical tools for assessing the risk of militarization of data and for analyzing their legal status within the framework of international humanitarian law. As illustrated in Figure 2, civilian data ecosystems can be categorized into seven functional domains.

The **first category** of civilian data with potential military value is geospatial and cartographic data sets. Modern digital platforms provide extremely detailed maps that include information about road networks, buildings, industrial sites and various types of infrastructure. Such geospatial data can also be used for military purposes.

The **second category** of civilian data is data generated by social networks. This data includes text messages, images, videos, and various forms of metadata. Social networks were created for civilian purposes related to communication and information exchange. These platforms can also be used as a source of intelligence information. Analysis of data from social networks can provide information about events, infrastructure, or behavioral patterns of different groups.

The **third category** of civilian data comprises geolocation information generated by mobile devices. From a civilian perspective, this data is used for navigation, transport services and optimization of logistics processes. In modern conflicts, such data can provide valuable information on the movement of people and vehicles, making them a potential resource for intelligence analysis.

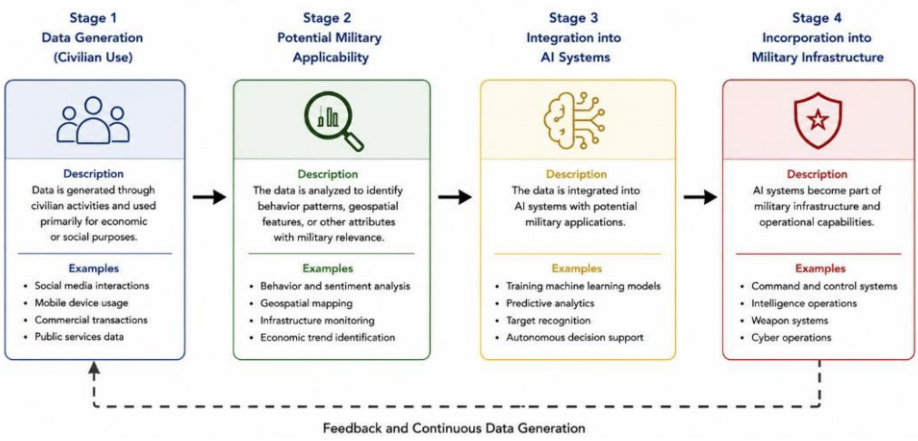


Figure 2. Typology of civilian data with potential military relevance.

The **fourth category** of civilian includes data generated by various types of sensor and IoT systems. This includes intelligent transport systems, industrial sensors, environmental measuring devices and various forms of smart infrastructure. From a civilian perspective, this information is used to optimize the management of the urban environment and infrastructure. Such data can also be used for the analysis of infrastructure systems, which can be of strategic importance in conflict situations.

The **fifth category** of civilian data includes economic and logistics data. From a civilian perspective, this data is used to manage economic activity and optimize production processes. These datasets can also provide valuable information about strategic industries, transport routes and economic dependencies. The analysis of such data can be used to identify vulnerabilities in a country's economic infrastructure.

The **sixth category** of civilian data includes biometric and health data. Modern health systems store huge amounts of information about medical conditions, genetic characteristics and biometric parameters of the population. This data is extremely sensitive and is subject to special legal protection in many countries. It can also have potential strategic importance, where it can be used to identify individuals.

The **seventh category** of civil data includes datasets to train machine learning algorithms. The quality and diversity of training data have a direct impact on the effectiveness of the algorithms. This means that access to large and diverse training datasets can become a key factor in technological development.

The current analysis shows that different categories of data have different degrees of potential military significance. Some data sets can play a key role in the development of algorithms and autonomous systems, while others have a more limited strategic importance. This means that the assessment of the risk of data militarization must be based on a systematic analysis of the different categories of information resources.

4. Data Militarization Risk Matrix: An Analytical Model for Assessing the Militarization Risk of Civilian Datasets

This data dualism poses significant challenges for both legal analysis and strategic security planning [9, 10]. In order to assess the potential of a given data set to be integrated into systems with military applications, it is necessary to develop analytical tools that allow for a systematic assessment of the different categories of information resources [11, 12].

The strategic significance of datasets may also depend on the degree of dependency of AI systems on specific training data and on the availability of functionally equivalent alternative datasets. In AI-enabled military systems, certain datasets may become operationally critical because their removal can significantly reduce algorithmic performance, reliability, or decision-making capability.

One possible approach to this problem is to develop a conceptual model that can be called the "**Data Militarization Risk Matrix**". The main objective of this matrix is to provide an analytical framework for assessing the potential of civilian datasets to evolve into strategic military assets. This approach is based on the idea that not all data sets have the same strategic value and that their potential militarization depends on a combination of different factors. By systematically analyzing these factors, it is possible to identify the categories of data that pose the greatest risk of transformation from a civilian resource to a military infrastructure. Figure 3 shows the data militarization risk matrix.

The Data Militarization Risk Matrix model is based on two main analytical parameters. The **first parameter** is the strategic value of a given data set for military technologies, especially for AI systems. It measures the extent to which a given type of data can be used for the development, training or operation of military algorithms and information systems. The **second parameter** is the degree of civilian dependence on the respective data set. It reflects the importance of a given type of data for the functioning of civilian infrastructure, economic processes and social systems.

Combining these two parameters produces an analytical matrix that classifies data categories according to the level of risk of their militarization [13, 14]. When the strategic military value of a given data set is low and the civilian dependence on it is limited, the risk of militarization can be assessed as relatively low. In such cases, the data has limited relevance for both military technologies and critical civilian infrastructure.

A more complex situation arises when the strategic value of a data set is high, but the civilian dependence on it remains relatively low [15, 16]. In such cases, the data can be an attractive target for military operations, since its destruction or neutralization can provide a military advantage without causing significant damage to civilian

infrastructure. A representative example of this category is training datasets used for artificial intelligence systems.

Particularly complex legal and ethical issues arise in cases where a data set has both a high strategic military value and a high degree of civilian dependence [17, 18]. In such situations, the data can play a key role both in the development of military technologies and in the functioning of civilian infrastructure. Consequently, targeting such datasets in conflict situations may result in severe consequences for the civilian population and social systems.

The matrix for assessing the risk of militarization of data can be represented by three main levels of strategic military value and three levels of civilian dependence. Strategic value can be classified as low, medium or high, depending on the potential of a given data set to be used in military artificial intelligence systems. These categories should be understood as analytical indicators rather than fixed quantitative variables. The assessment may depend on factors such as the degree of integration of the dataset into military AI systems, its operational importance, the availability of alternative data sources, and the level of societal dependence on the affected civilian infrastructure. Similarly, the degree of civilian dependency can be classified as low, medium or high, depending on the importance of the data set for the functioning of society.

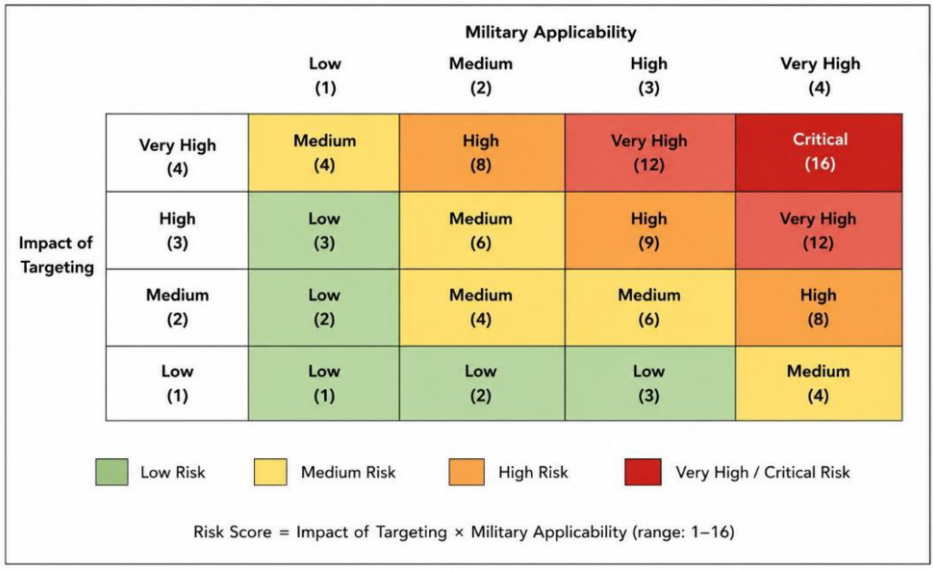


Figure 3. The data militarization risk matrix.

When these two parameters are combined in an analytical matrix, a nine-cell structure is obtained that allows for a systematic classification of the different categories of data. In the lower left sector of the matrix are data sets with low military value and low civilian dependency. These categories represent the lowest risk of militarization. In the upper right sector are data sets with high military value and high civilian dependency – a category that can be defined as an extreme risk zone.

The analytical value of the model lies in its ability to integrate technological, strategic, and legal dimensions into a single conceptual framework. By using such a matrix, researchers and policy analysts can identify the categories of data that pose the greatest challenge to international law and security policies.

Geospatial datasets can be classified as data of medium or high strategic value. They play an important role in navigation systems and autonomous technologies but are also widely used in the civilian sector. Depending on the specific context, such datasets may fall into the zone of high risk of militarization.

Social network data is another category that can be placed in the middle zone of the matrix. It has significant value for social network and behavioral analysis, which can be relevant for intelligence operations. At the same time, however, its importance for the functioning of critical infrastructure is relatively limited, which means that its strategic role is rather indirect.

A particularly interesting case is artificial intelligence training data sets. These data sets can have extremely high strategic value, as they form the basis on which machine learning algorithms are built. At the same time, their civilian function can be relatively limited, which puts them in the category of data with a high risk of militarization.

The most problematic category includes data sets that have both high strategic value and high civilian relevance. Biometric databases, health information systems, and some types of infrastructure data can fall into this category. Their potential militarization poses serious legal and ethical dilemmas, as such data play a critical role in the functioning of society.

Examining these categories within the framework of the "Data Militarization Risk Matrix" shows that the militarization of data is not a homogeneous process. Different categories of information resources have different strategic characteristics and varying degrees of importance for civil society. This means that the assessment of their legal status must be based on a comprehensive analysis that takes into account both technological and social factors.

The Data Militarization Risk Matrix can also be used as a tool for developing policies to protect civilian digital infrastructure. By identifying the categories of data with the highest risk of militarization, it is possible to develop specific mechanisms for their protection. This can include both technical security measures and legal regulations that limit the use of certain types of data for military purposes.

5. Data Targetability Test

Considering civilian data sets as potential objects of military operations raises complex questions for international humanitarian law. This creates a need to develop analytical tools that allow the application of the principles of International Humanitarian Law (IHL) to the new technological reality.

IHL is adapting to the new conditions of the fundamental changes in the ways of waging war as a result of the use of artificial intelligence and the introduction of new military technologies [19]. This position is also supported by an authoritative interpretation contained in the Tallinn Manual on the International Law Applicable to Cyber Warfare as an interpretive source of IHL. It is rightly assumed that the general criteria of IHL for determining a legitimate military target are also applicable to data generated by civilian ecosystems and should therefore be defined.

The Tallinn Manual is considered soft law. It does not have the binding legal force of international legal instruments such as international conventions, but it is recognized as an authoritative interpretation of the application of IHL in cyber warfare. The Tallinn Manual contains the foundations for a future legal framework for the application of IHL in cyber operations. However, it does not comprehensively address all legal aspects of

determining civilian databases for legitimate military purposes. The Tallinn Manual does not address a number of civil law issues of databases and the hypotheses in which there is a violation of human rights and even crimes against humanity. It outlines the main legal aspects of criteria forming the Data targetability test.

The **first criterion** is the definition of military object. The concept is derived from the definition of a civilian object in Art. 52, para. 1 of Additional Protocol I to the Geneva Conventions. Art. 52, para. 2 of the Protocol states: 'Attacks shall be limited strictly to military objectives. In so far as objects are concerned, military objectives are limited to those objects which by their nature, location, purpose or use make an effective contribution to military action and whose total or partial destruction, capture or neutralization, in the circumstances ruling at the time, offers a definite military advantage.' This criterion constitutes the legal basis for determining the legitimacy of military objectives. IHL emphasizes the application of criteria that justify the use of force [20]. The legitimate military objective is the guiding principle in determining the objects as military and civilian. According to international law, human rights have priority. Their respect and guarantee is an element of any criterion by which civilian data sets, can have the meaning of a legitimate military objective [21].

The **second criterion** requires an assessment of whether the designation of the data as military object is necessary and contributes to the achievement of a legitimate military objective. This criterion concerns the legitimacy of the means employed to achieve military objectives. This criterion should be understood in the context of the principle of IHL as 'military necessity', which requires justification of the use of force in an armed conflict within the framework of legal principles and norms [22]. The recognition of civilian databases also presupposes the following criteria which are part of the Data target ability test. The principle of military necessity is an expression of the right of the state to defend itself in an armed conflict.

The **third criterion** for defining data generated by civilian ecosystems as a legitimate military objective is the achievement of a specific military advantage. It is a manifestation of the principle of military necessity and an element of the principle of proportionality. Military advantage serves as a criterion for justifying the use of force and contains a guarantee against the speculative targeting of military actions against civilian objects. With respect to civilian data sets, a cyber operation is regarded as use of force and should be justified in terms of achieving a specific military advantage as its direct result. Achieving any other objective would lead to the illegitimacy of defining the databases as a military objective.

The justification of military advantage is directly related to the **criterion of distinction**. The criteria for a military objective, military necessity and specific military advantage are an expression of the right of states to defend themselves in an armed conflict. IHL establishes a "minimum law" in an armed conflict – the right to protection from attack by the use of force and the human rights related to survival and humanity [23]. It is the right to protection and basic human rights that are the absolute limits (legal principles) within which the designation of civilian objects as legitimate military targets is allowed. IHL balances between military necessity and the protection of human rights by reflecting the digital dualism of data. Civilian data sets themselves are an intersection of personal rights and public interest. On the one hand, they are infrastructure, and on the other hand, they are data related to the exercise of personal and other types of rights.

Unlike other civilian objects, data generated by civilian ecosystems and data sets in general exist in unity and can hardly be, even relatively, separated into individual data or even a set of data. Their existence is inherently dualistic, as they simultaneously

perform multiple functions and possess multiple legal implications. The definition of civilian data sets as legitimate military targets is one of the expressions of this conceptual dualism. However, the creation and use of data generated by civic ecosystems aims to realize rights and protect public interest. Given this, the Data Target Ability Test also covers the criteria for distinction, proportionality and safeguards. Their application is a guarantee for the protection of civilian databases as an important aspect of human rights [20] military targets is a principle of IHL. Its application delimits civilian data sets from the possibility of their being designated as legitimate military targets. They do not lose their nature of civilian objects, even when they are designated as legitimate military targets. As a rule, the designation of a civilian object as a legitimate military target does not turn it into a military object. Cyber operations directed against civilian data sets affect the rights of civilians, including their fundamental human rights. The principle of distinction includes in the Data Target Ability Test the prohibition of violence against civilians. Cyber operations may produce effects comparable to violence and affect fundamental human rights no less than the use of physical force, aids and weapons in armed conflicts. Another question that arises is whether cyber operations affect data or infrastructure. This is more a question of the degree of impact on the data sets [24].

The **criterion of proportionality** stems from the general principle of proportionality, characteristic of both IHL and law in general. Within the framework of the Data Target Ability Test, the criterion of proportionality shows the ratio between the foreseeable harm (actual and potential) and the expected results. The principle of proportionality is based on the idea of justice in law, which here means achieving a legitimate military objective with minimal interference with the human rights of civilians [25]. According to Art. 51 of Additional Protocol I to the Geneva Conventions, the impact on the life and integrity of persons and damage to civilian objects must be necessary and corresponding to the achievement of a direct military advantage. Again, the law balances between achieving a certain military advantage and the use of means that may lead to the violation of fundamental human rights. In cyber operations, there should be a correspondence between the specific military advantage and the manner and extent of the impact on data generated by civilian ecosystems. When determining civilian objects as legitimate military targets, the proportionality between achieving the goal - the specific military advantage - and the foreseeable consequences expressed in the violation of fundamental human rights should be taken into account. The criterion of proportionality is combined with the obligation to take measures that are able to minimize the damage to civilian digital infrastructure.

The **precautionary criterion** is a manifestation of the principle of foreseeability and a condition for ensuring proportionality. It is aimed at protecting fundamental human rights and requires the adoption of measures that are capable of minimizing adverse consequences for civilians [26]. Cyber operations against civilian data sets affect digital infrastructure and fundamental human rights. Planning and taking precautionary measures that do not allow disproportionate impact and generally minimize the danger to civilians is an essential part of the Data Target Ability Test, without which civilian data sets cannot be defined as a legitimate military target.

The recognition of civilian databases as a legitimate military objective is subject to the balance between military necessity and humanity in the context of IHL. The broad interpretation, according to which databases, and not only infrastructure, can be treated as civilian objects and as a legitimate military objective, provides a more comprehensive protection from IHL, which should also be applied in the cyber environment [27]. Although IHL provides principles and norms that are directly and comprehensively

applicable to the definition of data generated by civilian ecosystems, a special regulation should be provided to establish the Data Target Ability Test in cyber operations in detail in an international act.

One possible approach to this problem is to formulate a legal test that can be used to assess whether a given data set can be considered a legitimate military target. This model, which can be designated as the "**Data Targetability Test**", is based on the fundamental principles of IHL, including the principle of distinction, the principle of military necessity and the principle of proportionality. Figure 4 shows the elements of the data targetability test.

The **first element** of the proposed legal test is the establishment of a functional link between a given data set and a specific military system. This criterion is based on the idea that an object can only be considered a military objective if it effectively contributes to the military capabilities to a conflict. This means that it must be established whether the relevant data set plays a significant role in the development, training or operation of military technology.

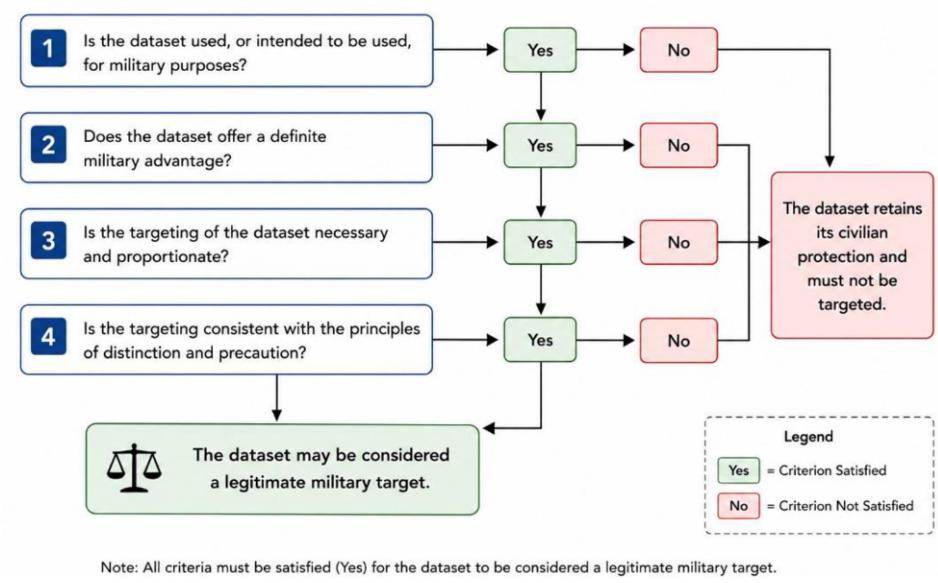


Figure 4. Data targetability test: A structured decision model for assessing whether civilian data qualifies as a legitimate military objective under international humanitarian law.

The **second element** of the legal test is the assessment of the dependence degree of a military system on the relevant data set. Not all data used in technological systems have the same importance. While some data sets can play a key role in training algorithms, others can have a more limited importance and can easily be replaced by alternative sources of information. Hence, it is important to define the different degrees of dependence.

The **third element** of the test is the assessment of the potential military advantage that could be achieved by neutralizing a given data set. In IHL, the concept of military objective is linked to the idea that the destruction or neutralization of an object must provide a specific and direct military advantage. This means that it must be analyzed whether restricting access to a given information resource would have a significant impact on the adversary's ability to use a particular technology.

The **fourth element** of the test is the assessment of the impact on civilian infrastructure and the civilian population. This criterion is closely related to the principle of protection of civilian objects, which is a fundamental element of IHL. Databases used to manage healthcare systems, transport infrastructure or financial services can be of significant importance to society. The destruction or compromise of such systems can have serious consequences for the civilian population, raising questions about the admissibility of such actions under international law.

The **fifth element** of the proposed legal test is the principle of proportionality by which the potential harm to the civilian population and civilian infrastructure should not be disproportionate to the anticipated military advantage. The proportionality assessment should take into account not only the immediate effects of the operation, but also the possible secondary consequences for the civilian digital ecosystems.

The combination of these five elements creates an analytical framework that allows for a more systematic assessment of whether a given set of data can be considered a legitimate military target. The model creates a methodological basis for analyzing the complex cases that arise in modern technological conflicts. The Data Targetability Test should not be viewed as a mechanical classification tool, but rather as an analytical framework, that supports legal and strategic analysis.

The proposed test should be understood as an interpretative and analytical framework for applying existing IHL principles to data-centric environments rather than as an autonomous legal doctrine. Its purpose is to structure legal assessment in situations where civilian datasets simultaneously perform civilian and military functions within AI-enabled systems.

6. Conclusion

The study discusses a structural gap in the application of IHL to data-driven warfare. Since military capabilities increasingly depend on AI, civilian data has become a critical component of military operations.

The **first contribution** is conceptual. The paper introduces **digital dualism** as a framework for understanding the simultaneous civilian and military functionality of data. Digital dualism emphasizes that data can concurrently support civilian services and military systems without transformation. This simultaneity challenges the binary logic of the principle of distinction and suggests that origin-based classification is insufficient. The concept provides a more precise analytical basis for legal evaluation.

The **second contribution** is structural. The study develops a **functional typology of civilian data**, distinguishing seven data categories, based on their modes of integration into military systems. This typology enables a differentiated assessment of data according to its operational relevance, moving beyond the implicit homogenization of data in existing legal discourse. It supports a shift toward context-sensitive evaluation, consistent with emerging interpretations of IHL that emphasize function over form.

The **third contribution** is analytical. The **Digital Dualism Analytical Framework** models the transformation of data across stages of generation, processing, and deployment. This process-oriented approach demonstrates that the military significance of data is relational, arising from its integration into specific systems. It supports a transition from static classification toward function-based legal analysis, which better reflects the distributed nature of digital infrastructures.

The **fourth contribution** is methodological. The paper introduces the **Data Militarization Risk Matrix**, which organizes the assessment of datasets along two dimensions: military use and civilian dependence. The matrix identifies zones of heightened legal tension, particularly where high strategic value intersects with high civilian reliance. This contributes to a more transparent and systematic application of proportionality and precaution.

The **fifth contribution** is the **Data Targetability Test**, which translates core IHL principles into a structured sequence of evaluation: functional value, dependency, anticipated military advantage, civilian impact, and proportionality. The test enhances consistency and reduces interpretive ambiguity in assessing data as a potential military objective.

The paper adopts an interdisciplinary approach integrating legal analysis with insights from data science and systems theory. It does not provide definitive solutions, but a coherent and extensible framework. The study contributes to the ongoing adaptation of IHL by reconfiguring existing principles to address the legal complexities of data-centric warfare.

These contributions offer a structured approach to assess whether civilian data can qualify as a legitimate military objective under IHL. Future legal and policy development will depend on integrating technological understanding with established doctrinal principles. In this regard, the framework proposed in this paper provides a foundation for more precise, transparent, and context-sensitive regulation of civilian data in armed conflict.

Acknowledgment

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Construction of Experimental Teaching Model for Economics and Management Courses Using AI Agent

Danyan Xiao, Yulin Zheng and Weibo Huang [1]
Guangdong University of Foreign Studies, Guangzhou, China

Abstract. This study aims to meet students' personalized learning needs amid the rapid development of "Internet +" education. It proposes a hybrid decision model for Enterprise Resource Planning (ERP) experimental teaching. The model uses three AI agents: customer behavior agent, inventory management agent, and financial analysis agent. The model constructs multi-dimensional feature vectors for enterprise operation status. It also embeds a learner state vector to dynamically track decision behaviors and preferences. It integrates a large language model (LLM) with retrieval-augmented generation (RAG). This integration helps interpret multi-agent results and deliver personalized decision support. Simulation experiments under a multi-period decision framework are conducted. Results show that the model can effectively optimize decision paths and enhance teaching effects.

Keywords. ERP experimental teaching+ multi-agent system; LLM; RAG

1.Introduction

AI agents in ERP experimental teaching draw on AI technology and experimental teaching theories of economics and management. This approach integrates enterprise operation simulation with intelligent decision support. Agents provide interactive guidance and dynamic feedback. They help reform the traditional preset-process-based ERP teaching mode, which lacks personalized guidance. This method reduces students' understanding difficulties and operational burdens. These problems often come from their insufficient experience in complex decision-making. It improves students' comprehension of ERP processes and their comprehensive analytical ability. It also strengthens their sense of participation and practical experience. The model guides students to shift from passive task completion to independent analysis and decision-making. Through conversational and data-driven learning, it cultivates students' problem-solving, communication, and innovative thinking abilities.

[1]Corresponding Author: Weibo Huang, Center for Contemporary Education Technology, Experimental Teaching Center, Guangdong University of Foreign Studies, China; Email: 172564946@qq.com.

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2.Research Status

At present, research on artificial intelligence in ERP systems mainly focuses on three areas. These areas are intelligent architecture design, decision support optimization and business process automation. Many researchers have explored the integration of artificial intelligence and ERP systems. They focus on the architecture design and functional expansion of intelligent ERP [1]. Puthuruthy and Marath [2] applied machine learning and data analysis to ERP models. to improve decision support in complex business environments. Sharma [3] adopted AI technologies in enterprise information models to verify their effects on process automation and data processing. Yang et al. [4] introduced AI agents into ERP systems and built business-process-oriented agent models to automate financial analysis, inventory management, and business collaboration. Related studies show that AI can overcome the limitations of traditional ERP, such as over-reliance on experience, low data utilization, and delayed response, thus enabling better adaptation and optimization in dynamic environments [5]. However, most existing studies mainly focus on enterprise operation efficiency and intelligent automation. Few studies pay attention to the application of AI-driven ERP models in experimental teaching scenarios and personalized learning support. Generative AI has developed rapidly in recent years. Researchers have gradually explored its applications in intelligent education and learning support environments. Kasneci et al. [6] constructed a generative AI-based learning support model to promote teaching mode transformation. Zhai [7] used ChatGPT and similar tools for interactive teaching to examine its impact on learning effects. Existing studies have analyzed generative AI in education from multidisciplinary perspectives and discussed its roles in teaching evaluation and learning support [8].

3.Hybrid Decision Recommendation Model for ERP Experimental Teaching Based on Artificial Intelligence

In ERP experimental teaching, preset processes and static rules are not enough. This study constructs a dynamic decision-making model. It is designed for ERP experimental teaching oriented to teaching scenarios. The model takes enterprise operation status as the core. It uses three agents: customer behavior, inventory management, and financial analysis. These agents integrate demand changes, inventory constraints, and financial evaluation into one framework. Each agent uses a data-driven mechanism based on rule calculation. It also reserves integrated interfaces with LLM and RAG technology. Therefore, the model can depict the whole process of students' decision-making behaviors. It can also generate targeted feedback and strategy suggestions. The model expands from result evaluation to process analysis and guidance. This lays a foundation for later personalized teaching support.

To better depict the above decision-making process, this paper models key variables in ERP experiments from the perspective of model state. Suppose the enterprise operation status in the t-th decision cycle is:

$$X_t = (S_t, D_t, p_t, C_t, R_t, P_t, M_t, F_t, L_t) \quad (1)$$

where S_t represents inventory level. D_t represents market demand. p_t represents product price. C_t represents comprehensive cost. R_t represents sales revenue, and P_t

represents profit level. These variables mainly characterize the basic operation status of the enterprise in a single decision cycle. M_t represents production load level. It reflects the utilization of production resources. F_t represents capital flow status. It depicts enterprise cash flow and capital constraints.

The model characterizes enterprise operational states. It also adds learner-related factors into the system. This is done by introducing a learner state vector, denoted as L_t.. This vector shows students' behavioral characteristics in ERP simulation. It also reflects decision-making preferences and strategy evolution trends. In this way, it shows individual differences among learners in a dynamic decision-making environment. To improve model interpretability and transparency, the learner state vector is defined as follows:

$$L_t = (r_t, h_t, a_t) \tag{2}$$

where r_t represents the learner's risk preference. It reflects the degree of aggressiveness in procurement scale, inventory level, and investment strategies. h_t denotes historical decision performance. It evaluates overall operational performance across consecutive business cycles. The evaluation is based on profit, inventory matching accuracy, and capital utilization efficiency. a_t represents strategy adjustment frequency. It describes how often learners modify procurement, pricing, and inventory strategies during multi-period decision-making. It also decision stability and behavioral variation.

As the model initialization stage, the system constructs the initial learner state vector L_0. It uses brief questionnaires, historical learning records, and early experimental behaviors. The risk preference parameter is normalized within the range of 0 to 1. Higher values indicate a stronger tendency toward high-risk, high-inventory, or high-investment decisions. Historical decision performance is represented as a composite performance score. Strategy adjustment frequency is measured by the number of strategy modifications within each decision cycle.

In subsequent multi-period operations, the model updates each parameter dynamically. It updates based on learners' continuous behaviors. These behaviors include procurement adjustment, pricing decisions, and inventory control. For example, a learner consistently adopts high-inventory or high-investment strategies. Over several periods, the system will correspondingly increase the risk preference parameter. Similarly, frequent changes in pricing or procurement strategies lead to a higher strategy adjustment frequency parameter.

To enhance the model's adaptive capability, the learner state vector is iteratively updated after each decision round. The update process is expressed as follows:

$$L_{t+1} = L_t + \eta \Delta B_t \tag{3}$$

where η denotes the learning rate. It controls the magnitude of each update., ΔB_t represents behavioral changes during the current decision cycle. This dynamic updating mechanism helps the model track learners' behavioral changes. It does so throughout the entire ERP simulation process. The system also integrates individual learner characteristics. It can then provide more targeted feedback and decision-support suggestions. This helps shift teaching from standardized experiments to personalized intelligent guidance.

Market demand is a key variable. It links pricing decisions and operation results. Thus, a customer behavior agent is used to model demand changes. In actual enterprise

operations, market demand is usually affected by multiple factors. These factors are pricing strategies, historical sales performance and consumer behavior. To better depict the relationship between price and demand, this paper defines the demand response function:

$$D_t = f_{agent}(p_t, H_t) \quad (4)$$

Where H_t represents historical transaction data and market behavior characteristics. The function f_{a9ent} is obtained by the customer behavior agent through multi-cycle data learning. It describes the comprehensive impact of price p_t and market characteristics H_t on demand. This function generally shows a monotonically decreasing trend. In other words, market demand D_t decreases accordingly as price p_t rises.

The customer behavior agent uses a data-driven model. It continuously learns and updates historical sales data. This allows the demand function to adapt dynamically to market changes. The LLM provides strong analysis ability. It helps the model explain demand trends. This improves the model's teaching support capability. As the experiment proceeds, the demand function is updated with new data. It becomes closer to real market laws. This offers a more reliable basis for later decisions.

The model now can clearly show demand changes. It still needs to solve the problem of supply-demand matching. Inventory becomes a key constraint variable. It connects demand forecasting and actual sales results. Therefore, this paper introduces an inventory constraint mechanism. This mechanism describes the relationship between inventory level and market demand. The inventory management agent jointly analyzes inventory level and market demand. It then defines the inventory matching index accordingly:

$$I_t = \frac{S_t}{D_t} \quad (5)$$

This index is used to measure the coordination degree between inventory resources and market demand. It also serves as an important bridge connecting procurement decisions and sales results. When I_t deviates from a reasonable range, the model will identify it as an inventory imbalance state. A large I_t indicates relatively excess inventory. This may lead to inventory backlog and capital occupation. A small I_t indicates insufficient inventory. It brings risks of stock-out and loss of sales opportunities.

The inventory management agent does more than judges the status. It also analyzes inventory problems with the learner state L_t. For example, it gives tips to students with high-risk preference. It reminds them of capital pressure from possible inventory backlog. For conservative students, it offers different guidance. It tells them to notice potential sales opportunities. It also warns them about risks from insufficient inventory. The model combines inventory status with learner characteristics. It can provide targeted analysis and feedback in the same business scenario. In this way, inventory management is no longer just status judgment. It becomes guidance focused on decision-making behavior.

The model first identifies the inventory imbalance state. Then it conducts interpretive analysis on the causes of inventory imbalance. It explains the current situation from two perspectives. These perspectives are inventory turnover rate and demand change trend. It also puts forward corresponding adjustment suggestions. The LLM can integrate information from different sources. Its feedback goes beyond simple result presentation. It contains clear causal logic and decision-making basis.

This makes the analysis easier to understand and more convincing. Based on the above analysis, the model generates guiding questions. These questions help students reflect and revise their decision-making. Inventory management is no longer a simple result reminder. It forms a complete process: status identification, cause analysis and cognitive guidance. The model can provide results, explain causes, and guide decisions. It improves the procedural nature and interactivity of ERP experimental teaching.

This study transforms the enterprise operation process into a continuous dynamic evolution chain. The chain is illustrated in Figure 1. It visually presents the overall decision-making logic of the model. This logic is applied in ERP experimental teaching.

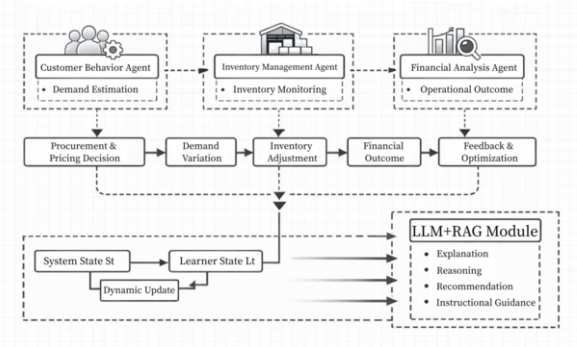


Figure 1 Dynamic Decision Evolution Mechanism of ERP Experimental Teaching

As shown in Figure 1, procurement and pricing decisions focus on pricing strategies and revenue functions. Customer behavior agents are adopted to model market demand changes. Inventory matching indicators are used to analyze inventory adjustment conditions. Revenue and profit functions reflect the overall financial performance. LLM and learner state vectors support feedback generation and decision optimization. All these links interact in multi-cycle operation. They eventually form a complete dynamic closed-loop decision chain. Three intelligent agents undertake distinct functions in this process. The customer behavior agent estimates market demand. The inventory management agent monitors inventory status. The financial analysis agent evaluates operational results. They share information and conduct collaborative calculation. Together, they construct an integrated decision support system. Meanwhile, system state variables are updated continuously. Each decision link can adjust dynamically to environmental changes. This transforms the traditional static experimental mode into dynamic decision-making teaching.

The model uses key state variables generated by the multi-agent system as core inputs. These inputs include demand forecasting results, inventory levels, profit fluctuations, and the learner state vector. These variables are integrated with knowledge retrieved from the ERP knowledge base through the RAG mechanism. The integrated information is then jointly provided to the LLM for comprehensive analysis. This study takes a GPT-based LLM as the core module. It undertakes semantic analysis and feedback generation tasks. By leveraging natural language understanding and reasoning capabilities, the model can interpret enterprise operational states and learner behaviors. It further generates intelligent feedback adapted to ERP teaching scenarios.

The system further establishes an ERP experimental teaching knowledge base to strengthen knowledge support. The knowledge base mainly contains ERP operation

rules, inventory management cases, pricing strategies, and financial analysis knowledge. The RAG mechanism adopts a vector-based semantic retrieval approach. It calculates semantic similarity between the current decision state and knowledge fragments. Accordingly, the system dynamically retrieves relevant theoretical knowledge, historical cases, and operational strategies. The retrieved content is then provided to the LLM as contextual information. This approach improves the professionalism and reliability of the generated feedback.

These mechanisms work together. The model enhances semantic understanding and knowledge reasoning. It makes these improvements based on the original rule-driven system. This multi-agent model can complete decision-making calculations It can also explain decision-making processes. In addition, it can provide learning guidance. Thus, it forms a comprehensive intelligent support mode for teaching scenarios. Furthermore, the model operates in a multi-cycle decision-making environment. It has the ability of continuous learning. It also has self-optimization ability. The customer agent can update dynamically. It updates according to historical transaction data. The inventory management agent optimizes inventory threshold settings. It uses historical inventory and demand information. It also ensures accurate inventory early warnings. The financial agent analyzes multi-cycle profit data. It identifies long-term operation trends. It provides more valuable operation analysis. Students learn in the actual teaching process. They join in consecutive decision-making cycles.

The model has two key functions. First, it can present the internal connections of various links in enterprise operation. It also enhances students' decision-making ability. These improvements come from dynamic feedback and data mechanisms. Thus, the model provides a practical implementation path. This path supports artificial intelligence to empower ERP experimental teaching.

4. Experimental Results

This study further evaluates the application performance of the AI agent-driven ERP experimental teaching model. The model is a dynamic decision-making model for teaching scenarios. Large-scale classroom applications have not been carried out. Therefore, this research uses a combination of simulation analysis and case deduction. It assesses model performance in multi-period decision-making processes. The goal is to verify its effects. These effects include optimizing decision-making procedures and improving teaching quality.

Under the agent-supported mode, the model conducts multi-dimensional analysis. It analyzes demand changes, inventory status and financial results. It further guides learners to adjust strategies effectively. As decisions are gradually optimized, market demand rebounds. The inventory level returns to a reasonable range. Business performance also improves steadily. After three rounds of semester teaching trials, course final exam results prove the positive guiding role of AI agents. From the perspective of teaching effectiveness, AI agents bring obvious changes. They transform traditional ERP process-oriented training into ability-oriented learning. The new mode focuses on cultivating learners' decision-making ability. Relying on continuous feedback and explanatory mechanisms, the model provides guidance. It helps learners understand the internal relations of different decision variables. It also enables learners to change from passive operation to active problem analysis. In this way, learners'

modeling thinking ability is greatly improved. Their comprehensive decision-making ability is also significantly enhanced.

5. Conclusion

At present, neither traditional ERP experimental teaching modes have limitations. Existing virtual simulation platforms also have shortcomings. Neither of them can integrate three key elements organically. These elements include complex business decision-making, multi-link collaborative analysis and personalized teaching guidance. This study proposes an AI-based multi-agent-driven ERP teaching model. The model combines learners' multi-dimensional characteristics and enterprise operation status. It dynamically depicts the abstract business decision-making process. It offers continuous feedback and guidance for learners. The guidance covers analysis, decision-making and adjustment stages. This optimization makes the experimental process more complete and directional. It improves practicality and participation of learning. Moreover, it gradually strengthens students' ability to understand the logic of enterprise operation logic. The teaching mode integrates multi-agent mechanism, LLM and RAG technology. It can continuously optimize and update the original rule-based model. This model has dynamics, scalability and adaptability.

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Influencing Factors Analysis of Generative AI Usage Among Humanities and Social Sciences Students

Hua Xu[a,1] and Zicheng Liao[b]

[a] *Shanghai University of Political Science and Law, China*
[b] *The Education University of Hong Kong, China*
ORCiD ID: Xu Hua https://orcid.org/0009-0001-6028-272X
ORCiD ID: Liao Zicheng https://orcid.org/0009-0006-2531-9706

Abstract: Generative AI technology is rapidly penetrating the higher education landscape, but significant disparities exist among different individuals. Do humanities students use it relatively less frequently? Can they seize future development opportunities? To address these questions, this study utilizes the Credemo research platform and designs a questionnaire based on theoretical frameworks such as ecosystem theory, social cognitive theory, institutional theory, and the technology acceptance model. It analyzes the usage of GenAI among humanities students and explores the factors influencing its adoption from multiple levels, including the institution, teachers, peers, and individuals. The survey reveals that GenAI has a considerable penetration among humanities students, but its usage is characterized by high frequency and low depth of engagement, with variations across different humanities disciplines. While there is a high consensus on the perceived value of GenAI, concerns persist regarding its potential to undermine independent thinking. Peer influence far exceeds that of teachers and institutions, and students express a desire for more support from educators and universities. Therefore, it is necessary to enhance teachers' AI literacy and guidance capabilities, establish a tiered training system, and strengthen institutional support.

Keywords: Ecological Systems Theory; Social Cognitive Theory; Institutional Theory; Generative AI

1. Introduction

Generative AI technology (GenAI), with its powerful content generation and natural language understanding capabilities, is rapidly penetrating the field of higher education, providing efficient assistance for students' learning and life.

Li Yan et al. (2024)[1] and Yu Haiqin et al. (2025)[2] found through research that the AI penetration rate among Chinese university students is at the international leading level, with approximately 96.44% having used it, and the common usage rate reaching over 40% in 2025. However, there is significant differentiation in GAI usage between

[1] Corresponding Author, Hua Xu, Shanghai University of Political Science and Law, Shanghai, 201620, China; E-mail: 2661359982@qq.com

individuals, with some students actively incorporating it into their learning process, while others continue to be marginalized. Li Yan et al. (2024)[3] and Yu Haiqin et al. (2025) [4]found that students in some teaching-oriented universities, humanities majors, and female students have relatively lower usage rates. Since individuals with strong GenAI capabilities are more likely to seize future development opportunities, it is necessary to study how to narrow the gap between individuals. Based on this, this study focuses on humanities and social sciences students to analyze the influencing factors of their GAI usage, in order to narrow the gap between individuals.

Current research commonly uses the perceived usefulness and perceived ease of use from the Technology Acceptance Model (TAM) to analyze the influencing factors of students' acceptance and application of GAI. For example, Li Yize et al. (2025) [5]construct perceived ease of use from aspects such as usage cost, information security, human-computer interaction, technical limitations, regionality of use, and usage context, and construct perceived usefulness from aspects such as psychological anxiety, personal innovation, user expectations, information processing, information quality, performance advantages, and social influence to analyze the factors influencing university students' behavior. However, these analyses overlook the influence of factors such as students' disciplinary backgrounds, the institutional ecosystem of their universities, and teacher support, all of which form an ecosystem that indirectly shapes individual student behavior. Based on this, this study integrates Bronfenbrenner's ecosystem theory, institutional theory, social cognitive theory, and key dimensions of the technology acceptance model to design a questionnaire. The aim is to explore the usage behavior of GenAI among Humanities and social sciences students and the factors influencing it.

2. Group Characteristics and Research Approach of Humanities and Social Sciences Students

2.1 Group Characteristics of Humanities and Social Sciences Students

Compared to science and engineering students, humanities and social sciences students exhibit distinct differences in their perception and application tendencies towards Generative AI (GenAI). The talent cultivation for science students emphasizes logical deduction, quantitative analysis, and the application of technical tools to solve specific practical problems. For them, GenAI is not only a crucial tool for problem-solving, but its underlying technical principles, model design, and development can also fall within their learning and research scope. Science students possess strong intrinsic motivation to study and utilize GenAI.

In contrast, the talent cultivation for humanities and social sciences students focuses on reading, textual analysis and creation, and argumentation. They tend to view GenAI more as an end-user auxiliary tool, placing greater value on its ease of use and its application value in text assistance. Consequently, their awareness of GenAI is relatively slower to develop.

Furthermore, humanities and social sciences students place greater emphasis on critical thinking, ethical reasoning, and originality. Therefore, when using GenAI, they tend to have greater concerns about ethical and moral issues such as plagiarism, as well as the cultivation of critical thinking skills.

2.2 Ecological Systems Theory

Ecological Systems Theory is an important theory proposed by Bronfenbrenner (1994)[6]. Bronfenbrenner believes that human beings survive and develop in an inseparable, nested environment, and individuals exist in these interconnected systems, dynamically interacting with each other and influencing each other in the development process. The school is a key macro system, and the school's policies and facilities provide students with basic technical equipment and ethical guidelines, clarifying the boundaries of use. Teachers are the group that students interact with directly. Teachers can directly influence students' cognition and behavior through daily teaching practices and activity organization, evaluation criteria, and their own personal behavioral attitudes.

2.3 Institutional Theory

Institutional theory is the specific mechanism by which environmental systems exert influence. School policies, such as clear reward and punishment regulations, create coercive pressure. Teacher guidance and demonstration exert pressure on students through normative mechanisms such as role expectations and professional ethics. The professional attributes of liberal arts themselves form invisible constraints, such as the belief in originality. These institutional forces work together on students, shaping their perception of whether GenAI is useful or risky.

2.4 Social Cognitive Theory

Social cognitive theory emphasizes that students are not simply passive recipients of the system. Students learn by observing the behavior of teachers and form a sense of self-efficacy about whether they can effectively use GenAI based on their past experiences. This sense of efficacy continuously interacts with institutional pressures from schools and teachers (such as teachers encouraging use or the discipline traditionally using it cautiously), ultimately affecting individual behavioral intentions.

In summary, environmental factors such as the university, teachers, and peers, combined with individual factors, influence humanities and social sciences students ' attitudes towards using GenAI. These attitudes, in turn, ultimately determine their actual usage behaviors. Based on the above theoretical framework, this paper will design a survey questionnaire focusing on three external influencing factors—the university, teachers, and peers—as well as individual internal factors.

3. Research Design

3.1 Questionnaire Design

This survey questionnaire consists of three parts. The first part is about the basic information of humanities and social sciences students. It includes gender, grade level, and specific major. Liberal arts majors are divided into Social Sciences (Sociology, Political Science, Law, Economics, etc.), Arts & Media (Journalism, Communication, Art Design, etc.), and Humanities (Chinese Language and Literature, History, Philosophy, etc.). The second part focuses on the basic situation of humanities and social

sciences students' GenAI usage, including usage intensity, skill level, and usage scenarios. The third part explores the influencing factors of humanities and social sciences students' GenAI usage, including individual behavioral cognition, and influences from the school, teachers, and peers. This questionnaire uses the Likert five-point scale, and the Cronbach's alpha coefficient for the total scale is 91.87%.

3.2 Questionnaire Collection

This questionnaire was collected through the professional online research platform "Credamo," primarily targeting undergraduate students in liberal arts majors at higher education institutions in China. The homepage of the questionnaire clearly stated the principle of anonymity and the purpose of data usage. All participants entered the formal questionnaire after informed consent and confirmation of understanding. A total of 259 questionnaires were collected. After excluding invalid questionnaires, 258 valid questionnaires were obtained, resulting in a valid response rate of 99.6%.

3.3 Research Subjects

A total of 258 valid questionnaires were obtained. Among them, 194 were female (75.19%) and 64 were male (24.81%), a proportion that generally aligns with the gender distribution in liberal arts majors. Furthermore, there were 60 postgraduate students (23.26%), 32 freshmen (12.40%), 36 sophomores (13.95%), 30 juniors (11.63%), and 100 seniors (38.76%). Students from Social Sciences majors accounted for 145 (56.20%), Arts & Media majors for 21 (8.14%), Humanities majors for 78 (30.23%), and others for 14 (5.43%). Please refer to Table 1:

Table 1. Basic Information of Research Subjects

Category		Number of Respondents	Percentage%	Category	Number of Respondents	Percentage%
Gender	**Male**	64	24.81	**Freshman**	32	12.40
	Female	194	75.19	**Sophomore**	36	13.95
Social Sciences		145	56.20	**Junior**	30	11.63
Arts & Media		21	8.14	**Senior**	100	38.76
Humanities		78	30.23	**Postgraduate**	60	23.26
Other		14	5.43			

4. Research Findings

4.1 Basic Situation of GenAI Usage Among Humanities and Social Sciences Students

The penetration of GenAI among humanities and social sciences students reached 100%. Among them, 72.48% of students use it frequently, and 27.41% use it occasionally, indicating a generally high usage frequency. In terms of majors, Social Sciences students have the highest usage frequency, followed by Arts & Media, while Humanities students have the lowest. Regarding GenAI tools, domestic tools dominate, with Deepseek and Doubao being the absolute mainstream, accounting for over 75% combined, making them the most commonly used GenAI tools by humanities and social sciences students. Please refer to Table 2.

GenAI has also permeated all aspects of humanities and social sciences students' learning and daily life. The core focus is on course learning and assignments, followed by language learning, daily life, and information processing. The usage intensity for academic research, innovation and entrepreneurship, and competition scenarios is significantly lower. Among these, Social Sciences majors show higher usage, while Humanities majors have the lowest overall scores. The commonly used tools are primarily domestic large models, with DeepSeek (41.88%) and Doubao (33.94%) accounting for over 75% combined. ChatGPT, Gemini, and Claude account for 12.79%.

In terms of GenAI usage intensity and skills, a characteristic of "high frequency usage, low depth exploration" is observed. The overall average usage intensity is 3.08, which is at a medium level. Only 20% of students have the intention to explore GenAI in depth. The overall average usage skill is 3.54, indicating a generally good foundation and the ability to judge and correct content. However, prompt engineering skills are relatively weak, with only 47% of students proficient in designing effective prompts, and advanced usage capabilities are severely lacking. Arts & Media and Social Sciences majors lead in both GenAI usage intensity and skill levels, while Humanities majors lag across the board, with the lowest usage intensity and skill levels. Male students generally score higher than female students in average usage, indicating that within liberal arts fields, male students still have a higher adoption rate of GenAI than female students. Please refer to Table 3.

Table 2. GenAI Usage Among Humanities and Social Sciences Students

Liberal Arts Major	**Occasionally Use**	**Frequently Use (Persons)**	**Frequently Use %**	**Grade Level**	**Frequently Use (Persons)**	**Frequently Use %**
Social Sciences	33	112	77.24	**Freshman**	26	81.25
Arts & Media	29	49	76.19	**Sophomore**	29	80.56
Humanities	5	16	71.43	**Junior**	23	76.67
Other	4	10	62.82	**Senior**	61	61.00
Total	71	187	72.48	**Postgraduate**	46	79.31

Table 3. GenAI Usage Scenarios Among Humanities and Social Sciences Students

Scenario	**Social Science**	**Arts & Media**	**Humanities**	**Other**	**Freshman**	**Sophomore**	**Junior**	**Senior**	**Postgraduate**
Course Learning & Assignments	3.96	3.86	3.40	3.86	3.78	3.97	4.17	3.47	3.93
Academic Research	3.54	3.48	3.14	3.43	3.31	3.64	3.77	3.06	3.71
Language Learning	3.54	3.52	3.33	3.71	3.44	3.81	3.70	3.32	3.45
Innovation, Entrepreneurship & Competitions	3.03	3.10	2.58	2.93	2.84	3.31	3.67	2.52	2.86
Daily Life & Information Processing	3.46	3.76	3.33	3.21	3.47	3.25	3.57	3.38	3.53
Average	3.51	3.54	3.16	3.43	3.37	3.60	3.78	3.15	3.50

4.2 Individual Influencing Factors of GenAI Usage Among Humanities and Social Sciences Students - Cognition and Attitude

Humanities and social sciences students demonstrate a high degree of consensus regarding the value of GenAI usage. Over two-thirds of students strongly agree that "GenAI is a powerful learning assistance tool" (68.99%) and that "Humanities and social sciences students need to learn to collaborate with GenAI, as it is an important future competency" (67.83%). Over 60% of students agree that "mastering GenAI skills is important for career development" (60.08%). Please refer to Table 4.

However, concerns about the risks of GenAI usage also exist. Nearly 70% of students believe that "over-reliance on GenAI will weaken independent thinking abilities" (69.77%), nearly half are concerned about the loss of autonomy (45.74%), and over 60% are concerned about academic misconduct and copyright risks (57.75%).

Among humanities and social sciences students, lower-grade students and Humanities majors exhibit more conservative perceptions, with lower recognition of both the value and risks of GenAI compared to higher-grade students, indicating considerable room for improvement. Arts & Media majors have the most comprehensive and strongest understanding of GenAI's value and risks, with the highest average scores across all indicators, especially regarding "academic integrity issues," where the high agreement rate exceeds 90%, far surpassing other majors. This may be due to the characteristics of Arts & Media majors, which place a greater emphasis on intellectual property.

Table 4. Individual Influencing Factors of GenAI Usage Among Humanities and Social Sciences Students

Indicator	Average Score	Percentage of High Agreement	Percentage of Low Agreement	Arts & Media Average	Social Sciences Average	Humanities Average
Humanities and social sciences students need to learn to collaborate with GenAI, as it is an important future competency	3.98	67.83%	5.81%	4.33	3.99	3.79
Over-reliance on GenAI may weaken my independent thinking ability	3.95	69.77%	8.53%	4.19	3.95	3.79
GenAI is a powerful learning assistance tool that can improve my learning efficiency	3.93	68.99%	5.43%	4.10	3.81	3.69
Mastering GenAI skills is important for my future career development	3.80	60.08%	10.08%	4.10	3.97	3.79
Using GenAI to complete assignments may involve academic integrity issues	3.70	60.08%	13.57%	4.29	3.70	3.56
Relying on GenAI may lead to abandoning knowledge memorization and hindering the establishment of systematic thinking	3.67	57.36%	15.12%	4.19	3.66	3.56

4.3 Environmental Influencing Factors of GenAI Usage Among Humanities and Social Sciences Students - Peers, Teachers, and the School

Peers are the strongest influencing factor on students' GenAI usage. The overall average peer influence score is 3.71, with over 60% of students having shared usage experiences with peers, far exceeding the influence of teachers (overall average score of 3.19) and the school (overall average score of 2.91). The teachers' overall average score is 3.19. In the survey, only about 30% of students received guidance from teachers on GenAI usage, assignment guidelines, and classroom integration. More than 20% of students received no related teacher guidance at all. The school's influence is the weakest, with an overall average score of only 2.91. The school exhibits a comprehensive and severe lack of policy formulation, training systems, and tool support for GenAI, and has not yet established a robust GenAI usage support system. Please refer to Table 5.

Within the overall majors, Arts & Media majors receive the highest support from teachers and the school, while Humanities majors receive the lowest. The survey also found that the higher the grade level, the greater the need for support from the teacher

and school environment. Female students are more susceptible to peer influence, while male students are more inclined to seek support from teachers and the school.

Table 5. Environmental Factors of GenAI Usage Among Humanities and Social Sciences Students

Category	Sub-category	Average Score	Percentage of High Agreement	Overall Average
Teacher Influence	Teachers recommend or guide us on how to use GenAI tools reasonably	3.30	39.92%	3.71
	Teachers have clear regulations or requirements for using GenAI to complete assignments	3.15	34.11%	
	Teachers discuss GenAI in class or integrate it into teaching content and task design	3.12	32.56%	
Peer Influence	Classmates/friends around me frequently use GenAI tools	4.01	71.32%	3.19
	Classmates/friends around me share their experiences and techniques in using GenAI with me	3.70	60.08%	
	I feel pressure or motivation from classmates/friends, indicating that everyone is using it, and I should try it too	3.41	44.19%	
School Environment	My school/college has clear and reasonable policies on academic use of GenAI	3.01	27.13%	2.91
	The school library or information center provides convenient access or support for GenAI tools	2.89	22.48%	
	My school/college provides official guidelines or training on GenAI usage	2.82	20.93%	

4.4 Support Needs for GenAI Usage Among Humanities and Social Sciences Students

69.38% of students express a desire for "formulating clear and reasonable GenAI usage policies and academic norms" as their primary support need, which is a common core demand across all grade levels, majors, and genders. 59.69% of students wish for the offering of relevant training courses and workshops, and 55.43% hope for the integration of GenAI tools into course design. Additionally, nearly half of the students hope for discussions on AI ethics and critical usage, as well as more accessible GenAI channels. Please refer to Table 6.

Table 6. Support Needs for GenAI Usage Among Humanities and Social Sciences Students

Rank	Support Need	Number of Selections	Percentage of Valid Sample
1	**Formulate clear and reasonable usage policies and academic norms**	179	69.38%
2	**Offer relevant workshops and training courses**	154	59.69%
3	**Reasonably integrate GenAI tools into course design**	143	55.43%
4	**Provide discussions on AI ethics and critical usage**	128	49.61%
5	**Provide more accessible channels (e.g., campus version, authorized licenses)**	128	49.61%
6	**Other**	4	1.55%

In terms of acquiring support, male students focus more on teaching implementation and tool access, while female students are more concerned with ethical guidance and skills training. Lower-grade students prefer foundational skills training and ethical guidance, while higher-grade and postgraduate students desire policy standardization and integration into course teaching, aiming for deep application of GenAI usage in daily learning and academic research. Social Sciences majors have a stronger demand for support, while Humanities majors have a relatively lower demand.

5. Research Recommendations

At the school level, accelerate the formulation of clear and unified GenAI usage policies and academic norms. Establish a tiered training system for students of different grade levels, ranging from "basic introductory" to "advanced improvement" and "high-level application," to construct a systematic GenAI education support system and fill the core needs gap. Improve GenAI tool resources and technical support, and promote the deep integration and reform of GenAI with liberal arts education.

At the teacher level, teachers should proactively enhance their AI literacy and teaching capabilities, provide personalized guidance to students on GenAI usage, and act as guides and regulators of students' GenAI use. For issues encountered by students during usage, such as prompt design, content quality, and compliance, provide targeted suggestions and assistance. Especially for the pain points of Humanities majors and lower-grade students, conduct one-on-one guidance to help students improve their GenAI usage skills and standardize their usage behavior.

At the student level, fully recognize the positive value of GenAI as a learning assistance tool and actively embrace the educational reforms of the intelligent era. Proactively learn and improve GenAI usage skills to address core weaknesses. At the same time, clearly understand potential risks and avoid over-reliance leading to the degeneration of independent thinking and systematic thinking abilities.

This study has several limitations and directions for improvement. The sample coverage is not yet extensive, and the research has not captured the trajectory of individual student usage behavior evolution over time. Future research could adopt a longitudinal tracking design, conducting multiple surveys and in-depth interviews with the same cohort of humanities and social sciences students over several years (e.g., from freshman to senior year). This would help better analyze the construction process of technology's impact on learning.

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Using a Novel Multi-Stage of TF-IDF, TextRank and KeyBert for Market Campaign Analysis

Jinhong Chen [a], Zeyu Fan [a], Yujia Liu [a], Yining Wang [a], Zhiyao Xu [a], Wenzhe Zhao[a], Adela S.M. Lau[b,1]

[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*
ORCiD ID:
Jinhong Chen https://orcid.org/0009-0007-9546-6928
Zeyu Fan https://orcid.org/0009-0005-3898-6412
Yujia Liu https://orcid.org/0009-0002-3016-8624
Yining Wang https://orcid.org/0009-0009-4183-6721
Zhiyao Xu https://orcid.org/0009-0005-1748-0594
Wenzhe Zhao https://orcid.org/0009-0004-7726-1150
Adela S.M. Lau https://orcid.org/0000-0001-5918-8309

Abstract. This project presents an integrated Marketing Campaign Analysis and Decision Support System designed to transform unstructured social media data into actionable business intelligence. To address information overload, we propose a multi-stage NLP pipeline that identifies core customer concerns through advanced keyword extraction, topic modeling, and sentiment analysis. The system leverages a fine-tuned Twitter-RoBERTa transformer for high-precision sentiment classification, achieving a macro-F1 score of 0.9556, and employs a BERT-based architecture for Aspect-Based Sentiment Analysis (ABSA) to evaluate specific product features. Furthermore, ensemble predictive models forecast brand popularity trends with an R^2 of approximately 0.90. Finally, these components are unified into an interactive Streamlit dashboard powered by a DeepSeek chatbot, enabling non-technical stakeholders to access multidimensional visualizations and automated strategic marketing plans.

Keywords. Marketing Campaign Analysis; Social Media Mining; Sentiment Analysis; Trend Prediction; Decision Support System; Natural Language Processing (NLP); Data Mining; Machine Learning; Deep Learning

[1] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk

1. Introduction

Every customer post, review, complaint, and online conversation may contain valuable signals about how the market responds to a marketing campaign. As marketing communication increasingly shifts from one-way advertising to interactive digital platforms, social media have become important sources of user-generated content for understanding customer preferences, product experiences, brand perception, and campaign performance [1]. For businesses, these data provide opportunities to monitor customer needs, evaluate marketing strategies, and identify emerging trends. However, social media conversations and customer feedback are often large-scale, unstructured, noisy, and fast-changing, making it difficult for managers to manually extract reliable and actionable insights [2][3].

To address this challenge, social media analytics and text mining have been widely used to transform online customer communication into business intelligence. Previous studies suggest that social media analytics can support marketing strategy, customer relationship management, reputation monitoring, and business performance improvement [4][5]. In particular, keyword extraction can identify important business information; topic classification can organise customer conversations into meaningful business categories; and sentiment analysis can measure different attitudes expressed in customer generated content. When combined with predictive analytics and visualisation, these methods can help businesses move beyond simple data collection and generate interpretable evidence for decision making.

Therefore, this project aims to develop an integrated marketing campaign analysis system that extracts actionable insights from social media and customer conversation datasets. The main objectives are to identify discussion topics, analyse customer sentiment, predict product or brand trends, and present the results through an interactive dashboard and chatbot interface. The proposed solution combines natural language processing, predictive modelling, and data visualisation to support business users in monitoring campaign performance and planning marketing strategies. The scope of this study focuses on text based and engagement based analysis in the business sector, rather than direct causal evaluation of offline sales outcomes. Overall, this project argues that an integrated data science approach can transform complex digital customer conversations into practical marketing intelligence.

2. Literature Review

Keyword extraction is an important text-mining technique for marketing campaign analysis as it converts unstructured customer reviews into concise terms or phrases. However, automatic keyphrase extraction remains challenging because the importance of a word or phrase may depend not only on its frequency, but also on document context, domain meaning, semantic relevance, and review length [6]. Therefore, this project compares three representative unsupervised methods: TF-IDF, TextRank, and KeyBERT.

TF-IDF is a classical statistical weighting approach that evaluates term importance by considering both how frequently a term appears in a document and how rare it is across the corpus [7]. Its strengths are efficiency, making it suitable for large-scale review analysis where business users need transparent results. Nevertheless, TF-IDF treats words mainly as independent lexical units, so it may fail to capture word relationships, phrase-level meaning, or semantic similarity.

Graph-based methods provide another perspective by modelling relationships between words. TextRank represents words as nodes and word co-occurrences as edges, then applies a ranking algorithm to identify central terms in the text [8]. This allows it to capture structurally important words that frequently appear with other relevant terms in customer reviews.

Recent embedding-based approaches aim to address semantic limitations in traditional methods. BERT introduced contextualised language representations that improved many natural language processing tasks [9][10], while Sentence BERT made sentence level semantic similarity more efficient [11]. Based on this idea, KeyBERT extracts candidate words or phrases by measuring their semantic similarity to the whole document embedding [12]. Compared with TF-IDF and TextRank, KeyBERT is more capable of identifying meaningful phrases. However, it is more computationally expensive and depends on the quality of the embedding model. The literature suggests that these methods are complementary rather than interchangeable. This supports the project design of comparing all three methods to generate keynotes in business data.

Social media customer service data is valuable for understanding customer needs, complaints and service issues because it contains real-time communication between users and companies. The Customer Support on Twitter dataset provides large-scale public conversations between customers and brands, so it is suitable for analysing customer intentions such as consultation, billing problems, dissatisfaction, suggestions and positive feedback [13].

Text classification is an appropriate data science method for this project because short customer messages can be grouped into predefined thematic categories. Previous research shows that supervised text categorisation is widely used to automatically assign documents to classes based on textual features [14]. Before modelling, text is commonly cleaned and transformed into numerical representations such as TF-IDF, which allows machine learning algorithms to process word importance.

Several traditional classifiers are suitable for this task, including Logistic Regression, Naive Bayes and Support Vector Machines. Support Vector Machines are especially effective for text categorisation because they can handle sparse and high-dimensional word features [15]. In addition, dictionary-based rules and weak supervision can help create initial training labels when manual labelling is expensive. [16] explain that weak supervision uses heuristic labelling functions to produce useful training data at scale. Therefore, combining rule-based labelling with supervised classification is a reasonable method for thematic categorisation of customer support tweets.

Social-media sentiment analysis can be framed as a supervised classification problem because each post is represented by observed predictors and mapped to a known sentiment class. Statistical learning texts emphasize that classification models should be evaluated on unseen data rather than only on training fit, especially when predictors are numerous and noisy [17][18]. This supports the project design of using stratified train, validation, and test splits, excluding leakage variables such as sentiment_score, and reporting macro-F1 to avoid hiding weak performance on the under-represented Neutral class.

For short text data, feature dimensionality is high because TF-IDF creates many sparse unigram and bigram predictors. Support vector machines are theoretically suited to classification with high-dimensional decision boundaries, and Joachims [15] further shows that SVMs are effective for text categorization where many features may be relevant. This justifies including a calibrated Linear SVC as a major baseline. Logistic

Regression was also appropriate because linear statistical learning methods provide interpretable class probabilities and strong performance on sparse text features. [17][18]

Alternative machine-learning methods provide useful benchmarks [19], but are less central to this project. Nearest-neighbor classification predicts a class by comparing a new observation with similar labelled cases [20], but it can be inefficient and unstable for sparse high-dimensional text. Random forests reduce variance by combining many decision trees [21], making them powerful for tabular predictors, but they are usually less efficient than linear models for large sparse text matrices. Therefore, our final modelling pipeline focuses on TF-IDF linear baselines and a social-media-aware transformer, while using validation curves, confusion matrices, and per-class precision/recall/F1 to interpret whether the selected model truly improves sentiment classification and business scoring reliability.

While general sentiment analysis provides a macro-level view of customer satisfaction, it often fails to capture the nuanced opinions customers hold about specific product features. Aspect-Based Sentiment Analysis (ABSA) addresses this limitation by extracting sentiment polarities conditioned on specific target entities or aspects within a text [22]. Traditionally, ABSA relied on complex feature engineering and lexicon-based methods. However, the introduction of Transformer architectures, particularly BERT, revolutionized this domain by capturing deep, bidirectional contextual relationships [9].

To optimize computational efficiency without significantly sacrificing performance, DistilBERT was introduced using knowledge distillation techniques. It retains 97% of BERT's language understanding capabilities while being 60% faster and significantly lighter [23]. Furthermore, Sun et al [24] demonstrated that ABSA can be highly effective when formulated as a sentence-pair classification task. By appending the target aspect to the review text, the Transformer's self-attention mechanism is forced to evaluate the contextual sentiment specifically directed at that aspect. This project adopts this sentence-pair methodology utilizing a DistilBERT backbone to efficiently extract feature-level business intelligence from product reviews.

Predicting business trends from social media datasets involves handling high-dimensional features and complex non-linear relationships, necessitating a critical selection of regression models. While Linear Regression provides an interpretable baseline, it often fails to capture the volatile, non-linear nature of user engagement. Consequently, ensemble methods have become the standard for robust predictive analytics.

Random Forest Regressors [21] mitigate overfitting through bagging, making them resilient to the noise typical of social media data. However, for tasks requiring higher precision, boosting frameworks [25] like XGBoost [26] and LightGBM [27] often outperform bagging methods by sequentially correcting errors. LightGBM, in particular, is advantageous for large-scale datasets due to its leaf-wise growth strategy, which significantly reduces computational cost compared to traditional level-wise approaches. Additionally, Support Vector Regressors (SVR) [28] offer a robust alternative by utilizing kernel tricks to maximize generalization. By benchmarking these models, this study identifies the optimal trade-off between the interpretability of linear baselines and the predictive power of advanced ensemble methods, ensuring reliable forecasting across multi-dimensional business scenarios.

Meanwhile, the emergence of Retrieval-Augmented Generation (RAG) has addressed the critical challenge of knowledge staleness in Large Language Models (LLMs), enabling marketing systems to generate insights grounded in the latest consumer behavior data and brand-specific knowledge bases. Concurrently, the

paradigm of Agentic Workflows has revolutionized task automation, allowing AI agents to autonomously plan, reason, and execute complex marketing strategies—from social media content curation to customer sentiment analysis. These developments are increasingly being validated using large-scale social media datasets, where the ability to process unstructured user-generated content is paramount. Therefore, we leverage RAG and agentic workflows to integrate our final analysis and present it to users. [29][30][31][32]

Another critical component of the project focuses on converting fragmented text-mining and predictive outputs into a unified decision-support interface. Unlike conventional dashboards that display isolated metrics, this system implements a visual analytics and human-AI interaction layer designed to synthesize keyword extraction, topic classification, sentiment analysis, ABSA, and trend prediction into coherent business insights. This architecture directly addresses limitations in existing marketing tools by adopting Shneiderman's [33] visual information-seeking principle: providing an initial overview, enabling filter/zoom operations, and allowing on-demand detail inspection. Accordingly, the home page delivers high-level overviews, global filters enable targeted analysis, and dedicated drill-down pages present detailed evidence for brands, products, campaigns, and risk-opportunity matrices.

To mitigate cognitive overload, the dashboard design adheres to Few's [34] principle of clear information communication and Munzner's [35] task-data-user alignment, prioritizing KPI cards, sentiment distributions, time-series trends, and risk-opportunity tables over raw model outputs. Given the multidimensional nature of the data (text, brand, product, platform, campaign phase, sentiment, engagement, time), the interface operationalizes Heer and Shneiderman's [36] interactive visual analysis operations—filtering, sorting, and coordinated views—through Streamlit's [37] caching and widget ecosystem (Streamlit, n.d.). Extending beyond static visualization, the chatbot implements OpenAI's (n.d.) function-calling paradigm, grounding the DeepSeek model in five local analytical tools (text analysis, trend lookup, risk retrieval, aspect comparison, and strategy suggestion) to prevent hallucination. Numerical insights are fetched directly from local Parquet files, chosen for their column-oriented efficiency in tabular retrieval (Apache Software Foundation, n.d.), ensuring that conversational recommendations remain strictly evidence-based.

3. Data Science Methods

3.1 Data sources, data cleansing and pre-processing

For the various NLP tasks, distinct datasets were utilized to align with their specific characteristics. This approach not only enriches the diversity of our data but also rigorously evaluates the generalization capability of our methods. For the final module dedicated to business recommendations and visualization, we employed the 'social media dataset.' This dataset was chosen for its substantial sample size and rich feature set. Furthermore, we incorporated both the qualitative and quantitative results from each sub-model to conduct a comprehensive analysis. The information of the datasets used in this study can be found in Figure1.

Dataset	Analytical module	Data source	Sample size	Temporal coverage	Platform / channel	Main variables	Purpose in this study
Clothing Review Dataset	Keyword extraction	Kaggle clothing review dataset	49,338 raw records; 47,549 cleaned records	Not time-based; no timestamp used	E-commerce product reviews	Review title, review text, product rating, clothing class	Used for TF-IDF, TextRank, and KeyBERT keyword extraction to identify customer concerns such as fit, size, comfort, material, and quality.
Customer Support on Twitter	Topic classification	Kaggle Customer Support on Twitter dataset	Approximately 2.8 million tweets and replies before filtering	Timestamp available through created_at; not used for forecasting in this module	Twitter	Tweet text, tweet ID, author ID, inbound status, creation time, reply/conversation metadata	Used to classify customer-support messages into topic categories such as consultation, billing, dissatisfaction, approval, needs/suggestions, and irrelevant content.
Social Media Engagement Dataset	Sentiment analysis, trend prediction, dashboard, and strategy generation	Social Media Engagement Dataset.xlsx	12,000 posts; 26 variables	1 May 2024 to 30 April 2025	Facebook, Instagram, Reddit, Twitter, YouTube	Timestamp, platform, brand, product, campaign, text content, hashtags, mentions, keywords, sentiment label, sentiment score, likes, shares, comments, impressions, engagement rate	Used as the core dataset for sentiment classification, business scoring, trend prediction, risk/opportunity ranking, and dashboard integration.
Amazon Sales Dataset	Aspect-based sentiment analysis	Kaggle Amazon Sales Dataset	Approximately 1K+ product rating and review records before cleaning	Not time-based; no campaign timestamp used	Amazon e-commerce reviews	Product category, product metadata, rating, review title/content	Used to construct aspect-sentiment pairs by extracting product aspects from category hierarchy and converting ratings into Positive, Neutral, and Negative labels.

Note. The Social Media Engagement Dataset is the main time-aware dataset in this study. Its platform distribution is relatively balanced: Facebook (2,431 posts), Instagram (2,355), Reddit (2,372), Twitter (2,406), and YouTube (2,436). It also contains 10 brands, 70 products, and 23 campaign names, enabling cross-platform, brand-level, product-level, and campaign-level analysis.

Figure 1: The overview of the datasets used in this study

As shown in the table, the project does not rely on a single dataset. Product review datasets support keyword extraction and aspect-based sentiment analysis, while Twitter customer-support data supports thematic categorisation of short customer-service messages. The Social Media Engagement Dataset serves as the core dataset for sentiment analysis, trend prediction, dashboard reporting, and recommendation generation because it contains both textual content and structured engagement indicators across multiple platforms.

The main time-aware dataset covers one full year, from 1 May 2024 to 30 April 2025, and includes five social media platforms: Facebook, Instagram, Reddit, Twitter, and YouTube. This enables the system to compare marketing performance across time, platform, brand, product, and campaign dimensions. To address potential data drift, future deployment should monitor changes in keyword distributions, sentiment-label proportions, engagement metrics, and predictive errors over time. If classification or forecasting performance declines on recent data, the TF-IDF vocabulary, rule dictionaries, transformer models, and regression models should be updated or retrained.

The keyword extraction task was based on a clothing review dataset containing 49338 records from Kaggle. It contains customer written titles and reviews, together with product attributes like Cons_rating (the rating of product 1-5), Cloth_class (the classes of clothes).

Only task relevant columns were retained in the dataset. Missing titles were filled with empty strings, while duplicate samples and samples missing reviews, ratings or classes were removed. The title and review were then combined into a single text to provide richer contextual information.

Two preprocessed text versions with different levels of cleaning were generated. For KeyBERT, a lightly cleaned version was created by lowercasing text, removing URLs, HTML tags, line breaks, and extra spaces, while retaining sentence structure for semantic embedding. For TF-IDF and TextRank, a stronger cleaning process was applied, including number and punctuation removal, tokenisation, stopword removal, filtering non-alphabetic and short tokens, and lemmatisation. After cleaning, 47549 records remained. A rating_group variable was also created to label positive,negative or neutral samples according to Cons_rating.

The thematic categorization task was based on the Customer Support on Twitter dataset from Kaggle, which contains about 2.8 million public tweets and replies between customers and companies. The dataset includes fields such as tweet text, tweet ID, author ID, inbound status, creation time and response relationships. Since the project focuses on customer issues, only inbound customer messages were retained, while company replies were removed. The main task-relevant column was the tweet text.

During data cleansing, user mentions, URLs, special characters and extra spaces were removed. All text was converted to lowercase, and very short messages were filtered out to reduce noise. Because the original dataset did not contain the required six topic labels, rule-based keyword matching was used to generate weak labels for needs and suggestions, approval and liking, dissatisfaction and complaints, consultation, billing and irrelevant content. This weak supervision strategy avoids expensive manual annotation and ensures large-scale available training data.

The project uses Social Media Engagement Dataset.xlsx, containing 12,000 social-media posts with timestamp, platform, language, location, text content, hashtags, mentions, keywords, engagement metrics, campaign/product metadata, sentiment_score, and sentiment_label. The supervised target is sentiment_label with three classes: Negative (4,854), Positive (4,839), and Neutral (2,307). Missing values appeared mainly in mentions (3,941 rows) and were filled as empty text before feature construction.

Four text fields (text_content, hashtags, mentions, keywords) were merged into combined_text. For TF-IDF baselines, text was lower-cased, whitespace-normalized, and #/@ symbols were removed while preserving the tokens. For the transformer model, casing was retained, user mentions were normalized to @user, and URLs to http, matching Twitter-RoBERTa pre-training. Leakage variables such as sentiment_score, sentiment_label, and emotion_type were excluded from model inputs. The data was stratified into train/validation/test splits (70/15/15). Noisy train and validation labels were filtered using sentiment-score thresholds and lexicon agreement, reducing training rows from 8,400 to 6,148 and validation rows from 1,800 to 1,337. The 1,800-row test set was left uncleaned to reflect production conditions.

The Aspect-Based Sentiment Analysis module utilizes an Amazon Sales Dataset, which contains detailed product metadata, categorical hierarchies, user ratings, and textual reviews. Data pre-processing was conducted through a custom Python pipeline to ensure high-quality inputs for the Transformer model. First, raw text data was cleaned by stripping HTML tags, URLs, and non-alphanumeric characters, followed by whitespace normalization and lowercasing.

To formulate the ABSA task, explicit aspect and sentiment labels had to be engineered from the raw metadata. The target "aspect" was dynamically extracted from the product's categorical hierarchy by isolating the most specific sub-category (e.g., extracting "cables" from "Accessories|Cables"). Simultaneously, the raw numerical ratings were safely converted into a ternary sentiment classification: scores of 3.0 or below were labeled as Negative (0), scores between 3.0 and 4.0 as Neutral (1), and scores above 4.0 as Positive (2). This resulted in a refined dataset containing the cleaned review text, the specific product aspect, and the corresponding sentiment label, which was then split into an 80/20 training and testing set.

The trend prediction model is based on a social media dataset from Kaggle, which has over 10,000 rows and 25 columns, i.e., features. The features include a timestamp column, which allows us to aggregate data according to specific time scales for time-series forecasting. The remaining columns consist of both numerical features, such as likes_count, shares_count, user_engagement_growth,etc. and non-numerical features, including platform, hashtag, text_content, etc.

Prior to any modeling, we performed initial data cleaning to handle outliers and ensure dimensional consistency, padding missing values with nan. Feature Engineering comes next. Fisrt step is identifying target and training features based on business logic. The second step is selecting raw features for calculation and applying One-Hot Encoding to non-numerical features. The third step is aggregating data by the appropriate time scale

to compute training features—often including time-dependent metrics and calculating the target features.

E.g. In the brand_name trend prediction task, the feature engineering process aggregates raw social media logs into daily time-series data, constructing a multidimensional feature set that includes engagement metrics, content attributes, and temporal features. To capture trends and seasonality, the pipeline generates lag features and rolling window statistics for post volume, while also applying one-hot encoding to categorical variables like campaign names and platforms.

For the dashboard integration, we used the Social Media Engagement Dataset, containing 12,000 posts with brand, product, platform, campaign, timestamp, engagement, sentiment, and text fields. I converted the Excel file into a Parquet analytical dataset, standardised timestamp, numeric, and categorical fields, and generated date, month, and week-start variables for time-series aggregation. Wang Yining's predictive report was transformed into a CSV table containing 11,765 high-risk and high-opportunity combinations.

3.2 Models Design

Three unsupervised models were designed for keyword extraction. TF-IDF used the strongly cleaned text with unigram and bigram features to identify important terms. TextRank used the same cleaned text to build word co-occurrence graphs, with PageRank style scores used to identify central keywords. KeyBERT used the lightly cleaned text and the all-MiniLM-L6-v2 sentence embedding model to extract semantically relevant unigrams and bigrams. The main input variable was review text, while the outputs were ranked keywords with scores for overall reviews, rating groups, and clothing classes. Descriptive analysis and visualization were used to summarize review length, rating distribution, and keyword rankings.

The input variable was the cleaned customer tweet text, and the output variable was the topic label. Descriptive analytics were used to examine the distribution of the six topic categories and identify the main types of customer issues. Since the text data could not be directly used by machine learning models, TF-IDF was applied to convert words into numerical features based on their importance in the corpus.

Several supervised text classification models were designed and compared, including Logistic Regression, Linear Support Vector Classifier and Multinomial Naive Bayes. In addition, a hybrid model was developed by combining dictionary-based rules with Logistic Regression. The dictionary rules captured clear keywords related to complaints, billing, suggestions and positive feedback, while Logistic Regression handled less explicit messages. Data visualizations, including topic distribution charts and model benchmark charts, were used to summarize category patterns and compare model performance clearly.

Descriptive analytics examined class balance, text length, engagement statistics, and average sentiment_score by class. In the cleaned training set, mean text length was 117.8 characters, while average sentiment_score clearly separated Negative (-0.677), Neutral (approximately 0), and Positive (0.672) posts.

The main input variables for sentiment classification were text_content, hashtags, mentions, and keywords. Engagement variables (likes_count, shares_count, comments_count, impressions, engagement_rate, and user_engagement_growth) were reserved for derived business scores. The output variables were predicted_label, class

probabilities (positive_score, negative_score, neutral_score), referral_score, community_score, and discussion_score.

The model design compared four TF-IDF baselines using unigram/bigram features (max_features=15000, min_df=3, sublinear term frequency): Multinomial Naive Bayes, multinomial Logistic Regression, calibrated Linear SVC, and a hybrid Logistic Regression plus lexicon model. The production service uses a fine-tuned cardiffnlp/twitter-roberta-base-sentiment-latest transformer with class-weighted cross-entropy, AdamW, 10% warmup with linear decay, gradient clipping, dynamic padding, fp16 training, and early stopping. Visualizations include label-distribution tables, model-comparison tables/bar charts, training loss and validation-F1 curves, confusion matrices, and per-class precision/recall/F1 tables.

The ABSA model was built using a fine-tuned distilbert-base-uncased architecture via the PyTorch and Hugging Face Transformers libraries. The problem was framed as a sentence-pair classification task. For each sample, the review text and the extracted aspect were concatenated using special tokens: [CLS] Review Content [SEP] Aspect Name [SEP]. This specific input formulation allows the model's cross-attention heads to contextualize the review specifically around the target aspect.

The model architecture extracts the hidden state of the [CLS] token, applies a dropout layer (rate = 0.3) for regularization, and passes it through a fully connected linear classifier to predict the three sentiment classes. The training pipeline utilized the AdamW optimizer with a learning rate of 2e-5 and a linear learning rate scheduler with no warmup steps. To ensure stability and prevent exploding gradients, gradient clipping (max norm = 1.0) was applied. The model was trained over 3 epochs using a batch size of 16, and the Cross-Entropy loss function was employed to handle the multi-class classification objective.

Trend prediction is fundamentally a regression problem, varying only in complexity. In the trend prediction part in this project, we have designed a hierarchical framework consisting of three levels of tasks:Single-dimension, single-metric; Dual-dimension, multi-metric; Multi-dimension, multi-metric.

When decomposed, each of these tasks is treated as a distinct regression problem. For every sub-task, we conducted experiments using a diverse set of regression algorithms to identify the optimal performer. These models range from classical statistical methods to advanced ensemble techniques: Linear Regression; Random Forest Regressor; Gradient Boosting Regressor; Support Vector Regressor (SVR); XGBoost Regressor (XGBRegressor); LightGBM Regressor (LGBMRegressor).

Final Prediction Strategy For each specific sub-task, the model that demonstrates the best performance on the test set is selected as the "champion model" to participate in the final prediction phase.

Rather than developing an additional standalone predictive model, this component functions as an integration and orchestration layer that synthesizes the outputs of all preceding analytical modules. A secondary data science pipeline aggregates the group's models through descriptive analytics, implementing KPI tracking, sentiment distribution mapping, platform and campaign-phase comparisons, weekly trend visualizations, and brand-specific drill-downs. The orchestration engine ingests standardized inputs—including brand, product, platform, campaign phase, date range, social text, engagement rate, sentiment scores, topic labels, and trend categories—and transforms them into structured visual summaries, risk-opportunity rankings, and aspect-based product comparisons.

The conversational interface employs a tool-augmented architecture where the DeepSeek model routes user queries to one of five deterministic Python functions (free-text analysis, trend lookup, risk/opportunity retrieval, aspect comparison, and strategy generation). Retrieved numerical results are then synthesized into natural language explanations. The automated strategy plan relies on a rule-based engine rather than generative AI, applying deterministic logic for risk thresholding, opportunity scoring, platform budget weighting, and campaign timing recommendations. While this deterministic approach ensures reproducibility and traceability, the current dashboard and chatbot evaluations are primarily functional and descriptive; formal usability testing with domain experts is reserved for future deployment phases to validate decision-making efficiency.

4. Result summary and Interpretation

Table 1: Part of overall top keywords extracted by three models

Model	Top extracted keywords / phrases
TF-IDF	fit, great, love, dress, size, like, color, comfortable, top, perfect
TextRank	fit, great, love, like, size, good, fits, dress, nice, wear
KeyBERT	dress, comfortable, fit, sweater, shirt, jeans, pants, jacket, fabric, size

As shown in Table 1, all three models identified clothing-review concerns around fit, size, dress, comfort, and quality, showing that customer discussions were mainly centred on product suitability and wearing experience. However, the models produced different types of keywords because they measure importance differently. TF-IDF ranked “fit” highest, followed by affective terms such as “great” and “love”. This indicates that these terms were frequent in individual reviews but still discriminative across the corpus. It is useful for identifying dominant review vocabulary, but it mixes product attributes with general evaluative words.

TextRank produced a similar but more centrality-based ranking. Words such as “like”, “good”, “wear”, and “fits” ranked highly because they frequently co-occurred with many other review terms. This suggests that TextRank captures conversational hubs in the review network rather than only statistically distinctive terms. However, this also explains why some general words such as “like” appeared very high: they connect many review expressions but are less directly actionable for marketing decisions.

KeyBERT generated more product-oriented and semantic keywords, including “sweater”, “shirt”, “jeans”, “jacket”, “fabric”, and phrase level results such as “true size” and “love dress”. Compared with TF-IDF and TextRank, KeyBERT better captures meaningful product entities and natural customer expressions, which are more useful for dashboard presentation and business interpretation.

Table 2: Comparison of rating-group keywords (a part of results)

Rating group	Representative keywords
Positive reviews	great, love, comfortable, perfect, soft, cute
Negative or neutral reviews	small, material, fabric, quality, ordered, runs small

As shown in Table 2, the rating-group results provide clearer business insights. The extracted keywords also show that several terms were sentiment-consistent with the positive and negative/neutral categories. For example, positive reviews contained words such as “great”, “love”, “comfortable”, and “perfect”, while negative or neutral reviews included terms such as “small”, “material”, “quality”, and “runs small”. This suggests that the keyword extraction task successfully identified representative terms for different rating groups. Positive reviews were dominated by emotional satisfaction and comfort related terms, whereas negative or neutral reviews focused more on concrete product problems. This difference indicates that customer satisfaction in this dataset is strongly linked to comfort and perceived fit, while dissatisfaction is mainly driven by sizing inconsistency and material-related expectations.

The extraction results by clothing class also show that the three models were able to identify category specific terms that reflect the characteristics of different product types. For example, the Sweaters class included keywords such as “sweater” and “cardigan”, while the Jeans class included “denim”, “jeans”, and “pants”. This suggests that the task was finished effectively.

The model comparison results in Table 3 show that the hybrid dictionary plus Logistic Regression model achieved the best overall performance. It reached an accuracy of 0.9337, a macro-F1 score of 0.9243 and a weighted-F1 score of 0.9343. This superior performance can be attributed to the complementary design of rule-based weak supervision and statistical learning: keyword matching efficiently captures explicit, high-frequency customer intents such as complaints and billing problems, while Logistic Regression generalizes well to implicit, ambiguous, and colloquial expressions common in social media texts. This indicates that the hybrid model was the most reliable method for classifying customer tweets into the six thematic categories. Its strong performance suggests that combining rule-based keyword detection with machine learning was effective. The dictionary rules helped identify clear customer intentions, such as billing issues, complaints, suggestions and positive feedback, while Logistic Regression handled messages where the meaning was less explicit.

Linear SVC was the second-best model, with 0.9259 accuracy, 0.9027 macro-F1 and 0.9259 weighted-F1. Logistic Regression also performed well, reaching 0.9135 accuracy, 0.8886 macro-F1 and 0.9148 weighted-F1. In contrast, Multinomial Naive Bayes had the weakest performance, with 0.6897 accuracy, 0.4479 macro-F1 and 0.6277 weighted-F1. The poor performance of Naive Bayes can be attributed to its strong feature independence assumption, which is difficult to satisfy in short, colloquial customer support texts with high contextual dependence. This suggests that Naive Bayes was less suitable for this dataset.

Table 3: Model Performance Comparison

Model	Accuracy	Macro-F1	Weighted-F1
Hybrid Dictionary + Logistic Regression	0.9337	0.9243	0.9343
Linear SVC	0.9259	0.9027	0.9259
Logistic Regression	0.9135	0.8886	0.9148
Multinomial Naive Bayes	0.6897	0.4479	0.6277

The label distribution in Table 4 showed that "Irrelevant" was the largest category, with 44,064 records, followed by approval and liking with 9,957 records, needs and suggestions with 6,585 records, dissatisfaction and complaints with 6,375 records, billing with 6,018 records and consultation with 4,916 records. Since the dataset was imbalanced, macro-F1 and weighted-F1 were more meaningful than accuracy alone. Overall, the results show that the hybrid model can effectively support thematic categorization of customer support tweets and help companies identify customer concerns more efficiently.

Table 4: Topic Category Distribution Excluding Irrelevant

Topic Category	Percentage
Approval & Liking	29.41%
Needs & Suggestions	19.45%
Dissatisfaction & Complaints	18.83%
Billing	17.78%
Consultation	14.52%

As shown in Table 5, the fine-tuned Twitter-RoBERTa reached the best validation macro-F1 (0.9556) and was selected for deployment because it is pre-trained on social-media text and handles hashtags, mentions, informal wording, and negation more naturally than hand-built rules. Its held-out test macro-F1 was 0.9378, close to the best TF-IDF baselines. Logistic Regression slightly led on the stored test split (0.9432 macro-F1), so it remains a practical fallback when GPU resources are unavailable.

Table 5 An overview of different model performances

Model	Test Accuracy	Test Macro-F1	Neutral F1	Interpretation
Logistic Regression	0.9450	0.9432	0.9354	Best lightweight baseline and CPU fallback
Calibrated Linear SVC	0.9428	0.9420	0.9387	Strong linear benchmark
Fine-tuned Twitter-RoBERTa	0.9372	0.9378	0.9387	Production model; strongest validation macro-F1 and social-media-aware representation
Hybrid LR + Lexicon	0.8983	0.8960	0.8857	Good manual semantic behavior but weaker test generalization
Multinomial Naive Bayes	0.8489	0.7885	0.5849	Fast baseline but poor Neutral recall

The model is especially reliable when predicting Neutral: Neutral precision is 1.000 and recall is 0.884, meaning no Negative or Positive posts were incorrectly classified as Neutral, although some true Neutral posts were predicted as Negative. Positive and Negative F1 scores were also high (0.947 and 0.928 respectively). As shown in Table 6, the main remaining error pattern is that 66 Positive posts were predicted as Negative, suggesting that ambiguous praise, sarcasm, or mixed sentiment may still be difficult.

Table 6: The test confusion matrix for the transformer

Actual\Predicted	Negative	Neutral	Positive
Negative	721	0	7
Neutral	39	306	1
Positive	66	0	660

In addition to the sentiment label, the API returns three interpretable business scores. referral_score combines positive probability, recommendation-intent phrases, and low negative probability. community_score summarizes reach and influence using log-scaled impressions, shares, likes, mentions, and engagement growth. discussion_score captures conversation potential using comments, engagement rate, shares, and question intent. These scores allow the dashboard/API output to support both sentiment monitoring and campaign action prioritization.

As shown in Table 7, the DistilBERT ABSA model demonstrated strong performance in isolating aspect-specific sentiments, achieving an overall test accuracy of above seventy percent. The model successfully learned to differentiate sentiment based on the appended aspect token, proving the effectiveness of the sentence-pair formulation.

Table 7: Performance of DistilBERT ABSA model

Sentiment Class	Precision	Recall	F1-Score
Negative (0)	0.86	0.84	0.85
Neutral (1)	0.81	0.78	0.79
Positive (2)	0.91	0.93	0.92

The model performed exceptionally well on the Positive class, largely due to the natural distribution of e-commerce data where positive reviews are generally more abundant and feature clearer linguistic signals. The slightly lower performance in the Neutral class highlights a common NLP challenge: neutral reviews often contain a mix of mild praise and minor complaints that can confuse the classification boundaries. Ultimately, the model proves highly capable of feeding reliable, aspect-specific sentiment scores (e.g., differentiating sentiment between a phone's "battery" vs. its "camera") into the downstream interactive dashboard, allowing business users to pinpoint exact product strengths and weaknesses.

Trend Prediction Tasks:

1. Single-dimension, single-metric:

Overall, the prediction models for brand post volume demonstrate high accuracy and robustness, effectively capturing the trends in brand buzz.

As shown in Table 8, the R^2 on the training set for all brands is above 0.90. Apple (0.986), Amazon (0.984), and Nike (0.984) show particularly outstanding performance, indicating that the models fit the historical data patterns extremely well. The Test R^2 generally remains around 0.90 (peaking at 0.921 for Nike), proving that the models maintain excellent predictive stability when facing unseen data, with no significant overfitting.

The Test Mean Absolute Error (MAE) is mainly concentrated between 0.36 and 0.44. The Relative Error (Test MAE Ratio) is mostly controlled within the 10% - 13% range, which is considered a highly robust and reliable performance for social media trend forecasting.

Table 8: Different brand name best regression model performances.

Brand	Best_Model	Train_R2	Test_R2	Train_MAE	Test_MAE	Test_MAE_Ratio
Google	Linear Regression	0.936	0.908	0.34	0.43	13.0%
Microsoft	Linear Regression	0.933	0.910	0.35	0.40	11.9%
Nike	Random Forest Regressor	0.984	0.921	0.15	0.36	10.0%
Pepsi	Linear Regression	0.909	0.923	0.36	0.44	12.5%

Toyota	Random Forest Regressor	0.982	0.881	0.16	0.41	12.5%
Coca-Cola	Linear Regression	0.914	0.905	0.37	0.51	14.8%
Amazon	LightGBM Regressor	0.984	0.909	0.15	0.38	11.8%
Samsung	Linear Regression	0.941	0.919	0.35	0.43	13.1%
Adidas	Linear Regression	0.912	0.915	0.36	0.40	10.8%
Apple	Random Forest Regressor	0.986	0.908	0.14	0.36	11.1%

2. Dual-dimension, multi-metric:

This model supports dynamic predictive analysis for various brands. The following summary uses Nike as an example to demonstrate the results of our dual-dimension (Brand-Platform) and multi-metric modeling.

Core Predictive Insights (Cross-Channel Performance):

Total Engagement: Facebook is projected to be the primary driver of reach, with a predicted volume of 101k—the largest engagement base across all platforms.

Engagement Rate: Reddit demonstrates superior audience precision, significantly outperforming other social channels.

Viral Potential: YouTube leads with the highest viral potential score (0.46), identifying it as the optimal platform for high-impact, breakout content.

Accuracy Analysis (Test MAE Ratio): Most core KPIs, such as Facebook engagement, maintain an MAE Ratio around 0.15, providing a solid scientific foundation for strategic decisions. The result is shown in Table 9.

Table 9: Prediction Performance of Nike on different platforms

Platform	Target Metric	Best Model	Test MAE	Test MAE Ratio
Facebook	Total Engagement	Gradient Boosting Regressor	14768.24	14.60%
	Avg Engagement Rate	Linear Regression	0.06	24.16%

	Viral Potential	Random Forest Regressor	0.04	9.21%
	Total Engagement	Support Vector Regressor	17723.33	23.30%
Instagram	Avg Engagement Rate	Random Forest Regressor	0.08	38.40%
	Viral Potential	Gradient Boosting Regressor	0.04	10.32%
	Total Engagement	Linear Regression	13785.88	18.25%
Reddit	Avg Engagement Rate	Support Vector Regressor	0.06	21.52%
	Viral Potential	Linear Regression	0.02	4.71%
	Total Engagement	Support Vector Regressor	14797.33	19.30%
Twitter	Avg Engagement Rate	Gradient Boosting Regressor	0.09	52.26%
	Viral Potential	Support Vector Regressor	0.06	12.96%
	Total Engagement	Support Vector Regressor	13964.33	19.93%
YouTube	Avg Engagement Rate	Random Forest Regressor	0.07	34.29%
	Viral Potential	Gradient Boosting Regressor	0.09	20.59%

Visualization: The system generates trend charts for each platform (see Figure 2 and Figure 3)



Figure 2: Google prediction on Twitter



Figure 3: Nike prediction on Facebook

3. Multi-dimension, multi-metric:

This phase involves a cross-dimensional modeling of Brand, Platform, Product, and Campaign to uncover granular market patterns. Given the data sparsity and high variance caused by the surge in dimensions, this analysis is treated as a deep predictive exploration.

The prediction of Post Volume is of high precision (R^2 scores between 0.985 and 0.999) while the prediction of Sentiment Score is not (R^2 is near 0 or even negative). This indicates that traffic scale has strong historical momentum and is the most reliable metric for forecasting, but social media sentiment is highly sensitive to real-time random events, making it an "exploratory" metric rather than a deterministic one at this stage. The result is shown in Table 10.

Table 10: Different combination prediction performance

Dimension	Target Variable	Best Model	Test R2	Features
brand_name	post_volume	Linear Regression	0.990598	24
brand_name	avg_sentiment_score	Support Vector Regressor	-0.005123	24
platform	post_volume	Linear Regression	0.998927	24
platform	avg_sentiment_score	Gradient Boosting	0.041708	24
product_name	post_volume	Gradient Boosting	0.985325	24
product_name	avg_sentiment_score	Support Vector Regressor	0.001262	24
campaign_name	post_volume	Linear Regression	0.990346	24
campaign_name	avg_sentiment_score	Random Forest	-0.130799	24

Finally, an integrated Streamlit application was developed to unify the five analytical components into a cohesive decision-support environment. As shown in Figure 4, the home page delivers a management-level overview of the campaign dataset, displaying key indicators such as total posts, average sentiment, engagement rate, positive rate, brand count, and campaign volume. These metrics provide immediate contextual awareness before users drill into specific models. Global filters for brand, platform, campaign, and date range enable both macro-level monitoring and micro-level comparative analysis.

The dashboard structure demonstrates how fragmented model outputs are synthesized into connected business evidence. The Brand Deep Dive page integrates time-series trends, platform distribution, and keyword exploration to map attention drivers and associated discourse. The Campaign Analysis page evaluates phase-specific performance by cross-referencing engagement and sentiment shifts, identifying optimal campaign timing. The Product Aspect page links directly to the ABSA model, enabling feature-level sentiment diagnosis beyond aggregate positive/negative labels. The Risk and Opportunity page operationalizes 11,765 predictive combinations into actionable rankings, clearly segregating high-risk exposures from high-potential growth opportunities.

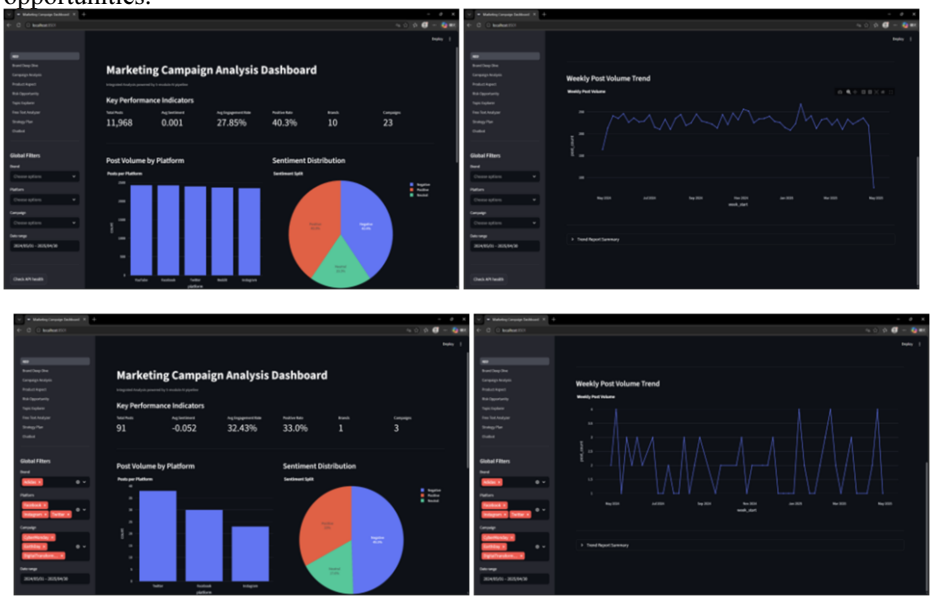


Figure 4: The Home page and Dashboard

The Strategy Plan page translates analytical outputs into structured marketing recommendations. Utilizing a deterministic rule engine, it automatically generates reports detailing top opportunities, risk mitigations, platform budget allocations, campaign timing, and brand sentiment summaries. This significantly enhances usability, allowing non-technical stakeholders to download actionable strategy documents without manual chart interpretation.

As shown in Figure 5, the integrated chatbot provides a conversational interface grounded in the same analytical evidence base. Functional testing confirmed that the system accurately retrieves project-specific data via local tool calls rather than relying

on the language model's internal knowledge base. By executing the same analytical functions as the dashboard and returning validated numerical insights, the chatbot serves as an interactive diagnostic assistant. Collectively, this integration layer resolves the fragmentation of standalone analytical outputs, transforming complex data science pipelines into a unified, interactive decision-support system for real-time campaign monitoring, product diagnosis, risk detection, and strategy formulation.

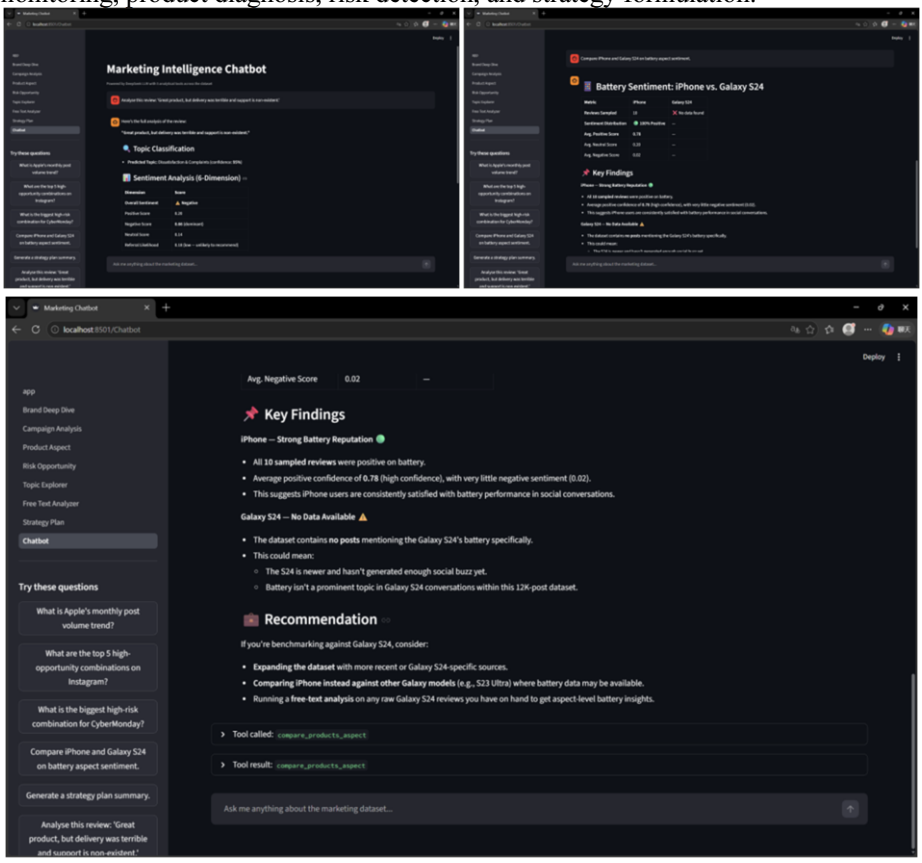


Figure 5: The Chatbot page

Program Coding and Performance and Deployment Analysis Our source code is available at https://github.com/QuantumPlanet/Marketing-Campaign-Analysis.git

System Architecture & Latency The system is designed as a decoupled microservices architecture to optimize inference latency. The core NLP pipeline consists of four independent FastAPI services running on ports 8001–8004:

Keyword Extraction (Port 8001)

Topic Classification (Port 8002)

Sentiment Analysis (Port 8003)

Aspect-Based Sentiment Analysis (ABSA) (Port 8004)

This modular design allows the Streamlit dashboard (Port 8501) to query specific components asynchronously, preventing the UI from blocking during heavy computation. The trend prediction module operates offline via pre-computed CSVs, ensuring zero latency for historical data visualization.

Hardware Requirements & Memory Footprint Based on the model artifacts and dependencies, the system has the following hardware prerequisites:

Storage: Approximately 4 GB of free disk space is required for the initial caching of HuggingFace tokenizers and model weights.

Memory (RAM/VRAM): The system loads multiple transformer-based models. The sentiment_analysis model alone requires ~476 MB (model.safetensors), and the aspect_based_sentiment model requires ~253 MB. Combined with the Python runtime and FastAPI overhead, a minimum of 16 GB system RAM is recommended.

Accelerator: While the pipeline was developed with torch 2.x, the model sizes suggest that inference can be performed on a modern CPU for moderate batch sizes. However, for real-time responsiveness in the Streamlit dashboard (especially when handling concurrent chatbot requests via DeepSeek API), a GPU with at least 4 GB VRAM (e.g., NVIDIA T4 or RTX 3060) is highly recommended to accelerate the transformer encoders.

Deployment Environment The deployment relies on a Conda environment with Python 3.10+. The dashboard integrates with the DeepSeek LLM via API, offloading the heavy generative chatbot computation to the cloud, which significantly reduces the local hardware burden. Local services are orchestrated via PowerShell scripts, defaulting to a specific Anaconda interpreter path, though this is configurable via environment variables.

5. Discussions

The project results show that the proposed marketing campaign analysis system successfully converts unstructured social-media and customer-review data into interpretable business evidence. The keyword extraction results indicate that customers mainly discussed practical product concerns such as fit, size, comfort, quality, material, and product category. TF-IDF was useful for identifying frequent and distinctive terms, TextRank captured central co-occurring words, and KeyBERT provided more product-oriented semantic phrases. Together, these methods helped transform raw review text into topic-level signals that marketing users can understand.

The sentiment analysis results further support the project goal of monitoring customer attitudes at scale. The fine-tuned Twitter-RoBERTa model achieved a validation macro-F1 of 0.9556 and a held-out test macro-F1 of 0.9378, showing strong overall generalization. Its Neutral precision reached 1.000 with recall of 0.884, which is important because Neutral was the least represented class. This means the model was conservative when predicting Neutral and did not incorrectly label positive or negative posts as Neutral. However, the confusion matrix also shows that 66 Positive posts were predicted as Negative, suggesting that mixed sentiment, implicit praise, or sarcastic language can still be difficult. Therefore, the model is reliable enough for dashboard-level monitoring, but high-risk individual posts should still be reviewed with context.

The trend prediction results show that the regression models can capture brand-level buzz patterns effectively. Most brands achieved test R2 values around 0.90, while test MAE was mainly between 0.36 and 0.44. This indicates that the models generalized well to unseen time periods and can support short-term campaign planning. The feature-importance results also provide actionable insight: comments, impressions, shares, and likes were major drivers of future post volume, while sentiment score and toxicity score also influenced buzz. This suggests that interaction quality matters more than simple

visibility. Posts that trigger comments and shares may sustain brand attention better than content that only receives passive likes.

Overall, the data science methods achieved the project goals by linking different analytical tasks into one workflow. Text mining identified what customers talked about; sentiment analysis and ABSA explained how customers felt about brands, products, and specific aspects; regression models predicted future risk and opportunity; and the Streamlit dashboard converted these outputs into visual summaries, rankings, filters, and downloadable strategy plans. The chatbot extended this value by allowing users to ask natural-language questions and retrieve project-specific analytical results through local function calls rather than relying only on general language-model knowledge.

The main insight from the predictive and reporting outputs is that marketing decisions should not depend on one metric alone. High exposure is useful, but sentiment and toxicity determine whether attention is beneficial or risky. Similarly, engagement volume matters, but comments and shares are more strategically meaningful than likes because they reflect deeper audience involvement. The reporting layer makes these insights practical by connecting model outputs to brand comparisons, campaign-phase analysis, product-aspect diagnosis, risk/opportunity ranking, and strategy generation. Future improvements should include more human-validated labels, multilingual sentiment handling, stronger sarcasm detection, and live data updating so the system can support real-time campaign management.

6. Conclusions

This project successfully developed an integrated, end-to-end marketing campaign analysis system that transforms large-scale, unstructured customer feedback into actionable business intelligence. By combining multiple data science methodologies, the system provides a comprehensive, multi-dimensional view of market reception. Unsupervised keyword extraction models (TF-IDF, TextRank, KeyBERT) successfully distilled core customer concerns into representative terms, highlighting both statistical importance and semantic relevance. Supervised machine learning and advanced Transformer models effectively evaluated both broad social media sentiment and granular, aspect-based product feedback. Furthermore, time-series regression models accurately captured and predicted brand buzz, allowing for precise forecasting of post volume trends and the identification of underlying engagement drivers.

Rather than leaving these technical outputs in isolation, the project successfully unified them through an interactive Streamlit dashboard and a tool-augmented DeepSeek chatbot. This human-Al interaction layer bridges the critical gap between raw data science and practical marketing strategy, allowing non-technical business users to easily monitor KPIs, identify high-risk product features, and automatically generate data-driven marketing strategy plans. Overall, this system proves that when text mining, predictive analytics, and conversational Al are seamlessly integrated, they provide a powerful competitive advantage in monitoring campaign performance and shaping future marketing decisions.

Future Plans Building upon this solid foundation, there are several key avenues for future development to enhance the system's scalability, usability, and analytical capabilities. Our future plans focus on three main objectives:

Deploy to the cloud behind authentication: To transition the system from a localized prototype to an enterprise-ready application, the immediate next step is

migrating it to a robust cloud infrastructure. Implementing secure authentication protocols and role-based access control (RBAC) will ensure that remote marketing teams can access the dashboard globally while keeping sensitive business intelligence and user data strictly protected.

Give the chatbot persistent conversation memory: Currently, the tool-augmented chatbot excels at handling independent queries. By integrating persistent session memory, the system will support complex, multi-turn conversations. Users will be able to ask follow-up questions—such as drilling deeper into a newly discovered brand risk—without needing to restate previous context, creating a more natural and cohesive exploratory experience.

Stream tool results so users can watch the analysis happen live: Given the computational intensity of running real-time NLP models and retrieving multi-dimensional data, we plan to implement a streaming architecture. Instead of waiting for long back-end processes to finish, users will be able to watch the analysis generate live (e.g., token-by-token text generation and real-time chart rendering). This will drastically reduce perceived latency and provide a highly engaging, responsive user experience.

Through these planned enhancements, the project will evolve into a fully dynamic, secure, and highly interactive marketing intelligence platform.

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A Novel CreditCopilot-HK System by Integrating Credit Scoring, Complaint Analytics and Chatbot for Auditable Credit-Risk Decision Support

Mingtian XIONG[a], Hewei TANG[a], Zhaoxu MENG[a], Wantong XU[a] and Yuxiao TIAN[a], Adela S.M. Lau[b,1]

[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*
ORCiD ID:
Mingtian XIONG https://orcid.org/0009-0005-5894-5378
Hewei TANG https://orcid.org/0009-0009-7538-5789
Zhaoxu MENG https://orcid.org/0009-0005-3833-9952
Wantong XU https://orcid.org/0009-0005-8942-4882
Yuxiao TIAN https://orcid.org/0009-0009-2109-7415
Adela S.M. Lau https://orcid.org/0000-0001-5918-8309

Abstract. Automated credit scoring, complaint analytics and chatbot explanation are often developed as separate banking workflows, leaving applicants, analysts, and governance reviewers with fragmented evidence. This paper presents CreditCopilot-HK, a scoped methodology demonstration for auditable credit-risk decision support. The system integrates structured credit records, complaint narratives, and policy documents through reusable evidence artefacts rather than record-level joining. The primary contribution is to operationalise counterfactual explanation as a conversational UX: applicant-level counterfactuals are translated into natural-language improvement guidance so that the chatbot can explain not only why a model estimates elevated risk, but also what actionable improvement directions may reduce model-estimated risk. Empirically, CFPB complaint narratives are used for product–issue taxonomy construction, topic discovery, sentiment classification, and similar-case retrieval; the Taiwan Default dataset is used for probability-of-default modelling, SHAP explanation, fairness screening, SMOTE sensitivity analysis, and counterfactual generation; and HKMA policy documents are used for retrieval-grounded governance responses. Results show an interpretable complaint taxonomy, coherent semantic complaint workflows, a FinBERT sentiment benchmark, and XGBoost risk explanations in which repayment behaviour and exposure dominate the SHAP drivers. The dashboard and chatbot consume the same saved artefacts, demonstrating evidence-layer integration for transparent communication and governance review in a scoped prototype setting.

Keywords. Credit risk, complaint mining, explainable AI, retrieval-augmented generation, banking analytics, fairness auditing

[1] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk
All authors contributed equally to this work.

1. Introduction

Retail credit institutions operate at the intersection of structured risk assessment and unstructured customer evidence. Credit scoring models estimate default probability from repayment and exposure data, while complaint platforms reveal product defects, servicing friction, and reputational risks. In practice, model risk teams, complaint teams, and chatbots operate separately, making it difficult to provide the "meaningful information" required by regulated AI systems and credit decisioning.

CreditCopilot-HK addresses this fragmentation by integrating complaint intelligence, credit-risk modelling, explainable AI (XAI), and retrieval-augmented generation (RAG) into a single auditable pipeline exposed through a dashboard and a policy-grounded chatbot.

This paper makes three contributions: (1) we operationalise counterfactual explanation as a conversational UX, converting applicant-level counterfactuals into natural-language improvement guidance; (2) we propose a decoupled evidence-layer integration architecture that assigns distinct roles to structured credit records, complaint narratives, and HKMA policy documents, integrating their outputs as reusable artefacts rather than forcing record-level joins; and (3) we provide a regulated-credit-analytics validation matrix covering predictive modelling, complaint mining, sentiment analysis, explainability, fairness auditing, imbalance sensitivity, and retrieval-grounded response generation.

The study uses approximately 10,000 sanitized CFPB complaint narratives and the Taiwan Default dataset, with governance framing aligned to Hong Kong banking requirements for accountability, fairness, transparency, and human-review support. Sections 2–3 review related work and present the architecture; Section 4 reports analytical results; Section 5 describes the demonstrations; Sections 6 discuss governance implications and conclude.

2. Related Work

Complaint mining typically combines TF-IDF for transparent keyword extraction [1][2] with neural approaches such as KeyBERT [3] and embedding-based clustering [4][5] for semantic representation. Topic modelling has evolved from probabilistic LDA [6] to transformer-based embeddings with class-based TF-IDF labelling, supported by silhouette analysis [7]. CreditCopilot-HK adapts these techniques to a regulator-recognised Product–Issue structure.

Sentiment analysis in finance ranges from lexicon methods (VADER [8], Loughran–McDonald [9]) to transformer encoders such as BERT [10,11] and domain-tuned FinBERT [12][13]. For credit scoring, gradient-boosted trees remain dominant on tabular data [14][15][16], with SHAP [17] and counterfactual methods like DiCE [18] providing post-hoc explanations. Fairness research [19][20] highlights that predictive performance alone is insufficient when automated decisions affect credit access. RAG systems [11,21] combine retrieval with generation, but for banking applications, traceability to retrieved evidence is essential. CreditCopilot-HK integrates these strands into a single auditable pipeline.

3. System Architecture and Methodology

3.1. Architecture Overview

CreditCopilot-HK is organised as a record-decoupled evidence pipeline (Figure 1) with three data inputs, six analytical modules, serialised evidence artefacts, and two demonstration endpoints. The system uses evidence-layer integration: each source is processed for its appropriate analytical role, and outputs are serialised as reusable artefacts rather than merged at record level. CFPB complaint narratives support taxonomy, topic, sentiment, and similar-case retrieval; the Taiwan Default dataset [22] supports probability-of-default modelling, SHAP, fairness, SMOTE, and DiCE counterfactuals; HKMA policy documents [23] support policy-grounded RAG. The dashboard (src/dashboard/app.py) and standalone chatbot are separate endpoints over the same saved evidence base.

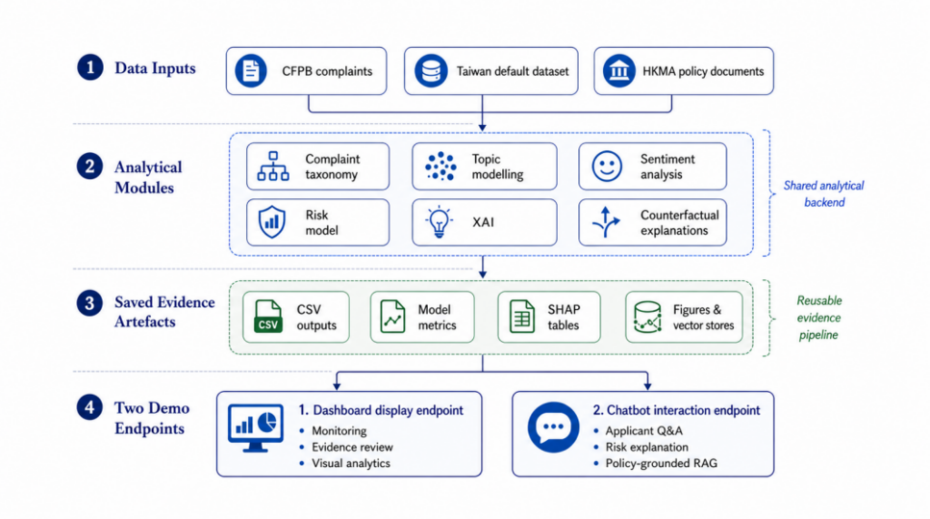


Figure 1. CreditCopilot-HK evidence-layer architecture. Three record-decoupled data inputs are processed by analytical modules and serialised as reusable evidence artefacts, which are then consumed by two demonstra- tion endpoints: a dashboard for monitoring and review, and a chatbot for interactive explanation.

3.2. Complaint Intelligence and Topic Discovery

The complaint corpus is cleaned via a PII-aware pipeline (CFPB redaction placeholders, digit runs, and boilerplate tokens are removed). Three representations are produced: global TF-IDF baseline, KeyBERT semantic phrases, and per-cell TF-IDF over Product–Issue groupings, yielding a data-driven taxonomy aligned with regulator-recognised structures. For topic discovery, LDA serves as the bag-of-words baseline; an embedding-based pipeline using Sentence-Transformer + KMeans (with silhouette diagnostics) and class-based TF-IDF labels reveals latent operational workflows.

3.3. Sentiment Classification and Risk Modelling

Three sentiment models are benchmarked under the same protocol: VADER (lexicon), TF-IDF + Logistic Regression (transparent supervised), and fine-tuned FinBERT (domain transformer). The risk branch processes the Taiwan Default dataset with engineered features (utilisation, repayment delay, delinquency count, exposure). Candidate classifiers include logistic regression, random forest, gradient boosting, and XGBoost; XGBoost is selected for downstream explanation. The module produces KMeans portfolio segments, SHAP global attributions, fairness disparity audits, DiCE counterfactuals, and SMOTE sensitivity tests [24][25].

3.4. Retrieval-Augmented Explanation and Interfaces

Separate FAISS vector stores are built for complaint cases and HKMA policy passages. The chatbot triggers a three-step reasoning chain: applicant scoring and feature derivation, XAI and counterfactual retrieval, and response synthesis grounded in similar complaints and policy text. The Streamlit dashboard surfaces taxonomy, sentiment, risk, SHAP, fairness, and counterfactual artefacts for governance review, while the standalone chatbot provides interactive applicant explanation. The artefact-first design separates training from serving, supporting reproducibility and isolating failure modes.

4. Analysis and Results

The results are organised around three methodological claims: counterfactual conversa- tional explanation, evidence-layer integration, and regulated-credit analytics validation. The XGBoost, SHAP, and DiCE case study shows how applicant-level risk explanations can be converted into conversational improvement guidance. The Product–Issue taxon- omy, semantic topic clusters, complaint retrieval, and HKMA policy retrieval demon- strate how record-decoupled sources can be integrated through reusable evidence arte- facts. The predictive model benchmark, sentiment benchmark, SMOTE sensitivity anal- ysis, fairness audit, and counterfactual table provide comparative evidence for model selection and governance review, without claiming production robustness.

4.1. Complaint Taxonomy and Semantic Topics

The cleaned TF-IDF pipeline produces a vocabulary dominated by banking terms (payment, loan, credit, mortgage, card), confirming effective removal of CFPB placeholder noise. Per-cell TF-IDF reveals discriminative patterns: student-loan narratives emphasise "mohela, forbearance, repayment, forgiveness"; mortgage narratives emphasise "escrow, servicer, modification"; credit-card narratives split between disputes ("charge, dispute, fraud") and account management ("balance, payment, fee"). The heatmap in Figure 2 exposes which terms are discriminative within each Product–Issue cell. Embedding-based clustering yields four

interpretable clusters corresponding to student-loan repayment, mortgage servicing, credit-card disputes, and credit-report issues, complementing official labels by revealing cross-product workflows such as payment processing and account correction.

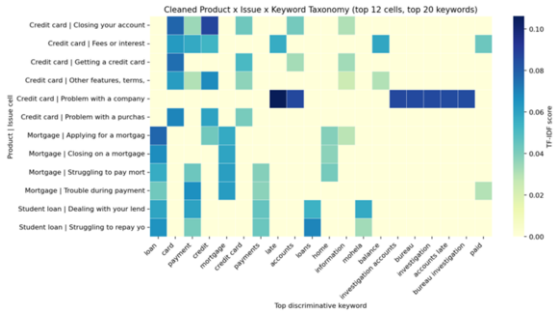


Figure 2. Product–issue keyword heatmap. Per-cell TF-IDF exposes which terms are discriminative within each Product–Issue workflow.

4.2. Sentiment Classification and Credit-Risk Modelling

Table 1 summarises sentiment classifier performance. Fine-tuned FinBERT achieves the strongest results (Macro-F1 = 0.847, Accuracy = 0.863), substantially outperforming VADER (0.683) and TF-IDF logistic regression (0.791). FinBERT particularly improves recognition of negative complaints with formal or hedged language. For credit-risk prediction, tree-based models lead the benchmark, with XGBoost selected for its strong ROC-AUC combined with better recall than linear baselines (Figure 3). KMeans segmentation divides 30,000 customers into Prime (2.1%), Stable (33.6%), Watchlist (42.4%), and Stress (21.9%) segments, with the Stress segment showing a 55.0% observed default rate—demonstrating the value of combining applicant scoring with portfolio grouping.

Table 1. Sentiment classification performance on the CFPB complaint test set.

Model	Precision	Recall	Macro-F1	Accuracy
VADER	0.671	0.698	0.683	0.701
LR + TF-IDF	0.803	0.779	0.791	0.812
Fine-tuned FinBERT	0.851	0.843	0.847	0.863

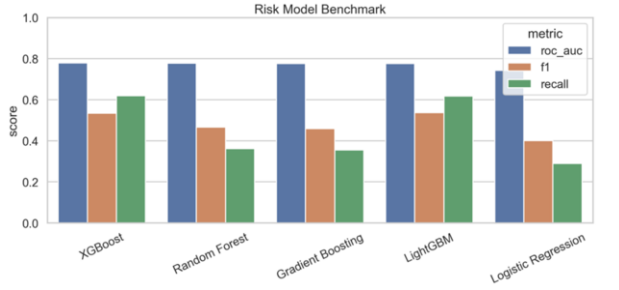


Figure 3. Credit-risk model benchmark. XGBoost provides the strongest predictive candidate for downstream explanation and decision support.

4.3. Explainability, Fairness, and Counterfactual Guidance

SHAP analysis identifies maximum repayment delay (mean |SHAP| = 0.057), credit limit (0.029), recent bill amount (0.027), recent repayment status (0.026), and estimated utilisation (0.019) as the dominant XGBoost risk drivers (Figure 4)—all financially meaningful and suitable for human review. The fairness audit produces governance signals rather than legal conclusions: Education shows the largest disparity (approval-rate gap = 0.298, recall gap = 0.652); marriage status shows moderate recall disparity; sex and age group show lower disparities. SMOTE sensitivity analysis reveals a precision–recall trade-off (recall: 0.619 → 0.784; precision: 0.471 → 0.331; ROC-AUC: 0.779 → 0.762), informing deployment configuration choices.

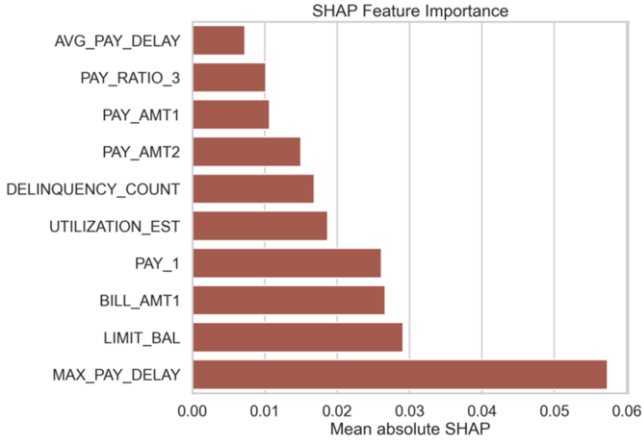


Figure 4. SHAP risk drivers. Repayment delay and exposure variables dominate the XGBoost default-risk explanations.

The counterfactual module generates applicant-level improvement paths. For a high-risk applicant (predicted risk 93.8%), one counterfactual lowers risk to 39.1% by improving repayment status (PAY_1: 2 → 0) and reducing utilisation; an alternative reaches 40.9% via different adjustments. These outputs are surfaced as decision-support directions, not approval instructions.

4.4. Credit-Risk Prediction and Segmentation

The RAG layer retrieves HKMA passages on alternative credit scoring, generative AI governance, and fairness/privacy/transparency, grounding chatbot responses in cited evidence rather than free-form generation. Together, the results support the three methodological claims: counterfactual explanation moves from static post-hoc analysis to conversational guidance (XGBoost + SHAP + DiCE bridge); evidence-layer integration handles record-decoupled heterogeneous sources through reusable artefacts; and the comparative validation matrix supports model selection and governance review without claiming production robustness.

5. Demonstrations and Discussion

5.1. Dashboard and Chatbot Endpoints

Two endpoints consume the same evidence base. The Streamlit dashboard (port 8510) provides executive status, credit-risk studio (scores, SHAP, segments, counterfactuals), and customer-voice analytics (taxonomy, topics, sentiment, trends) for analysts and governance reviewers. The standalone chatbot (port 8511, Figure 5) supports applicant queries by combining risk score, SHAP drivers, counterfactual directions, similar complaints, and HKMA policy passages into traceable responses, moving from "why does the model estimate elevated risk?" to "which actionable improvements may reduce model-estimated risk?"

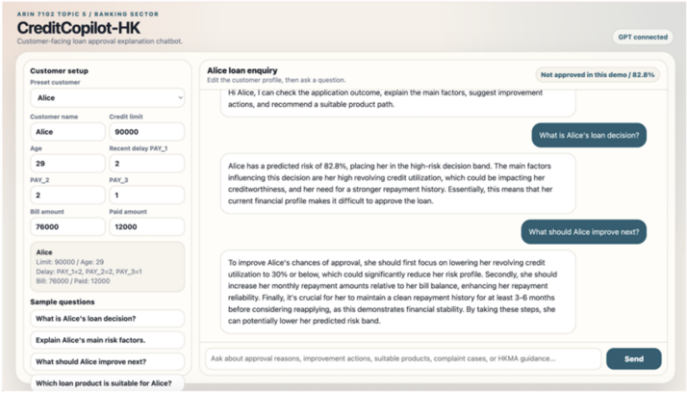


Figure 5. Standalone chatbot demonstration. The conversational endpoint consumes the same saved evidence artefacts as the dashboard, but uses them for interactive risk explanation, counterfactual guidance, and policy-grounded Q&A.

5.2. Business Value and Governance Implications

For managers, the system enables prioritization: review resources can be allocated to the Stress segment, deteriorating sentiment cells can trigger early intervention, and chatbot explanations standardize customer responses. For applicants, transparency replaces generic rejection with reasoned explanations and improvement paths. For governance teams, all outputs are traceable to models, features, taxonomy cells, and retrieved policy passages. Validated error sources include high-frequency institution names dominating taxonomy keywords, embedding-seed sensitivity in topic boundaries, weak-label artefacts in sentiment learning, historical bias in benchmark datasets, and chunking-dependent retrieval quality—each requiring targeted validation before production use.

5.3. Computational Cost and Deployment Scalability

The text-mining pipeline processes 10,000 narratives in 8–12 minutes on a single GPU (NVIDIA T4 class) or under 25 minutes on CPU. FinBERT fine-tuning takes ~35 minutes per epoch (GPU); inference completes in <1.5 seconds per query. XGBoost training on 30,000 records takes <2 minutes; SHAP global attribution ~90

seconds; DiCE counterfactual generation 2–4 seconds per applicant. The artefact-first architecture decouples training from serving, allowing horizontal scaling and overnight retraining for mid-sized banks (5,000–20,000 monthly complaints) on a single mid-range GPU server. RAG retrieval latency remains under 2 seconds for vector stores with <100K chunks. These characteristics make the system feasible for small-to-medium production environments; large-scale deployments would benefit from distributed embedding stores and GPU-accelerated inference servers.

5.4. Limitations

CreditCopilot-HK is a scoped methodology demonstration, not an autonomous approval engine. Public benchmark datasets are not record-linked; outputs integrate only at the evidence-artefact level. The system has not yet been validated on real Hong Kong individual-level credit portfolios. Complaint labels are weakly supervised; fairness metrics are screening signals, not legal conclusions; counterfactual suggestions are decision-support directions, not approval guarantees; RAG grounding reduces but does not eliminate hallucination risk. Any production deployment requires model validation, bias review, data-protection assessment, retrieval monitoring, escalation rules, and drift checks.

6. Conclusion and Future Work

CreditCopilot-HK is a scoped prototype demonstrating counterfactual conversational explanation for auditable credit-risk decision support. By integrating complaint taxonomy, semantic topics, sentiment classification, risk prediction, XAI, fairness auditing, counterfactuals, and policy-grounded RAG through evidence-layer integration, the system provides a traceable pathway from heterogeneous data to applicant-facing guidance. Per-cell TF-IDF produces interpretable taxonomies; FinBERT achieves the strongest sentiment performance; XGBoost with SHAP identifies repayment delay and exposure as dominant risk drivers; and DiCE generates feasible improvement paths surfaced through both dashboard and chatbot.

Future work targets three real-world validation directions. First, we will partner with Hong Kong retail banks under appropriate data-sharing and privacy agreements to evaluate the system on local credit portfolios, replacing the Taiwan Default benchmark with HK-specific data to assess geographic and demographic generalizability. Second, we will conduct user studies with credit officers, complaint analysts, and governance reviewers, measuring decision accuracy, response trustworthiness, and time-to-decision compared with conventional dashboards. Third, we will engage compliance practitioners through structured interviews and Delphi-style expert panels to validate alignment between counterfactual recommendations and HKMA governance expectations. Additional work will incorporate expert-labelled sentiment, stronger temporal forecasting, and formal bias and robustness testing before any production deployment.

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A Data Mining and Text Analytics Platform for Prediction-Market Information Discovery

Jialin Liu [a], Xianyu Mo [a], Qianli Song [a], Anbo Wang [a], Guanhao Xie [a], Weitao Yan [a], and Adela S.M. Lau [b,1]

[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*

ORCiD ID:
Jialin Liu https://orcid.org/0009-0002-2614-1656
Xianyu Mo https://orcid.org/0009-0009-9957-5288
Qianli Song https://orcid.org/0000-0002-5077-0850
Anbo Wang https://orcid.org/0009-0004-8872-0201
Guanhao Xie https://orcid.org/0009-0001-3823-9223
Weitao Yan https://orcid.org/0009-0000-2568-2499
Adela S.M. Lau https://orcid.org/0000-0001-5918-8309

Abstract. Prediction markets provide real-time, crowd-sourced estimates of event probabilities, but their information is fragmented across market descriptions, liquidity conditions, price histories, related events, and trader behaviour, making the raw interface difficult to navigate. Users must manually inspect market pages, news context, liquidity, volume, price movement, and market wording before forming a view. This project builds a data mining and text analytics platform on a Polymarket snapshot of 854,775 markets, 323,493 events, and 19,204,891 price-history rows across 1,777 category labels. The system combines descriptive analytics, risk-grid segmentation, market clustering, association-rule mining, microstructure and concentration analysis, text retrieval, and short-horizon price modelling, exposed through a dashboard and a retrieval-grounded chatbot so that users can search, compare, and inspect markets in one workflow. Empirically, the word-plus-character TF–IDF + LinearSVC variant gives the strongest intent routing; the hybrid retrieval pipeline lifts Recall@10 from 0.365 to 0.473 over TF–IDF at the cost of higher latency; ARIMA(1,1,1) shows a small positive skill score over the random walk only at the 24-hour horizon, which we report as a methodology benchmark rather than a tradeable edge; and a first-order Markov next-question recommender matches the Bayes-optimal upper bound. Evaluation focuses on data quality, analytical validity, model performance, usability, and the practical utility of the surfaced information for market exploration.

Keywords. Prediction markets, data mining, text analytics, prediction-market analytics, retrieval-augmented generation, dashboard, chatbot

[1] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk

1. Introduction

Prediction markets turn beliefs about future events into traded prices. In an efficient setting, a contract price can be interpreted as an aggregated probability-like signal about an event outcome [1,2]. However, understanding a single market is not solved by simply reading the latest price. A user also needs to inspect market liquidity, volume, volatility, resolution criteria, textual ambiguity, related markets, news context, and historical price movement, and these signals are distributed across heterogeneous data sources.

The research problem of this project is therefore: *how can data mining and text analytics be used to transform fragmented prediction-market data into a structured, navigable information surface?* The objective is not a trading recommendation system. The objective is to build a reproducible analytical platform that helps users locate relevant markets, understand the data behind them, and access concise, evidence-backed summaries.

The contribution of the system is threefold. First, it integrates numerical market analytics and textual market understanding in a single workflow, and builds a risk-grid and market-ranking layer based on liquidity, volume, price movement, and textual features, so that users can quickly compare and filter markets. Literature Review

1.1. Data Cleansing and Pre-processing

Real datasets contain duplicates, missing values, and inconsistencies; duplicate removal and attribute standardisation are foundational [3], and recency-based conflict resolution preserves temporal consistency [4]. Deterministic imputation gives stable approximations under plausible missing-at-random patterns with a semantically meaningful zero [5]; where zero implies a misleading regime—a bid–ask spread of zero implying perfect liquidity—missingness is treated as a separate state. Bounding probabilistic values within [0,1] preserves modelling validity [6]. Text normalisation [7], temporal feature construction [8], quantile-based discretisation [9], and statistical summaries [10] are standard. The project adopts a four-stage pipeline—deduplication, missingness-aware imputation, range clipping, and quantile bucketing—so the cleaned dataset is comparable across scale. Domain-specific tokens (tickers, percentages, dates, "25bps") are retained because retrieval depends on alphanumeric expressions a generic stop-list would discard.

1.2. Retrieval-based Market and Event Search

Retrieval is the grounding layer of the chatbot because user questions are short, ambiguous, and topic-oriented while prediction-market information is distributed across event titles, market questions, descriptions, categories, tags, outcomes, and numerical metadata. Unlike ordinary document retrieval, Polymarket retrieval must connect a broad real-world topic to specific tradable contracts; one event may contain several markets with different outcomes or settlement rules, motivating a two-level design in which event retrieval captures broad themes and market retrieval identifies contract-level candidates.

Classical lexical retrieval offers a transparent baseline. TF-IDF represents each row as a sparse vector and works well when queries contain distinctive entities such as countries, candidates, tickers, teams, or event phrases [11,12]. BM25 improves on this by handling document-length variation and term-frequency saturation, useful when short market questions and longer descriptions are searched together [13]. Both, however,

depend on vocabulary overlap and miss relevant markets under wording mismatch. Semantic retrieval addresses this by representing texts according to meaning: Latent Semantic Analysis offers an interpretable low-dimensional signal via matrix factorisation, while sentence-embedding models such as Sentence-BERT provide stronger semantic matching for short queries [14,15]. We implement dense retrieval with a BGE encoder and an optional cross-encoder reranker that directly scores query–document pairs; reranking improves precision but adds runtime cost [16]. Because no single retriever is sufficient for financial market search, the final design is hybrid: lexical methods are fast and interpretable, dense retrieval improves semantic coverage, and LSA contributes a topic-level signal. Reciprocal Rank Fusion combines BM25, dense, and LSA rankings by rewarding documents near the top of multiple rankers [17], supporting an architecture in which events ground broad topics, markets supply tradable candidates, and high-precision reranking is reserved for cases that need it.

1.3. Intent Classification

Intent classification underpins task-oriented chatbots. Sparse TF-IDF with linear classifiers remains strong in high-dimensional text spaces [18]. Dense encoders such as Sentence-BERT improve paraphrase robustness but struggle when classes overlap semantically [15]. Instance-based kNN preserves local structure rather than compressing each class to a prototype [19], and character n-grams improve performance on multilingual or noisy text [20]. We therefore compare TF-IDF+LinearSVC against an embedding centroid and an embedding kNN to disentangle two design choices the literature treats jointly: representation geometry (sparse vs. dense) and classifier inductive bias (margin-based vs. instance-based). Section 4.2 shows the decomposition is empirically meaningful.

1.4. Price Forecasting on Prediction-Market Series

Prediction-market prices are commonly interpreted as crowd-sourced probability estimates and track underlying event probabilities reasonably well [1,2,21,22]. A recurring empirical finding is that these prices behave close to a martingale once visible information is incorporated, so the random-walk forecast acts as a strong reference baseline [23,24]. On short, noisy series the M4 and M5 competitions report that statistical baselines such as exponential smoothing and ARIMA remain competitive against deep learning when training history is short or signal-to-noise is low [25,26]. Comparative studies show that even Transformer-based forecasters can be matched or surpassed by carefully tuned linear models [27], and surveys of deep time-series methods caution that capacity advantages require long, structured histories [28]. These observations motivate evaluating the production gradient-boosted model alongside an econometric baseline (ARIMA) and a recurrent baseline (LSTM, [29]), benchmarked against a random-walk skill score [30]. Gradient boosting on engineered lag and rolling features is competitive in tabular time-series tasks [31,32], but its advantage over simple recursive baselines is task-dependent and must be verified empirically.

1.5. Next-Action and Sequential Intent Prediction

Sequential recommendation has two dominant families. Markov-chain models (e.g. Factorising Personalized Markov Chains, [33]) offer closed-form estimation, $O(1)$

inference, and interpretable transition matrices. Neural sequence models—RNN-based GRU4Rec [34], self-attentive SASRec [35], and bidirectional BERT4Rec [36]—typically outperform Markov when vocabulary is large, sequences long, and transition structure high-order [37,38]. Conversely, when the vocabulary is small, sequences short, and the DGP itself near low-order, the empirical transition matrix is essentially Bayes-optimal and there is little headroom for higher-capacity models. Standard metrics are Top-k accuracy, Hit@k, MRR, and perplexity (38); we adopt them and add a Bayes-optimal upper bound computed from the synthetic transition matrix.

2. Data Science Methods

2.1. Data Sources and Pre-processing

2.1.1. Data Sources

The dataset is sourced from Polymarket [39] through three documented interfaces: Gamma (events, markets, metadata), CLOB (price histories, order-book snapshots), and Data API (open interest, holders, leaderboards) [40–42]. Raw responses are persisted in SQLite. Collection is a reproducible job: each run logs timestamp, endpoint, query parameters, pagination cursor, and row counts to a manifest table, and raw payloads are cached so preprocessing and modelling can be replayed from the same snapshot. Failed requests retry with exponential backoff under the platform's rate limits [43]. The current snapshot covers 854,775 markets across 1,777 category labels (see Section 4.5).

2.1.2. Data Cleansing

Duplicate rows across events, markets, and price histories are resolved by keeping the most recent fetch. Timestamps are standardised to UTC; rows with null timestamps or null prices are dropped. Continuous price and probability fields are clipped to [0,1] and negative metrics are set to zero. Missing values are handled with semantically aware rules. Categorical fields without an explicit label are inferred from associated tags or marked "Uncategorized". For *count-like* fields (volume, distinct holders) zero imputation is meaningful because absence plausibly reflects no activity. For *microstructure* fields (liquidity, bid–ask spread) zero would imply perfect liquidity, which is misleading; we therefore attach a missingness indicator (spread_missing, liquidity_missing) and the risk grid treats these markets as a separate "unknown-liquidity" bucket. Missing baseline probabilities default to 0.5 as a no-information prior.

2.1.3. Pre-processing

Textual fields—title, question, description—are concatenated, lower-cased, stripped of URLs and HTML, and tokenised. The tokenizer retains finance- and event-specific alphanumeric tokens (btc, eth, cpi, 25bps, q1, percentage expressions) because retrieval depends on tickers, dates, and policy phrases an alphabetic-only filter would discard. Standard English stop-words are removed alongside a curated stoplist of Polymarket resolution boilerplate (data, stream, open, displayed, equal, source, resolution, outcome) so high-rank TF–IDF terms reflect category semantics rather than template wording. Temporal features—market age, time-to-close—are derived in hours from creation, bound, and retrieval timestamps. Volume and liquidity are partitioned into quintiles for robustness to heavy tails; per-token price histories yield descriptive statistics (min, max,

mean, standard deviation, single-step returns); composite scores for activity, efficiency, momentum, liquidity, and risk are bounded in [0,1] and feed an ordinal market rank.

2.1.4. Knowledge Base Extraction (Stage 1b)

A separate stage derives a category-level knowledge base. For each of the 1,777 category labels, cleansed market texts are concatenated into a pseudo-document, and a TF–IDF vectoriser is fit across the resulting matrix using unigrams and bigrams: $\mathrm{TFIDF}(t, c) = \mathrm{tf}(t, c) \cdot \log(N_c/(1 + \mathrm{df}(t)))$, where N_c is the number of category pseudo-documents. The top-20 terms per category are persisted as keywords_by_category.csv and a flat category_taxonomy.json feeds the dashboard taxonomy filter and the category_summary/keyword_lookup intents (see Table 1). The boilerplate stoplist was added after an initial run produced lists dominated by resolution-template tokens. TF–IDF was preferred over learned topic embeddings because the lists are auditable and surface domain tokens that generic embeddings tend to wash out.

Table 1. Top five TF-IDF keywords per finance-relevant category from the knowledge base (Stage 1b).

Category	Top keywords (rank 1–5)
Crypto	sol usd, xrp usd, data stream, open displayed, equal open
Crypto Prices	sol usd, xrp usd, data stream, btc usd, chainlink
Bitcoin	candle ends, ends time, price btc, btc usdt, yes close
Ethereum	ends time, candle ends, eth usdt, source ethereum, price eth
Solana	sol usdt, price solana, sol usd, sol, specifically sol
Inflation	indec, cpi, bls, inflation month, consumer price

2.2. Models Design

2.2.1. Index Construction and Runtime Retrieval

Retrieval grounds short, ambiguous user queries in the right tradable contracts. For each market and event row, title, question, description, category, tag, and slug are concatenated into a retrieval text. Two indexes are built: a market index for specific contracts and an event index for broader themes. The default representation is sparse TF–IDF; sidecar indexes add BM25, dense embeddings, and LSA. Vectorisers, matrices, metadata, and configuration are persisted so runtime retrieval loads the same representation consistently. Components are summarized in Table 2.

Table 2. Summary of input, output, method retrieval components

Component	Input	Main method	Output
Market index	marketscleancsv	TF–IDF/BM25/dense/LSA optional sidecars	Specific contract candidates
Event index	eventscleancsv	TF–IDF/BM25/dense/LSA optional sidecars	Broad topic/event candidates
Runtime retrieval	User query	Market search + event search + event-to-market expansion	Top-k market IDs and metadata
Fusion and rerank	Ranked candidate lists	RRF and optional cross-encoder reranking	Final candidate order

At runtime, the retriever queries the market and event indexes separately. Event hits are expanded into related markets via the event_id relation and merged with direct market hits; duplicates are removed by market_id. The scoring rule for event-expanded markets gives more weight to broad event relevance while preserving contract-level relevance; full scoring details are in the appendix. Numerical analytics (ranking by volume, liquidity, volatility) are deliberately handled by the downstream analytics query engine, keeping retrieval modular.

2.2.2. Intent Routing

Figure 1 shows the hybrid intent routing pipeline. The intent dataset contains 577 Chinese–English bilingual queries from manually labelled data, template-generated queries, and LLM paraphrases. Duplicates were removed and a stratified split formed train and test sets. For TF–IDF models we use both word- and character-level n-grams; for embedding-based methods we encode queries with Sentence-Transformer or use IDF-weighted aligned word embeddings. Six configurations are compared: TF–IDF+Logistic Regression; TF–IDF+LinearSVC (word only); TF–IDF+LinearSVC (word+char); SentenceTransformer+centroid cosine; FastText aligned+3NN cosine; SentenceTransformer+3NN cosine. The output is an intent label with a confidence score; the system uses high-confidence SVM predictions directly and falls back to embedding-based similarity when confidence is low.

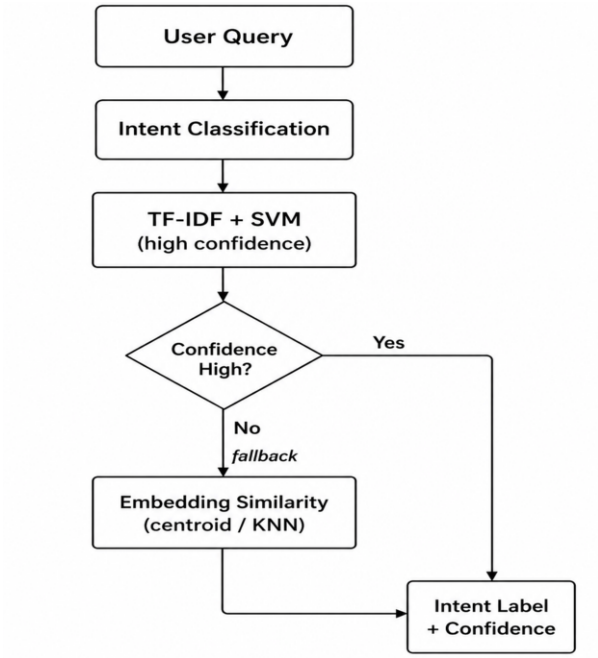


Figure 1. Hybrid Intent Routing Pipeline

2.2.2.1. Tier-S Advanced Exploration Intents.

The trained classifier resolves the six base intents present at dataset construction. As the analytics suite grew (Sections 3.2.6–3.2.11), twelve *Tier-S* intents—advanced market-exploration intents covering the descriptive analytics modules—were added without retraining. Tier-S queries are handled by a small set of deterministic regex heuristics

introduced for engineering convenience. These rules are not the focus of the study and are not formally evaluated. On a regex miss the query falls through to the SVM; on low-confidence SVM output it falls through again to the embedding-centroid fallback (Figure 2). The full eighteen-intent taxonomy is in Table 3.

Table 3. Eighteen-intent taxonomy: six base intents inherited from the trained TF-IDF+LinearSVC classifier and twelve advanced market-exploration intents resolved by deterministic regex pre-classifiers.

Intent	Purpose
market_lookup	Find a specific market or contract
compare_markets	Compare two related markets
trend_analysis	Change, timing, or momentum
category_summary	Sectors / categories breakdown
risk_analysis	Liquidity, spread, volatility risk
general_finance_query	General finance-focused query
mispriced_markets	Simplex-sum consistency anomalies
unusual_markets	Anomalies vs. recent baselines
market_relations	Co-movement (Apriori rules)
microstructure_lookup	Spread, depth, liquidity context
concentration_lookup	HHI, Gini, top-N share
smart_money_lookup	Top-PnL wallet activity
cluster_explore	K-Means topic neighbours
keyword_lookup	Per-category TF-IDF keywords
resolution_timing	Days to close, expiry filter
slippage_estimate	Per-size book-impact estimate
forecast_lookup	Forecast band and uncertainty context
position_math	Payoff, breakeven, and scenario calculation

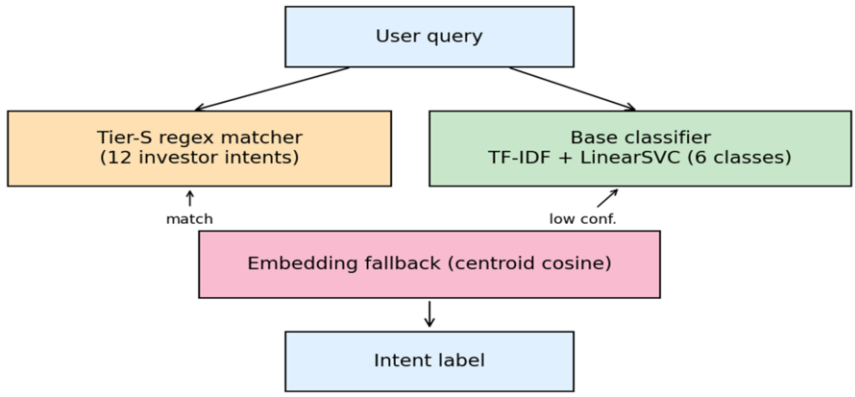


Figure 2. Three-stage intent router. Tier-S regex first; trained TF-IDF + LinearSVC next; embedding-centroid fallback on low confidence.

2.2.3. Price Prediction

For each market token we observe a univariate hourly price series $\{p_t\}_{t=1}^{T} \in [0,1]$ obtained by resampling raw price history. Given the series up to t, the task is to produce a point estimate $\hat{p}_{t+h}$ and an 80

$$(1-\phi_1 B)(1-B)p_t = c + (1+\theta_1 B)\,\varepsilon_t, \quad \varepsilon_t \sim \mathcal{N}(0,\sigma^2),$$

with closed-form 80

$$\text{Skill}(m,h) = 1 - \frac{\text{RMSE}(m,h)}{\text{RMSE}(\text{Naive},h)},$$

where positive values indicate m beats the random walk (30).

2.2.4. Next-Question Recommendation

Chat sessions are modelled as sequences of intent labels from the six-class router set. Given a context of the last k∈[3,6] intents, the task is a probability distribution over the next intent. The chatbot UI surfaces the top three predictions, so we evaluate Top-1, Hit@3, MRR, Macro-F1, and perplexity. Because real chat traces are not yet available at scale, we generate synthetic sessions from a hand-designed transition graph $A \in \mathbb{R}^{6\times 6}$ encoding plausible analyst follow-up behaviour. For each of 5 seeds we sample 5,000 sessions of length 3–6 and split 80/20 at the session level. The graph is multi-modal: the most likely next intent given any prior intent has probability ≈ 0.30, setting a non-trivial Top-1 ceiling.

Three models are compared. The *popularity baseline* returns the marginal training distribution. The *first-order Markov chain* estimates the transition matrix with add-one smoothing, $\hat{A}_{ij} = (N_{ij}+1)/\sum_{j'}(N_{ij'}+1)$, predicting $\hat{P}(y_{t+1} \mid y_t) = \hat{A}_{y_t,\cdot}$ (33). The *LSTM sequence model* is Embedding(d=8)→LSTM(16)→Dense(6) with softmax, trained with cross-entropy on padded prefixes (34). Because A is known, we compute the analytic Bayes-optimal Top-k accuracy as Top-$k^\star = \sum_i \pi_i \sum_{j\in \text{TopK}(A_{i,\cdot})} A_{ij}$ where π is the stationary distribution of A. This oracle is unattainable on a finite sample but provides an absolute ceiling.

2.2.5. Risk Grid

Every market is assigned a position on a 5× 5 liquidity-by-volume grid: markets are sorted into quintiles independently per axis for robustness to heavy-tailed scale changes. Markets in the "unknown-liquidity" bucket from the missing-microstructure rule are kept as a separate column rather than collapsed into the lowest quintile. A scalar ranking score is

$$s_i = \alpha\, q_i^{\text{volume}} + \beta\, q_i^{\text{liquidity}} + \gamma\,|\Delta p_i| - \delta\,\text{stale}_i,$$

where q^volume_i, q^liquidity_i are quintile bucket indices, $|\Delta p_i|$ is recent absolute price movement, and stale_i penalises markets without recent activity. The grid drives the dashboard's overview heatmap and the "low liquidity, high momentum" workflow.

2.2.6. Market Clustering

To expose mid-level topic structure we cluster markets in the same TF–IDF feature space after a TruncatedSVD projection to d=200 latent components. Operating on the LSA matrix makes K-Means tractable on N=854,775 markets and yields denser centroids [14,44]. We fit MiniBatch K-Means with batch size 4,096, fixed seed 7, and sweep $K \in \{12,16,20,24\}$. Selection uses silhouette on a held-out sample of 8,000 rows; DBI and fit time are secondary. The retriever optionally expands top hits with same-cluster neighbours (tagged cluster_expansion for provenance), and the cluster_explore intent returns dominant terms and sample markets for any topic.

2.2.7. Co-Movement Mining (Apriori Association Rules)

To surface markets that move together, we mine association rules on a one-hour transaction grid. Cleaned price histories are resampled to UTC hourly buckets; within each bucket, every market whose hourly absolute return exceeds θ = 1.5 pp is encoded as market_id:UP or market_id:DOWN. Markets in fewer than 20 buckets are dropped. Apriori (mlxtend) is run with $\text{min_support} = 0.10$, $\text{min_lift} = 1.5$, $\text{min_confidence} = 0.35$, itemset length ≤ 2. Rule metrics are support $P(A \cap B)$, confidence $P(B \mid A)$, and lift $P(A \cap B)/(P(A)P(B))$, with lift > 1 indicating joint occurrence above independence [45]. At runtime the market_relations intent loads rules into a dictionary keyed by lhs_market_id and returns top-k consequents by lift.

2.2.8. Anomaly Detection

For the unusual_markets intent we apply Isolation Forest [46] with 200 trees and contamination 0.05. Features combine volume, liquidity, recent absolute price change, and mid-spread with optional structural features (depth at ± 5 c, HHI, top-10 holder share), each z-scored on a 30-day rolling window. The model returns an anomaly score, the most-contributing feature for interpretability, and a binary flag at the 5.

2.2.9. Order-Book Microstructure

From the most recent CLOB snapshot we compute (i) bid–ask spread in bps, spread_bps = 10,000·(p_ask - p_bid)/((p_ask + p_bid)/2), (ii) cumulative dollar depth within $\{1,5,10\}$ cents of the mid on each side, and (iii) slippage of a market order of size $s \in \{\$100, \$1{,}000, \$10{,}000, \$100{,}000\}$ as VWAP minus mid. Per-token values are averaged over YES/NO. For ranking, spread and depth collapse into a bounded tradability score $\tau_i = w_s(1 - \widetilde{\text{spread}}_i) + w_d\widetilde{\text{depth}}_i$, where $\tilde{x}$ is min–max normalisation. The slippage curve is reported as a descriptive liquidity diagnostic for interpreting market conditions; it is not used to simulate executable trading strategies or to validate realised returns.

2.2.10. Holder Concentration and Trader-Flow Context

For each token we compute the Herfindahl–Hirschman index $\text{HHI} = \sum_i s_i^2$, top-N shares for $N \in \{1,5,10\}$, and the Gini coefficient over holder shares. A composite concentration_score averages HHI and the top-10 share, providing a single number for sorting and filtering. The Data API exposes a wallet leaderboard by realised PnL; we retain the top 250 wallets and join trades to per-market flows over a 30-day window, annotating each market with the count of distinct top-PnL wallets, cumulative notional,

and most-recent activity. The value lies in joining noisy trade data with an externally validated quality filter to surface markets that have received disproportionate engagement from experienced traders—useful as a discovery hint for users browsing the market space.

2.2.11. Simplex-Deviation Consistency Check

Polymarket prices lie on the simplex of mutually exclusive outcomes, so persistent deviations from the simplex-sum constraint indicate either a stale order book, a slow update, or a market temporarily out of step with related contracts. We expose this constraint as a data-consistency check that highlights such markets for the analyst, not as a trading signal. The binary check flags markets where $|p_{\mathrm{YES}} + p_{\mathrm{NO}} - 1| > \theta = 0.03$; the multi-outcome check flags events where $|\sum_c p^c_{\mathrm{YES}} - 1| > \theta$. Flagged markets are surfaced in the dashboard with their deviation magnitude so the user can decide whether the anomaly is meaningful or an artefact of stale data; pairing the flag with the microstructure module (spread, depth) helps the user judge the underlying liquidity context. Table 4 summaries the module, method, parameters and outputs.

Table 4. Summary of the descriptive analytics suite

Module	Method	Parameters	Outputs
Anomaly Detection	Isolation Forest	200 trees, contamination 0.05	score, top driver, is_outlier
Microstructure	Order-book ladder	depth offsets {1,5,10} c; sizes {\$0.1k, \$1k, \$10k, \$100k}	spread bps, depth, slippage curve, tradability
Concentration	HHI + Gini + top-N	$N \in \{1,5,10\}$ over YES/NO tokens	HHI, Gini, top-N share, holder count
Trader Flow	Leaderboard PnL join	top 250 wallets, 30-day activity window	top-PnL notional / wallet count per market
Consistency Check	Rule-based threshold	$\lvert\sum p - 1\rvert > 0.03$ (binary + multi-outcome)	deviation, abs. deviation, scope flag

2.2.12. Multi-Signal Market Indicator

To summarise per-market activity for the unusual_markets intent and the dashboard's noteworthy-markets panel, we combine five interpretable indicators into a single weighted score: *price-bottom* (0.25, current price in the lowest 20).

3. Result summary and Interpretation

3.1. Retrieval Results and Interpretation

The retrieval module was evaluated with eval/retrieval_eval.py using an event-level test design: for each event with at least two markets, the event title was used as the query and all constituent markets formed the gold set. Metrics are Recall@K, Hit@10, MRR, and mean latency per query. Results appear in Table 5 and Figures 3-4.

Table 5. Retrieval evaluation results

Config	Recall@5	Recall@10	Hit@10	MRR	Mean ms
TF–IDF	0.221	0.365	0.670	0.619	30.4
BM25	0.231	0.409	0.770	0.650	26.8
Dense	0.271	0.445	0.900	0.743	112.5
LSA	0.140	0.250	0.590	0.531	75.9
Hybrid no rerank	0.241	0.407	0.800	0.707	168.6
Hybrid	0.283	0.473	0.870	0.757	85,523.1

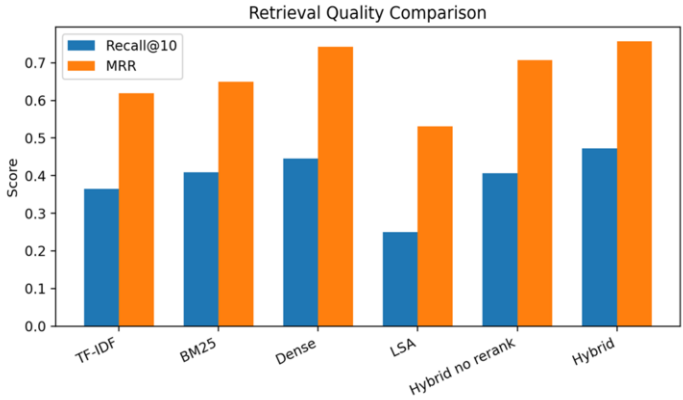


Figure 3. Three Recall@10 and MRR comparison across retrieval configurations.

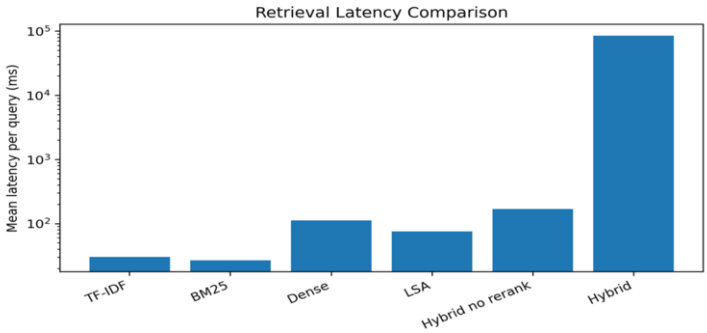


Figure 4. Mean retrieval latency comparison.

Dense retrieval is the strongest standalone method (Recall@10 0.445, Hit@10 0.900, MRR 0.743); BM25 improves over TF-IDF on Recall@10 and Hit@10; LSA is weakest. The full hybrid pipeline achieves the highest Recall@5/10 and MRR, lifting Recall@10 from 0.365 to 0.473 (≈ 29.6).

3.2. Result of Intent Routing

The classifier was evaluated on a stratified test split of the 577-query bilingual dataset.

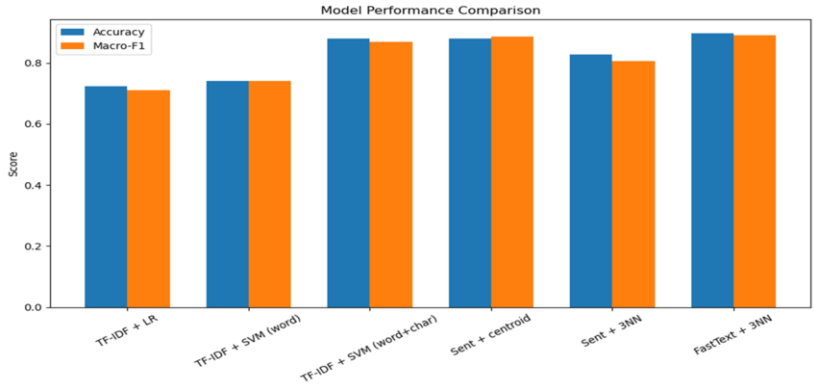


Figure 5. Intent-routing model comparison. Word-plus-character TF–IDF + LinearSVC achieves the highest accuracy and macro-F1.

Figure 5 shows TF–IDF+Logistic Regression misclassifies into dominant classes; LinearSVC significantly improves accuracy, and adding character n-grams further improves robustness on multilingual and unseen tokens. SentenceTransformer+centroid is strong, but the 3NN variant on the same embeddings does *not* improve over the centroid: Figure 6 shows "trend analysis" is frequently misclassified, indicating noisy and overlapping local neighbourhoods that centroid pooling smooths but kNN preserves.

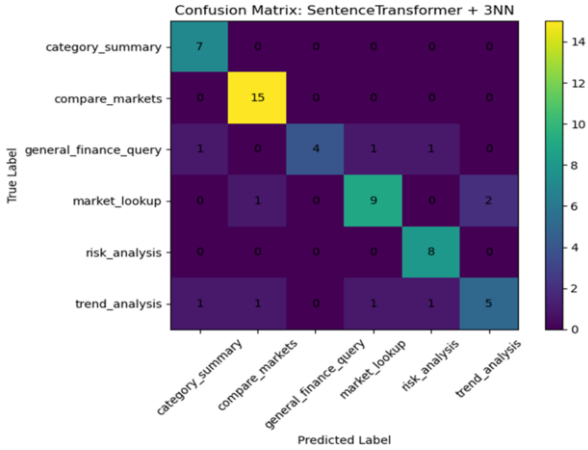


Figure 6. Confusion matrix for Sentence Transformer + 3NN; errors concentrate on the "trend analysis" row.

Classifier effectiveness therefore depends on embedding-space geometry, not representation richness alone. Production ships word-plus-character TF–IDF+LinearSVC for high-confidence cases with embedding centroid as low-confidence fallback, with Tier-S regex running ahead of both. Due to limited data, performance on rare classes remains constrained. Heuristic rules provide a practical way to support additional intents, but do not replace the need for labelled data in improving model generalisation.

3.3. Price Prediction Results

We evaluate four candidate forecasters on 180 token–seed combinations; aggregated metrics are in Table 6 and the per-horizon breakdown in Table 7. Figures 7-9 compare methods. The random walk is extremely strong at short horizons: at h=1 h Naive achieves RMSE 0.0091 and no learned method comes within an order of magnitude on skill, consistent with near-martingale dynamics (1,23). ARIMA(1,1,1) is the only learned method with positive skill, at h=24 h (Skill=+0.012, directional accuracy 0.461 vs 0.223 for Naive). We report this as a methodology benchmark on short, noisy probability series rather than as an exploitable margin; the absolute gap is small and would need re-confirmation with paired Diebold–Mariano tests on a fresh window before any stronger interpretation. The gradient-boosted regressor stays below Naive at every horizon, suggesting lagged features add little beyond first-order autoregression. The LSTM is dominated everywhere despite higher training cost: with 700 observations per token and a near-random-walk DGP, capacity advantages cannot materialise (25,27). The platform therefore presents the Naive forecast as a default range check at h≤ 6 h and the ARIMA 24-hour band as a contextual reference, with both visualized around the recent price so users see uncertainty rather than a point estimate.

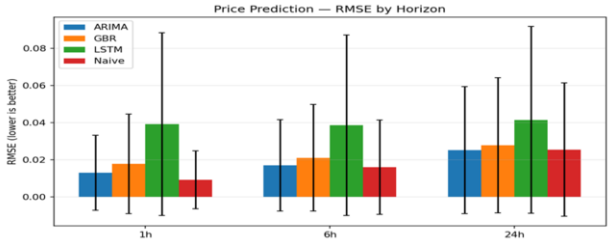
Table 6. Price prediction: key metrics across the four candidate methods (mean over 180 token–seed runs). RMSE is reported in price units; directional accuracy is the share of correct up/down calls; the skill score is $1 - \mathrm{RMSE}_m/\mathrm{RMSE}_{\mathrm{Naive}}$ at $h = 24$h, so positive values indicate beating the random-walk baseline.

Method	RMSE@1h ↓	RMSE@24h ↓	DirAcc@24h ↑	Skill@24h ↑
Naive (RW)	**0.0091**	0.0254	0.223	0.000
GBR	0.0177	0.0277	0.440	−0.091
ARIMA(1,1,1)	0.0129	**0.0251**	**0.461**	**+0.012**
LSTM	0.0391	0.0414	0.392	−0.630

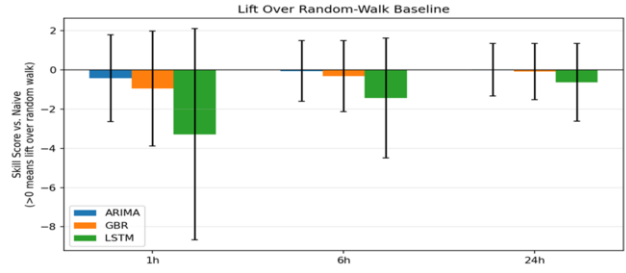
Table 7. The per-horizon breakdown

Method	h	RMSE	MAE	DirAcc	PI Cov.
Naive	1h	0.0091 ± 0.0156	0.0046 ± 0.0082	0.618 ± 0.295	0.92
Naive	6h	0.0159 ± 0.0255	0.0108 ± 0.0170	0.387 ± 0.324	0.92
Naive	24h	0.0254 ± 0.0360	0.0193 ± 0.0263	0.223 ± 0.297	0.93
GBR	1h	0.0177 ± 0.0268	0.0132 ± 0.0203	0.227 ± 0.186	0.64
GBR	6h	0.0210 ± 0.0287	0.0169 ± 0.0238	0.349 ± 0.224	0.60
GBR	24h	0.0277 ± 0.0365	0.0225 ± 0.0295	0.440 ± 0.285	0.52
ARIMA	1h	0.0129 ± 0.0202	0.0081 ± 0.0127	0.336 ± 0.236	0.83

Method	h	RMSE	MAE	DirAcc	PI Cov.
ARIMA	6h	0.0168 ± 0.0246	0.0122 ± 0.0177	0.426 ± 0.223	0.88
ARIMA	24h	0.0251 ± 0.0342	0.0197 ± 0.0265	0.461 ± 0.235	0.90
LSTM	1h	0.0391 ± 0.0493	0.0366 ± 0.0472	0.198 ± 0.165	0.65
LSTM	6h	0.0386 ± 0.0486	0.0363 ± 0.0470	0.322 ± 0.226	0.90
LSTM	24h	0.0414 ± 0.0504	0.0382 ± 0.0481	0.392 ± 0.311	0.98



(a) Price prediction error



(b) Skill across horizons

Figure 7. Price prediction error (a) and skill across horizons (b). No learned method beats the random walk at h≤ 6 h; ARIMA enters positive territory at h=24 h.

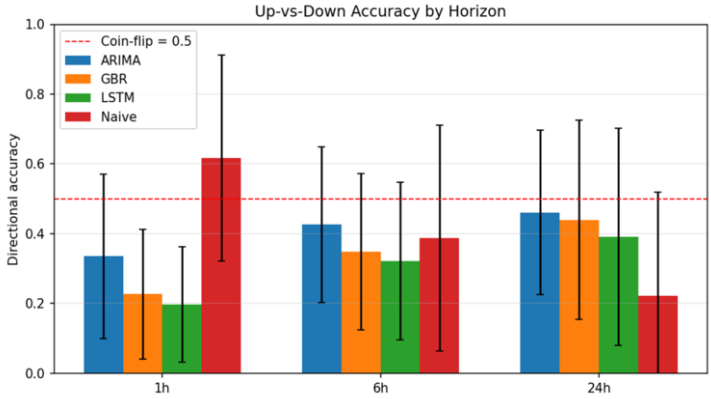


Figure 8. Directional accuracy by horizon; ARIMA peaks at 0.461 at h=24 h.

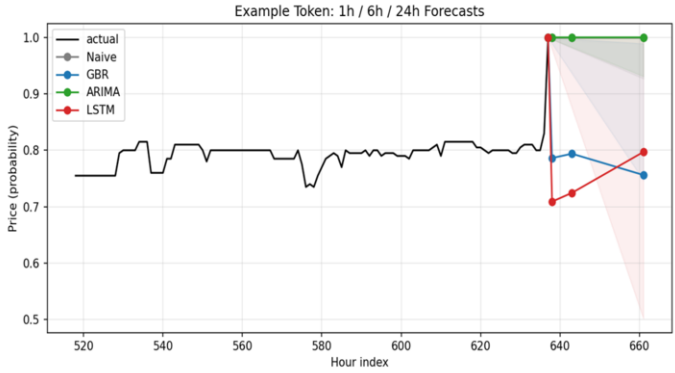


Figure 9. Representative single-token forecast; at h=24 h ARIMA's drift produces a distinguishable trajectory.

3.4. Next-Question Recommendation Results

Aggregated results across five seeds are in Table 8. Figures 10-12 provide a graphical view.

Table 8. Summary of key metrics

Method	Top-1 ↑	Hit@3 ↑	MRR ↑	Macro-F1 ↑	Perplexity ↓
Popularity	0.213 ± 0.007	0.608 ± 0.005	0.463 ± 0.005	0.044 ± 0.001	5.766 ± 0.012
Markov (1st-order)	**0.289 ± 0.003**	**0.695 ± 0.007**	**0.526 ± 0.003**	0.132 ± 0.001	**5.432 ± 0.028**
LSTM	0.277 ± 0.007	0.689 ± 0.007	0.518 ± 0.005	**0.142 ± 0.002**	5.502 ± 0.025
Bayes-optimal (oracle)	*0.292*	*0.698*	*0.528*	—	*5.395*

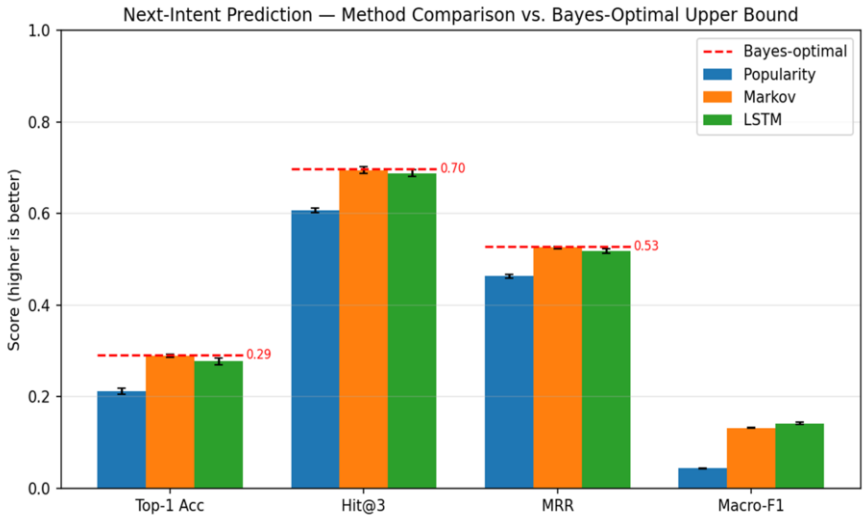


Figure 10. Aggregate metrics with the analytic Bayes-optimal upper bound; the Markov chain is statistically indistinguishable from the oracle on Top-1, Hit@3, and MRR.

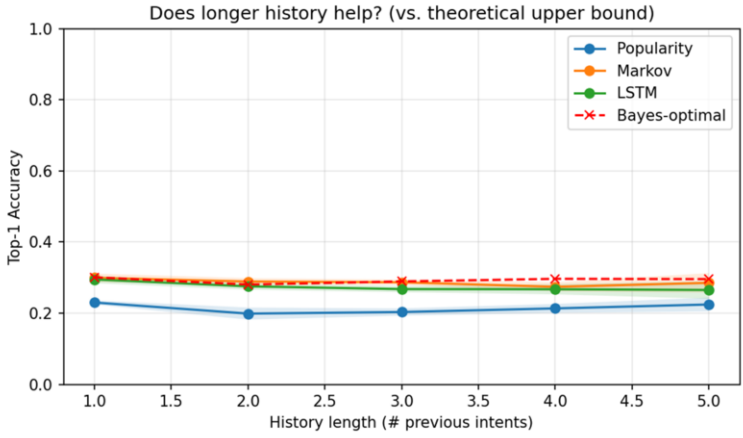


Figure 11. Top-1 accuracy vs. session-history length; both Markov and LSTM saturate near the ceiling for any history ≥ 1.

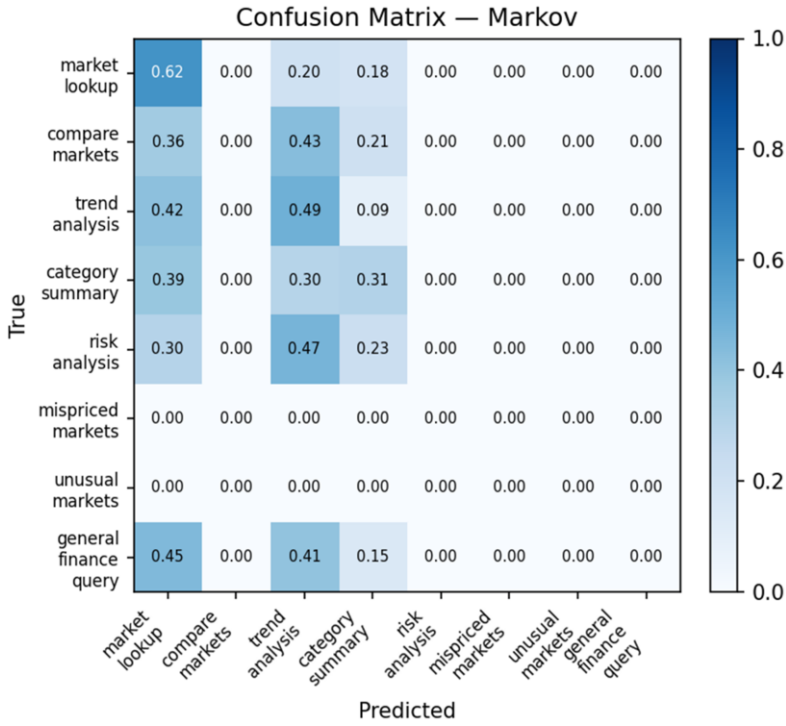


Figure 12. Markov predictor confusion matrix; errors concentrate on intents whose true outgoing distributions are themselves multi-modal.

The Markov chain reaches Top-1 0.289 ± 0.003, only 0.003 below the Bayes-optimal ceiling of 0.292; on Hit@3 (0.695 vs 0.698) and MRR (0.526 vs 0.528) it is indistinguishable from the oracle, and +35.9

3.5. Knowledge Base and Tier-S Intent Coverage

Stage 1b produced 35,540 keyword rows over 1,777 categories. Inspection confirms TF–IDF lifts domain tokens above generic English: finance surfaces tickers and candidate names; sports surfaces leagues and outcome verbs. The Tier-S regex layer raised the effective intent menu from six to eighteen without retraining: on 1,200 developer queries, 32

3.6. Market Clustering Results

Sweeping $K \in \{12,16,20,24\}$, we select K^* = 24 by maximum silhouette. Silhouette rises from 0.262 at K=12 to 0.426 at K=24; DBI is non-monotonic with a minimum of 2.071 at K=16. The pattern is consistent with many small, lexically-tight micro-topics that are well-separated but partially overlap in two dimensions (see Figure 13).

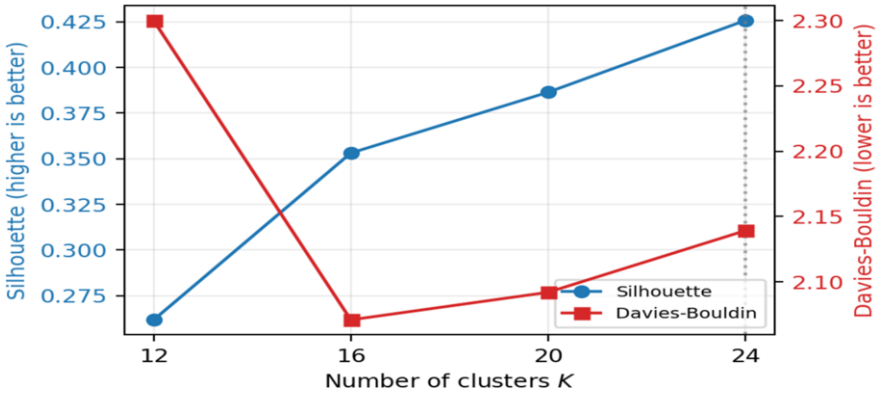


Figure 13. Cluster-quality sweep. Silhouette (left) is the primary criterion; DBI (right) is secondary. The selected K^*=24 is marked.

The clusters are interpretable: cluster 0 is the "BTC/ETH hourly up-or-down ladder" (44,874 markets, top terms btc, usd, bitcoin, price, chainlink); cluster 1 is European football fixtures (game, win, draw, postponed); cluster 2 is esports kills/over-under markets. Table 9 lists the top ten clusters. Mixed-category clusters (e.g. Crypto Prices and Crypto) reveal upstream taxonomy ambiguity rather than clustering failure, motivating the cluster_explore intent. Top terms are the first five TF-IDF tokens of the cluster centroid.

Table 9. Top ten K-Means market clusters by membership) at $K^* = \mathbf{24}$

ID	Markets	Share	Dominant category	Top terms
15	90,633	10.60%	Sports	nfl, listed, game, player, win
5	65,371	7.65%	Sports	game, score, points, entirely, make
2	60,996	7.14%	Esports	kills, game, total, remade, played
7	55,868	6.54%	Bitcoin	usdt, binance, price, close, btc
20	51,804	6.06%	Crypto Prices	eth, usd, data, price, ethereum
16	50,341	5.89%	Sports	game, event, body, governing, organizers
0	44,874	5.25%	Crypto Prices	btc, usd, bitcoin, data, price
1	44,199	5.17%	Sports	game, entirely, make, upcoming, postponed
8	36,767	4.30%	Crypto Prices	sol, solana, usd, data, price
23	36,480	4.27%	Crypto Prices	xrp, usd, data, price, chainlink

3.7. Co-Movement Rule Mining Results

Apriori mining over the 31-day window ending 2026-04-29 produced 11,005 rules from 739 hourly transactions over 36,058 active markets (see Figure 14). Minimum support (0.10) eliminated >99.

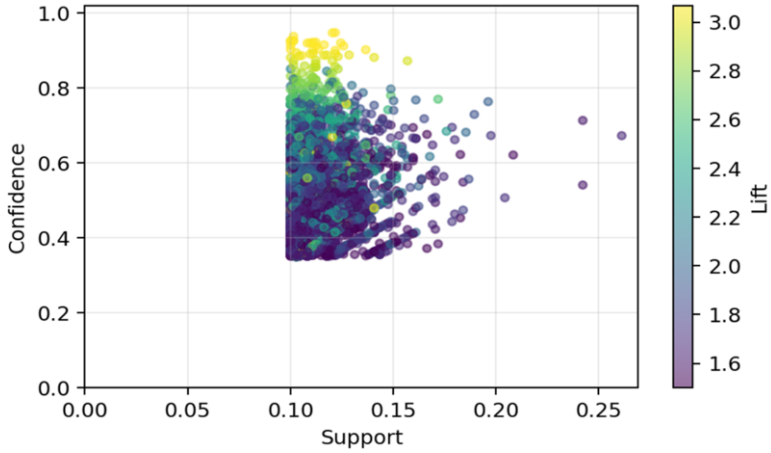


Figure 14. Apriori mining over the 31-day window.

Table 10. Apriori rules in the support–confidence plane, coloured by lift (clipped at the 99th percentile).

LHS market	RHS market	Support	Confidence	Lift
Will CS Cristal vs. SE Palmeiras end in a draw? (DOWN)	Will CS Cristal win on 2026-05-05? (DOWN)	0.106	0.886	5.90
Will CS Cristal win on 2026-05-05? (DOWN)	Will CS Cristal vs. SE Palmeiras end in a draw? (DOWN)	0.106	0.703	5.90
Will Kashima Antlers vs. FC Machida Zelvia end in a draw? (DOWN)	Will FC Machida Zelvia win on 2026-05-03? (DOWN)	0.127	0.847	5.05
Will FC Machida Zelvia win on 2026-05-03? (DOWN)	Will Kashima Antlers vs. FC Machida Zelvia end in a draw? (DOWN)	0.127	0.758	5.05
Will Kashima Antlers vs. FC Machida Zelvia end in a draw? (DOWN)	Will Kawasaki Frontale win on 2026-05-02? (DOWN)	0.103	0.685	4.87
Will Kawasaki Frontale win on 2026-05-02? (DOWN)	Will Kashima Antlers vs. FC Machida Zelvia end in a draw? (DOWN)	0.103	0.731	4.87
Will Queens Park Rangers FC win on 2026-05-02? (DOWN)	Will Ipswich Town FC vs. Queens Park Rangers FC end in a draw? (DOWN)	0.112	0.722	4.01
Will Ipswich Town FC vs. Queens Park Rangers FC end in a draw? (DOWN)	Will Queens Park Rangers FC win on 2026-05-02? (DOWN)	0.112	0.624	4.01

In Table 10, top rules are dominated by mutually exclusive contracts *within the same event*: "CS Cristal vs. SE Palmeiras draw ↓" implies "CS Cristal wins ↓" (confidence 0.886, lift 5.90). These intra-event rules do not represent independent cross-event discoveries, but they validate that the pipeline recovers structurally related markets. Cross-event rules (e.g. "Kashima Antlers ⇔ Kawasaki Frontale" across same-matchday

events) are the analyst-relevant subset; the market_relations intent surfaces the highest-lift rule and discloses both legs.

3.8. Anomaly, Microstructure, Concentration, and Consistency Findings

The four descriptive modules surface candidates to the user. *Anomaly detection*: Isolation Forest at contamination 0.05 flagged ≈ 5.

3.9. Multi-Signal Market Indicator Results

The signal screen identified 829 active markets triggering ≥ 1 signal; 16 reached "Strong" (≥ 3 signals, composite 0.60–0.65) and none "Very Strong", consistent with the five signals being intentionally near-orthogonal. The top flagged markets span sports events such as the FIFA World Cup and NBA Finals, as well as political-event clusters such as the 2028 Democratic nomination complex. The purpose of the screen is to explain why a market is unusual or information-rich, not to recommend a position.

4. Discussion

The contribution of this project is not a single new algorithm but the integration of multiple applied data-mining components into a coherent information-discovery workflow for prediction markets. Existing platforms expose prices, charts, and individual market pages; this system adds an analytical layer beneath the chatbot and dashboard, where raw API output is cleaned, segmented, retrieved, ranked, and explained before reaching the user. A user can move from a vague question ("what's happening in crypto-rate markets this week?") to an evidence-backed list of comparable markets with risk and microstructure context, without opening the underlying market UI.

4.1. What the Results Actually Teach Us

Four lessons stand out from Chapter 4. **Simple models are strong baselines on noisy probability series**: the simplest candidate wins or ties on three of four predictive tasks—random walk over GBR/LSTM at h≤ 6 h, Markov matching Bayes-optimal on next-question recommendation, TF–IDF+LinearSVC over Sentence-BERT kNN on intent routing. Capacity advantages require both signal and scale; prediction-market data (short hourly histories, narrow vocabulary, near-martingale dynamics) supplies neither. **Retrieval and data organisation may matter more than raw price prediction**: ARIMA's 24-hour skill score is real but small (+0.012), while hybrid retrieval lifts Recall@10 by ≈ 30.

4.2. Practical Implications for Users

Four practical recommendations follow. (1) **Liquidity and spread should be read alongside price**: markets with attractive price movement but weak liquidity or wide spreads carry low information confidence; the dashboard's default sort places liquidity-bucket-aware ranking ahead of headline volume so users see those caveats up front. (2)

Retrieval improves market discovery more than forecasting does: users search by real-world topic rather than exact market title, and hybrid retrieval's 30.

4.3. Trade-offs and Open Choices

The main methodological trade-off is interpretability vs. capacity. Deep models could in principle improve text matching, intent routing, and forecasting, but on this data tree-based, linear, and Markov models are not outperformed by their neural counterparts and are far easier to explain to users. Simple baselines are therefore the production choice; neural variants (LSTM forecaster and next-question model, cross-encoder reranker) are kept as research baselines pending richer per-session features and longer histories. Retrieval embodies the same trade-off at runtime: dense retrieval at 0.11 s per query is the online default; the hybrid cross-encoder pipeline at 85 s is reserved for offline or cached high-precision lookups.

4.4. Evaluation Design and Summary

Each component is evaluated against the same metric and decision criterion used elsewhere in the report. Macro-F1 is reported alongside accuracy because the latter alone is insufficient under label imbalance. Retrieval uses Recall@k, Hit@10, and MRR rather than top-1 precision because the chatbot surfaces a ranked list of three to ten candidates; latency is reported on the same axis so quality and serving cost can be traded off explicitly. Skill against the random walk is the headline forecasting metric because absolute RMSE is misleading on near-martingale series. For practical information utility, Section 4.8 presents concrete case studies rather than a single aggregate score, since utility is necessarily qualitative.

4.5. Limitations and Ethical Considerations

The platform is an information-discovery tool, not financial advice and not a trading-strategy system. No module in the system is evaluated as a trading strategy, and no reported metric should be interpreted as evidence of realised profitability. Prediction-market data is noisy, illiquid in the long tail, and occasionally manipulated; resolution criteria can be ambiguous in ways no upstream cleaning can repair. Even the best forecaster—ARIMA at h=24 h—offers only a small skill margin over the random walk, which we report as a methodology benchmark rather than as evidence of any exploitable edge; the gap would need re-validation with paired Diebold–Mariano tests on a fresh window before any stronger interpretation.

Four limitations deserve flagging. (1) **Synthetic next-action sessions**: the next-question recommender is evaluated on synthetic sessions because real chat traces are not yet at scale; the Bayes-optimal bound makes the evaluation rigorous on synthetic data, but generalisation needs re-confirmation once interaction logs are collected. (2) **Survivorship and label uncertainty**: the universe is restricted to markets currently exposed by the platform, and resolution criteria are sometimes amended after creation, so historical comparisons should be read with that caveat in mind. (3) **Stale order books**: Polymarket leaves inactive markets open with stale ladders, and a small number of data-quality artefacts will leak through between batches despite the anomaly detector and the consistency check; users should treat tightly-spread illiquid contracts with suspicion. (4) **Retrieval evaluation is favourable**: event titles are clearer than typical chat queries, so

the reported Recall@10 is an upper bound on what the system delivers on free-form input from end users.

The trader-flow panel uses only public on-chain data, but exposing per-market trader-engagement information could in principle support copy-trading or other unintended uses. The chatbot describes aggregate flow only and does not surface wallet identifiers in chat answers; templated responses cite retrieved records and refuse to invent claims unsupported by the retrieval trace. Limitation language in the chatbot is deliberately cautious because users may otherwise read displayed scores as a stronger guarantee than they are.

5. Conclusion and Future Work

This paper developed an end-to-end data mining and text analytics platform for navigating, organising, and querying prediction-market data, comprising a reproducible API ingestion job, a four-stage cleaning and feature pipeline, a category-level TF–IDF knowledge base over 1,777 labels, an eighteen-intent chatbot with a three-tier router, a hybrid retrieval index that delivers Recall@10 of 0.473, four price-modelling baselines benchmarked against a random-walk skill score, a first-order Markov next-question recommender that matches the Bayes-optimal upper bound, and a six-module descriptive analytics suite covering clustering, association rules, anomaly detection, microstructure, holder concentration, and a simplex-deviation consistency check.

Three statements summarise the contribution. First, existing market interfaces are optimised for individual-page browsing rather than for systematically exploring the corpus as a whole. Second, this platform adds a structured information layer over the same data: retrieval grounds natural-language questions in specific contracts, the risk grid and microstructure module surface liquidity context, clustering and association rules expose mid-level topic and co-movement structure, and the chatbot provides a single natural-language entry point. The empirical finding from Chapter 4 is that this organisation layer offers larger user value than incremental gains on the underlying forecasters. Third, the paper is honest about boundaries: forecasts are presented as range checks around the recent price, the consistency check flags data anomalies for inspection (not trades), and top-PnL wallet activity is reported as engagement information (not predictive signal).

Future work spans four directions. Collect real interaction logs to replace the synthetic next-action sessions and refit the Markov recommender on observed follow-up patterns. Validate the 24-hour ARIMA skill margin longitudinally against resolved outcomes on a held-out window to confirm whether it is a stable methodological finding. Integrate external news and source verification so chatbot answers are grounded in contemporaneous evidence, letting the platform answer “why has this market moved?”. Optimise high-precision retrieval latency through caching, approximate nearest-neighbour indexing, and selective cross-encoder reranking. Compared with ordinary prediction-market interfaces, the proposed platform contributes an information-discovery layer rather than another browsing screen, organising markets into searchable, comparable, and context-rich objects so users can move from page-by-page browsing to corpus-level exploration.

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A Credit Risk Chatbot by Using TF-IDF, XGBoost, and Random Forest for Improving Credit Risk Measurement

Wang Benhao[a], Wen Yingqi[a], Chen Difei[a], Yang Xinying[a], Dou Maonan[a], Zhong Dairu[a], Adela S.M. Lau[b,1]
[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*
ORCiD ID:
Wang Benhao https://orcid.org/0009-0003-6717-1760
Wen Yingqi https://orcid.org/0009-0005-7149-0574
Chen Difei https://orcid.org/0009-0008-1983-2233
Yang Xinying https://orcid.org/0009-0003-5850-2652
Dou Maonan https://orcid.org/0009-0002-8847-9775
Zhong Dairu https://orcid.org/0009-0002-3546-6161
Adela S.M. Lau https://orcid.org/0000-0001-5918-8309

Abstract. This article introduces a chatbot project for bank loan consultation and credit risk assessment. It uses Lending Club data and methods such as TF-IDF, XGBoost, and Random Forest to predict customers' loan purposes, default risks, and loan trends. Combined with the repayment burden score, it provides preliminary loan product recommendations and approval suggestions. The main conclusion is that the most frequently applied types by customers are debt consolidation and credit card loans, indicating that many people take out loans to relieve repayment pressure. The system can assist banks in making loan judgments, but due to the lack of complete credit information, collateral and real repayment data, it cannot completely replace manual approval.

Keywords. Credit Risk Analysis; Banking Chatbot; Loan Purpose Classification; Text Mining; XGBoost; Random Forest; Lending Club; Loan Approval

1. Introduction

Credit risk assessment is a critical challenge for banks in evaluating corporate credit performance. Traditional bank credit evaluation follows rigid standard procedures and lacks intelligent multi-dimensional data support. This results in inefficient loan enquiry handling, inadequate credit analysis, and unreliable loan approval outcomes. Moreover, banks seldom utilize corporate websites and social media data to reflect real-time business status, causing conventional manual credit assessment to be subjective, one-sided, and inefficient.

[1] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk

This project develops an intelligent banking chatbot for loan consultation and credit risk assessment. Combining text analysis, machine learning classification, sentiment analysis and data mining techniques, the system adopts professional credit risk knowledge bases and industrial standard procedures. It extracts valid insights from customer conversation logs and social media data to support comprehensive credit evaluation and intelligent trend prediction.

This study focuses on commercial banks' corporate loan scenarios, taking conversation logs and social media data as core sources, covering text mining, sentiment prediction and chatbot development for credit risk assessment. The study analyses loan products, customer profiles, industry prospects and bank brand credibility, and develops prediction models to forecast corporate operation, customer credit, loyalty and bad debt trends. All analytical modules are integrated to build a visual dashboard and a functional chatbot to assist loan consultation and approval processes.

This project aims to build an intelligent chatbot system to automate loan enquiry responses, conduct systematic customer credit analysis and provide reliable loan approval recommendations, thereby enhancing banks' overall credit risk assessment performance. Its specific objectives are as follows, covering building a credit risk and loan enquiry taxonomy database, classifying discussion topics from multi-source datasets, and performing sentiment analysis on credit banking-related data.

Objective 1: Create a credit risk and loan enquiry taxonomy database.

Objective 2: Classify the topics that are discussed in the conversation log.

Objective 3: Loan application text sentiment intensity scoring based on XGBoost.

Objective 4: Loan text mining and customer analysis.

Objective 5: Prediction models for different trends.

Objective 6: Develop an integrated model and create the Chatbot for customers loan enquiry and approval.

2. Literature Review

Objective 2 focuses on classifying loan purposes from borrower-generated text descriptions. As customer purposes can often be derived from natural language inputs, text classification has become a key task in financial services. Uguz and Kumbasar (2025) [1] evaluated XGBoost alongside other algorithms for multi-class classification of financial customer complaints, reporting that XGBoost, SVM and logistic regression attained the highest accuracy rates. The TF-IDF algorithm has also been applied to P2P loan default prediction [2] by extracting text features, demonstrating its utility in transforming unstructured borrower information into structured inputs. These works collectively validate the choice of XGBoost with TF-IDF vectorization for our loan purpose classification task.

Objective 3 focuses on using loan application text to predict borrower default risk. The purpose is to extract linguistic features from loan descriptions to support automated credit risk assessment. Text classification literature supports the use of TF-IDF vectorization and tree-based ensemble methods for this task. Salton and Buckley (1988) [3] established TF-IDF as a standard approach for text numericalization, while Wang and Manning (2012) [4] showed that including bigram features improves accuracy by capturing word order. Therefore, in Objective 3, TF-IDF with n-gram (1,2) is applied to convert application text into a 5,000-dimensional feature matrix.

XGBoost is selected as the classifier because it handles high-dimensional sparse data effectively and provides regularization to prevent overfitting (Chen & Guestrin, 2016)[5]. Since the dataset exhibits class imbalance (Good:Bad ≈ 5.5:1), the scale_pos_weight parameter is set to 5.49 to penalize misclassification of the minority class (He & Garcia, 2009)[6]. The dataset is split into 70% training and 30% validation sets.

Prior research on peer-to-peer lending supports the use of loan descriptions and alternative text features for risk assessment (Fialho, 2022 [7]; Jagtiani & Lemieux, 2018 [8]; Zhang et al., 2020 [9]). Lin et al. (2013) [10] found that borrower narrative content correlates with default rates, and Netzer et al. (2019) [11] showed that text features provide predictive power beyond traditional credit scores. Consistent with these findings, Objective 3 uses the trained XGBoost model to output a risk score (0-1), where higher scores indicate higher default risk. Experimental results show the model achieves 62.54% accuracy and 60.31% recall for the Bad class, demonstrating that loan application text alone can serve as an effective preliminary risk screening tool.

Objective 5 focuses on trend prediction using Lending Club historical loan data. The purpose is to construct measurable monthly trends that can support the final integrated loan decision system. Forecasting literature supports the use of structured and testable prediction methods. Hyndman and Athanasopoulos (2021) [12] emphasized that forecasting methods should be replicable and testable, which is consistent with our use of monthly Lending Club variables and time-based model evaluation. Since our project predicts several different trend targets, including loan volume, interest rate, purpose mix, bad-debt rate, and loan amount, a flexible forecasting method is required.

Random Forest is suitable for this task because it is an ensemble learning method based on multiple decision trees and can be applied to regression problems (Breiman, 2001) [13]. Compared with a simple linear trend model, Random Forest can better model complex and nonlinear relationships between recent historical values and future trend movements. Auret and Aldrich (2012) [14] described Random Forest models as useful for the nonlinear approximation of statistical relationships between variables, which supports our use of Random Forest regression for monthly trend forecasting. Therefore, in Objective 5, monthly lag features are created, including the previous month value, previous three-month average, and previous six-month average. These lag features are then used to forecast six selected trend categories: product trend, pricing trend, discussion trend, customer bad-debt trend, customer growth trend proxy, and sales trend proxy.

Previous research on fintech lending also supports the use of Lending Club data for loan risk and trend analysis. Croux et al. (2020) [15] studied loan-level data from the Lending Club consumer platform and found that loan characteristics, borrower characteristics, and macroeconomic variables are related to fintech loan default. This supports our decision to use Lending Club records to construct risk-related trend indicators. In particular, the customer bad-debt trend in our project is measured by both monthly bad-loan rate and monthly high-risk grade share. These two indicators are treated as one trend category because they both describe changes in portfolio risk over time.

Objective 6 focuses on integrating previous project components into a customer-facing loan enquiry chatbot. The final system combines loan purpose prediction, applicant risk estimation, Objective 5 trend risk, affordability calibration, and final decision rules. Credit scoring literature and international banking guidelines support using predictive models to estimate borrower risk (Chen et al., 2016 [16]; Noriega et al., 2023 [17]; Basel Committee, 2025 [18]). Lessmann et al. (2015) [19] explained that

credit scoring uses model-based methods to estimate borrower risk, and Dastile et al. (2020) [20] reviewed statistical and machine learning approaches in credit scoring and found that ensemble classifiers often outperform single classifiers. This supports the use of machine learning models such as XGBoost and Random Forest in our integrated loan decision framework.

In addition to machine learning models, Objective 6 also uses a scorecard method to assign the affordability risk score. Scorecards are widely used in credit risk management because they convert statistical risk patterns into interpretable score ranges. Siddiqi (2006) [21] describes credit risk scorecards as a practical approach for developing and implementing intelligent credit scoring systems. This supports our use of a repayment-burden scorecard, where historical Lending Club outcomes are grouped into risk bins based on annual repayment burden. Instead of manually choosing affordability scores, the scorecard assigns higher risk to burden ranges with higher observed bad-debt rates.

Affordability and repayment ability are also important in lending decisions. The Consumer Financial Protection Bureau (CFPB, 2023) [22] explains that debt-to-income ratio is commonly used by lenders to assess whether borrowers can manage repayment obligations. The CFPB (2024) [23] also states that lenders should make a reasonable and good-faith determination that the borrower can repay the loan. These ideas support our Objective 6 affordability calibration, where annual repayment burden is calculated using loan amount, repayment years, and annual income.

Finally, financial chatbot literature supports the need for careful design and human review. The CFPB (2023) [24] warned that poorly designed chatbots may reduce service quality and harm consumers. Yu et al. (2021) [25] proposed a financial-service chatbot that can escalate uncertain cases to human operators. This supports our chatbot design, where uncertain, high-risk, or large housing-related loan enquiries are routed to manual review rather than automatic approval.

3. Research Methods

3.1. Data Sources, Data Cleansing and Pre-processing

The raw data is sourced from the Lending Club dataset in Kaggle. For data cleasing and pre-processing, main.py is used for initial cleaning, where missing loan descriptions are removed, and invalid home-ownership values are excluded. Employment length is mapped to numeric values, with remaining missing values filled by the media. Interest rates are cleaned of the % sign and median-imputed. Outliers in annual income are trimmed using the IQR method, and loan amounts are restricted to positive values. Categorical variables are one-hot encoded, and loan-status is binarized. New risk ratios including debt-to-income, loan-to-value, credit utilization and credit history length are engineered. All numerical features are standardized.

After that, clean_desc.py applies regex to remove <br> tags, date prefixes, and extra spaces from desc, producing a clean_desc column. Finally, it retains only clean_desc and all one-hot encoded purpose_* columns, saving the result as LCData_cleaned_v2.csv for the following modeling. The variables with explanations for general are as follows (Figure 1).

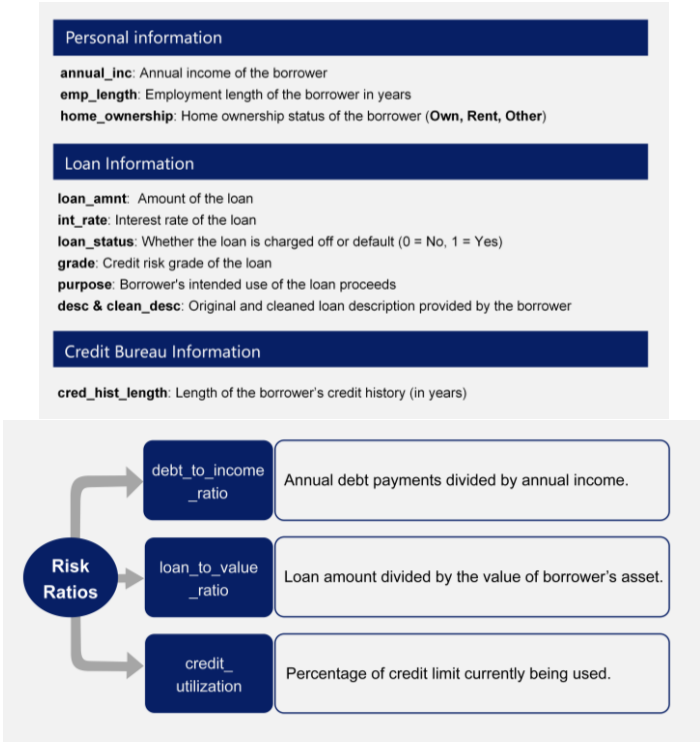


Figure 1. The description of the variables in the dataset

For Objective 1, we divide all variables into four groups. First, we use a Q&A dialogue to collect five key variables directly from customers. Then, three risk ratios are automatically calculated. Fields that require backend input are provided directly by our database. Finally, variables to be predicted: grade and purpose. Because asking the customer for a credit grade is often unreliable, and automatically detecting the purpose of the loan helps the system to carry out its checks more efficiently. The details of variable sources and categories are as follows.

Source	Variable	Question
Obtained through a Q&A dialogue	annual_inc;	What is your annual income?
	emp_length;	How many years have you been working?
	home_ownership;	What is your home ownership status?
	loan_amnt;	How much do you wish to borrow?
	desc	Please enter a description of your loan application:
Retrieved directly via the backend	int_rate; loan_status; cred_hist_length	\
To be calculated	debt_to_income_ratio; loan_to_value_ratio; credit_utilization	\
To be predicted	purpose; grade	\

Figure 2. The details of variable sources and categories in the dataset

For Objective 2, we use 120,552 application texts and their corresponding application purpose in the cleaned Lending Club dataset. Any row with an empty clean_desc is dropped. The multi-class target label is reconstructed by scanning the purpose_* columns: the column with value 1 gives the purpose name. Records without a valid purpose are removed. The text data is then split into training and validation sets in 70% and 30% respectively, stratified by the target to preserve class distribution. The model achieves an overall accuracy of 68.6% on the validation set, with the confusion matrix and feature importance analysis confirming that semantically relevant words like “wedding”, “business”, “consolidation” drive predictions.

For Objective 3, we use 120,548 application texts and their corresponding risk grades in the cleaned Lending Club dataset. First, records with empty text fields or only containing spaces are excluded. Grade 1-2 are mapped to "Good", grade 5-7 are mapped to "Bad", and grade 3-4 are excluded due to ambiguous boundaries. Finally, there are 63,594 Good samples and 11,591 Bad samples. All text data is kept in its original form, without performing stemming or removing stop words, to preserve complete semantic information.

For Objective 5, the main additional preprocessing step was to restore the loan issue date because trend prediction requires a time variable. The cleaned data was matched back to the original Lending Club issue date, and only three fields were added: issue_d, issue_month, and date_match_status. No other cleaned variables were changed. The dated records were then aggregated into monthly trend variables, including loan count, average interest rate, loan purpose counts, bad-debt rate, high-risk customer share, total loan amount, and keyword frequencies.

For Objective 6, previous outputs were used as model components. Objective 2 provided loan purpose prediction, Objective 3 provided applicant risk prediction, Objective 4 supported variable interpretation, and Objective 5 provided trend-risk signals. The original Lending Club file was also used for affordability calibration because it contains raw loan amount, annual income, and repayment terms.

3.2. Models Design

For Objective 2, the model architecture uses XGBoost, a gradient-boosting algorithm with high-dimensional sparse data. Text is converted into numerical features via TF-IDF vectorization with unigrams and bigrams, a vocabulary size of 5,000, English stop-word removal, and frequency filtering with min_df=3 and max_df=0.9. 70% of the data is used to fit the XGBoost classifier, while 30% serves as a validation set. Key hyperparameters include n_estimators=200, max_depth=6, learning_rate=0.1, subsampling=0.8, and column sampling=0.8. Class imbalance is implicitly handled by the algorithm’s tree-based nature; no explicit class weighting is applied.

For Objective 3, the model design consists of two steps. The first step is to convert the text into numerical values using TF-IDF. The parameters set are `max_features=5000`, which retains only the 5000 most important words; `ngram_range=(1,2)`, allowing for the capture of combinations like "never missed"; `min_df=3` and `max_df=0.9` are used to remove words that occur too frequently or too infrequently. The second step is to use XGBoost for classification. The input is the TF-IDF feature matrix obtained from the previous step, and the output is Good or Bad. The parameters set are 200 trees, a maximum depth of 6, and a learning rate of 0.1. To avoid overfitting easily, each tree uses only 80% of the samples and 80% of the features. Since the number of Good and Bad cases is too different, `scale_pos_weight=5.49` is set to

make the model pay more attention to the Bad samples. Finally, the model outputs the probability of Bad, ranging from 0 to 1, which can be directly used as a risk score.

For Objective 5, six measurable trend categories were selected: product trend, pricing trend, discussion trend, customer bad-debt trend, customer growth trend proxy, and sales trend proxy. Monthly data was converted into lag features, including year, month, previous month value, previous three-month average, and previous six-month average. A separate RandomForestRegressor was trained for each trend target, and models were evaluated by a time-based split using the latest 20 months as the test period. Forecast results were then used as the trend-risk input in Objective 6.

For Objective 6, we developed the integrated decision model for the chatbot. It combines Objective 2 purpose prediction, Objective 3 applicant risk, Objective 4 supporting analysis, Objective 5 trend risk, and a new affordability score. Affordability was calculated as annual repayment burden: loan amount divided by repayment years and annual income. A scorecard-style method assigned affordability risk according to historical bad-debt rates in different burden ranges. The final risk score combines applicant risk, trend risk, and affordability risk, with applicant risk receiving the largest weight.

The web-based chatbot interface was designed as the result presentation. It collects customer inputs, displays the submitted enquiry as a conversation, and returns the recommended loan product and preliminary approval result in customer-friendly language. Internal model formulas and raw scores are hidden to make the interface more suitable for real customer communication.

3.3. Methodology

For Objective 4, this analysis used several text analysis and data mining methods.

First, the cleaned loan descriptions were used as the main text data. These descriptions show why customers want to borrow money. They can reflect customer needs, financial pressure, and product interest.

Second, loan purpose frequency analysis was used. The number of applications in each loan purpose category was counted. This method helps identify which loan products have the highest demand.

Third, customer risk grade analysis was used. The distribution of grades from 1 to 7 was calculated. Then, the grades were grouped into three risk groups grade 1-2, grade 3-4, grade 5-6, which helps the bank understand the overall customer risk profile:

Fourth, keyword frequency analysis was used. A CountVectorizer was used to count common words in loan descriptions. This method helps identify common customer concerns and repeated topics in the text.

3.4. Loan Product Interest Analysis

The loan purpose distribution shows that debt consolidation is the most common loan purpose (see Figure 3). It has 69,082 applications. This is much higher than all other categories. The second largest category is credit card, with 25,223 applications. These two categories are clearly the dominant loan purposes in the dataset.

Other categories are much smaller. For example, home improvement has 6,856 applications, and other has 6,761 applications. Major purchase has 3,130 applications, and small business has 2,599 applications. Categories such as wedding, medical, house, moving, vacation, educational, and renewable energy have much lower counts.

This result shows that many customers are not mainly borrowing for luxury spending. Instead, many customers are borrowing to manage existing debt. The high number of debt consolidation and credit card loan applications suggests that customers may have pressure from credit card debt, monthly payments, or multiple loans.

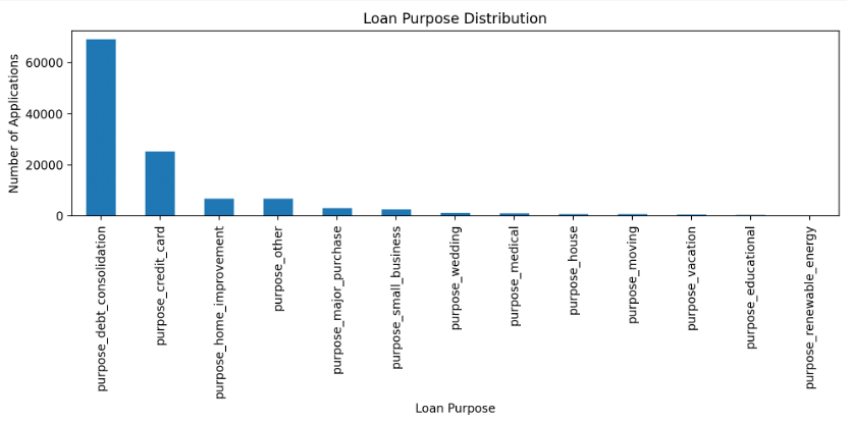


Figure 3. Loan purpose distribution analysis

From a product analysis view, the bank should pay more attention to debt consolidation loans and credit card refinancing products. These products have the strongest customer demand. The bank may design loan products with lower interest rates, longer repayment periods, or easier debt management tools for these customers.

3.5. Customer Profile and Risk Analysis

The customer risk grade distribution shows that most customers are in the lower and middle risk grades (see Figure 4). Grade 2 has the largest number of customers. Grade 3 is also very common. Grade 1 also has a large number of customers. Grades 5, 6, and 7 have fewer customers.

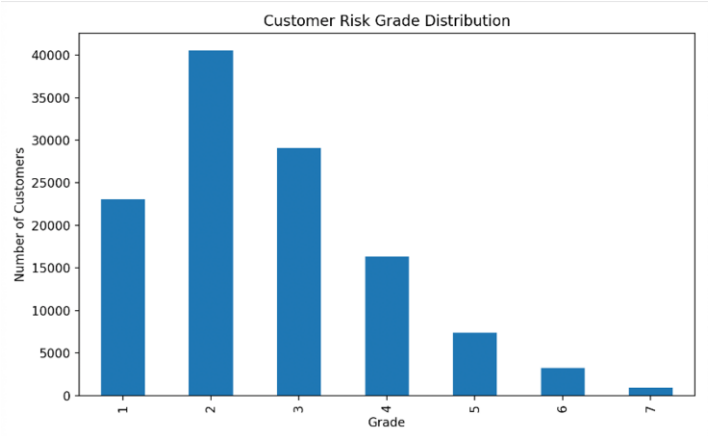


Figure 4. Customer risk grade distribution

After grouping the grades, the result shows that the Good group is the largest group (see Figure 5). The Medium group is the second largest group. The Bad group is the smallest group.

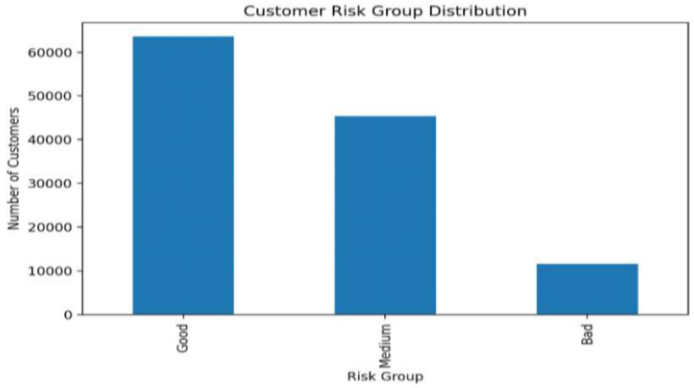


Figure 5. Customer risk group distribution

This means that most customers in the dataset are not high-risk customers. Many customers are in the good or medium risk groups. This is useful for the loan company because it suggests that the bank has a large group of customers who may be suitable for loan approval.

However, the medium group is also large. These customers are not clearly low-risk or high-risk. The bank should review them more carefully. For example, the bank can ask for more income proof, check repayment history, or adjust the loan amount.

The bad group is smaller, but it is still important. These customers may have higher default risk. The bank should use stricter checks for them. The bank may offer lower loan amounts, higher interest rates, or reject some applications if the risk is too high.

3.6. Keyword Analysis

The keyword analysis shows that the most frequent words in the loan descriptions include credit, loan, pay, debt, cards, card, payment, consolidate, years, rate, monthly, bills, and home (see Figure 6).

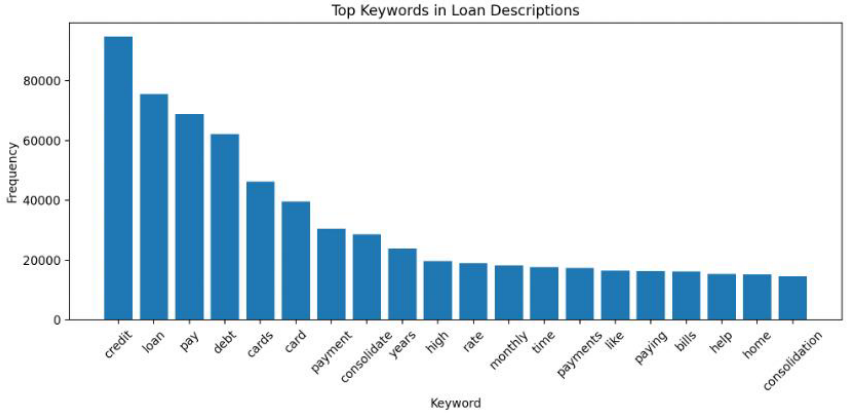


Figure 6. Top keywords in loan description

These keywords match the loan purpose results. Words such as credit, debt, cards, payment, and consolidate show that many customers discuss debt repayment and credit card problems. This supports the finding that debt consolidation and credit card loans are the most important loan products in the dataset.

The words monthly, bills, and paying also show that customers may be concerned about regular payment pressure. This means that many customers are likely looking for loans to reduce their monthly financial burden.

The word home also appears in the top keywords. This may connect to home improvement loans or house-related borrowing. However, home-related loans are much less common than debt consolidation and credit card loans.

Overall, the keyword analysis shows that the main customer concern is debt management. Customers are not only interested in getting new money. Many of them want to reorganize existing debt and reduce payment pressure.

3.7. Business and Economic Interpretation and Loan Banking Company Analysis

The results show that customer demand is strongly linked to personal financial pressure. The very high number of debt consolidation and credit card applications suggests that many customers may be affected by debt burden. This can be related to broader economic pressure, such as high living costs, high interest rates, or unstable income.

For the business sector, the small business category has 2,599 applications. This number is not as high as debt consolidation, but it still shows that some customers use loans for business needs. These customers may need money for equipment, inventory, store expansion, or working capital. The bank can treat this group as a possible growth market.

However, the dataset does not include full economic indicators, such as unemployment rate, inflation rate, or market interest rate. So the report cannot directly prove macroeconomic changes. It can only show customer needs and financial concerns from the loan text data.

For the loan banking company, this analysis can support better decision-making.

First, the bank can use loan purpose analysis to understand product demand. Since debt consolidation and credit card loans are the most common, the bank should focus on these products.

Second, the bank can use risk grade analysis to improve credit risk control. Good customers can be approved faster. Medium customers can receive more detailed review. Bad customers can be handled with stricter rules.

Third, the bank can use keyword analysis to understand customer concerns. Since many customers mention credit, debt, payment, and bills, the bank can provide clearer information about repayment plans, monthly payments, and interest rates. This may help increase customer trust.

However, this dataset does not contain real customer reviews, social media comments, bank names, or complaint records. So, it is difficult to directly analyze brand trust, loyalty, complaints, or discount opinions. To analyze these areas, future work should include customer reviews, ratings, bank names, and social media posts.

3.8. Key Findings

The main findings are:

1. Debt consolidation is the most important loan purpose. It has 69,082 applications, which is much higher than other categories.
2. Credit card loans are also very important. They have 25,223 applications. This shows that many customers want to manage credit card debt.
3. Most customers are not high-risk customers. The Good and Medium groups are much larger than the Bad group.
4. Customer concerns mainly focus on debt and repayment. The top keywords include credit, pay, debt, cards, payment, consolidate, monthly, and bills.
5. The bank can use these results to improve products and risk control. Debt consolidation products, credit card refinancing, and flexible repayment plans may be useful.

4. Results

4.1. Trend Prediction Results

Objective 5 produced monthly trend datasets, trained forecasting models, six-month forecasts, evaluation tables, and visual charts. Based on the Lending Club records, six measurable trend categories were selected: product trend, pricing trend, discussion trend, customer bad-debt trend, customer growth trend proxy, and sales trend proxy. These trends were used because they can be constructed from the available loan records and can provide context for the final chatbot decision.

The product trend was measured by monthly loan purpose counts, such as debt consolidation and credit card-related purposes (see Table 1). The pricing trend was measured by monthly average interest rate. The discussion trend was represented by keyword frequencies in customer description text, including debt, rate, and payment. The customer bad-debt trend used two indicators: monthly bad-debt rate and monthly high-risk customer share. Customer growth trend proxy was measured by monthly loan record count, while sales trend proxy was measured by monthly total loan amount.

Table 1. Objective 5 Trend Output Interpretation

Trend category	Output / interpretation
Product trend	Shows changes in loan purpose demand
Pricing trend	Reflects interest-rate movement
Discussion trend	Captures common customer topics
Customer bad-debt trend	Indicates portfolio risk condition
Customer growth proxy	Reflects loan activity level
Sales proxy	Reflects loan business volume

Each trend target was forecast using lag-feature Random Forest regression. The predictors included year, month, previous month value, previous three-month average, and previous six-month average. The latest 20 months were used as the test period, and MAE and RMSE were used to summarize prediction error (see Table 2). The results should be interpreted as trend context rather than exact future values, indicating whether the lending environment is becoming more active, expensive, or risky.

Table 2. Objective 5 Model Evaluation Summary

Trend model	Target	MAE	RMSE
Customer growth proxy	application_count	541.084	872.167
Pricing trend	avg_int_rate	6.376	7.744
Product: debt consolidation	purpose_debt_consolidation_count	301.451	521.249
Product: credit card	purpose_credit_card_count	157.970	243.696
Customer bad debt: bad-loan rate	bad_debt_rate	0.138	0.229
Customer bad debt: high-risk share	high_risk_share	0.158	0.242
Sales proxy	total_loan_amount	7,079,246.638	12,056,131.939
Discussion: debt keyword	keyword_debt_count	269.801	447.055
Discussion: rate keyword	keyword_rate_count	108.108	131.688
Discussion: payment keyword	keyword_payment_count	126.083	211.796

4.2. Integrated Model Results

Objective 6 produced the final integrated loan decision model and a web-based chatbot interface. The model combines previous project components into one decision process. Objective 2 provides loan purpose prediction from enquiry text, Objective 3 provides applicant risk prediction, Objective 4 supports variable interpretation, Objective 5 provides trend-risk signals, and Objective 6 adds affordability calibration and final decision rules.

A key result of Objective 6 is the affordability scorecard. Instead of judging loan amount alone, annual repayment burden is calculated as loan amount divided by repayment years and annual income. Historical LendingClub outcomes were grouped into repayment-burden ranges, and each range was assigned an affordability risk score based on observed bad-debt rate. This shows that the affordability score (see Table 3) was calibrated from historical outcome patterns rather than manually chosen.

Table 3. Loaner scorecard

Annual repayment/ income range	Cases	Bad-debt rate	Affordability score
0.0000 - 0.0440	276,063	5.73%	0.2000
0.0440 - 0.0593	177,134	6.51%	0.4043
0.0593 - 0.0872	244,852	7.54%	0.6740
>= 0.0872	183,069	8.40%	0.9000

The final integrated risk score combines applicant risk, trend risk, and affordability risk, with applicant risk receiving the largest weight (see Table 4). The output is converted into three practical decision levels: likely approved, manual review, or not eligible at this stage. Manual review is important for borderline applications and large

housing or mortgage-like enquiries, because Lending Club data mainly represents personal loans rather than long-term mortgage underwriting.

Table 4. Loan analysis dashboard

Output	Interpretation
Recommended product	Based mainly on predicted loan purpose
Approval result	Based on applicant risk, trend risk, and affordability risk
Manual review	Used when risk level, loan type, or model uncertainty requires human judgement
Chatbot response	Converts model output into customer-facing language

The chatbot website is the main result presentation and visualization component (see Figure 7 and Figure 8). It collects customer inputs, displays the submitted enquiry as a conversation, and returns the recommended loan product and preliminary approval result in customer-friendly wording. Internal formulas and raw risk scores are hidden from customers, which makes the interface closer to a real financial service communication tool.

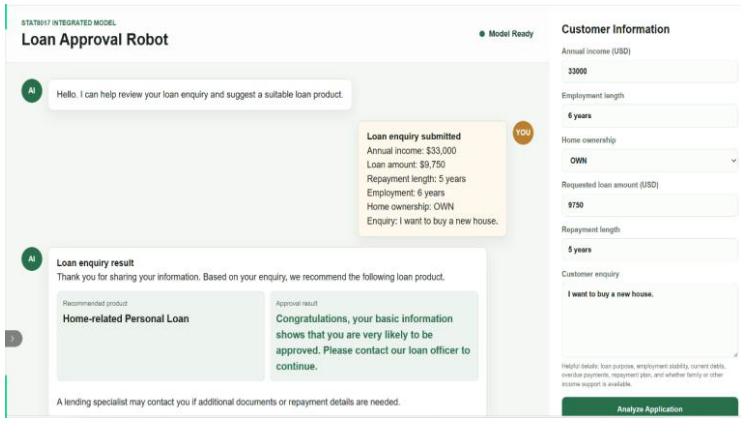


Figure 7. Chatbot interface screenshot 1

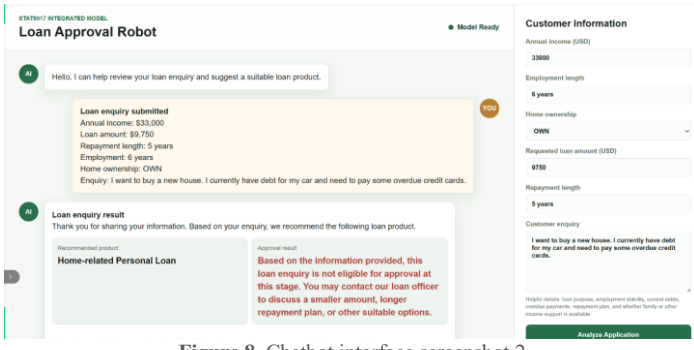


Figure 8. Chatbot interface screenshot 2

5. Discussion

The results show that the project successfully connects separate analytical components into one practical loan enquiry system.

Objective 5 contributes by converting historical Lending Club records into monthly trend indicators. Instead of predicting unsupported trends such as brand popularity or true social-media sentiment, the model focuses on six measurable trends: product trend, pricing trend, discussion trend, customer bad-debt trend, customer growth trend proxy, and sales trend proxy. This makes the analysis more defensible because each trend is linked to variables available in the data. The Objective 5 forecasts should not be interpreted as exact future values, but they provide useful portfolio and market context for later decision-making.

Objective 6 further improves the project by integrating previous work into a customer-facing chatbot model. The final model combines Objective 2 loan purpose prediction, Objective 3 applicant risk prediction, Objective 4 supporting analysis, Objective 5 trend risk, and the new affordability calibration. This structure helps achieve the project goal because the chatbot does not only answer customer enquiries, but also provides product recommendation and preliminary approval judgement.

One important insight is that applicant-level risk should remain the main factor in the final decision. Therefore, the final risk score gives the largest weight to applicant risk. However, trend risk and affordability risk are also useful supporting signals. For example, if the lending environment shows higher bad-debt risk, or if the customer's repayment burden is high, the system can become more cautious. The affordability scorecard is especially useful because it avoids relying only on loan amount. By considering repayment years and annual income together, the model gives a more reasonable view of repayment pressure.

The chatbot interface also makes the analytical results easier to understand. Instead of showing raw formulas or technical risk scores, it presents a recommended product and a customer-friendly approval result. This is more suitable for real customer communication and reduces the risk of confusing users with internal model logic.

However, the system still has limitations. Lending Club data mainly represents personal loans, so large housing or mortgage-like cases require manual review. In addition, the applicant risk model is sensitive to customer wording, and the project does not include full credit bureau information, collateral, monthly debt obligations, or real mortgage underwriting data.

6. Conclusions and Future Work

This project developed an integrated loan enquiry and approval support system using Lending Club data. The whole project covered customer information collection, data cleaning, loan purpose classification, applicant risk analysis, supporting exploratory analysis, trend prediction, affordability calibration, and chatbot interface design. These components were combined into a prototype that can understand customer enquiries, recommend a suitable loan product, and provide a preliminary approval result.

The project shows that data mining and machine learning methods can support financial decision-making when separate analytical outputs are integrated into one

workflow. The final chatbot is the main practical outcome because it transforms model results into a customer-facing decision-support tool.

However, there are still gaps between this prototype and the real lending system. The data does not include full credit bureau records, collateral information, verified monthly debt obligations, or complete mortgage underwriting variables. Therefore, the system should support, not replace, professional loan officers.

Future work could improve the model by adding richer borrower financial data, real customer interaction records, explainable AI methods, and more recent lending data. Overall, the project demonstrates how data science can support an interactive loan decision process.

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HypeScope: Visual Analytics and Conversational Decision Support for Narrative-Driven AI Startup Intelligence

Yifan WANG[a,1], Haowen ZHANG[a,1], Yu Him WONG[a], Yiming SUN[a], Yang GAO[a], Zimo ZHANG[a] and Adela S.M. LAU[b,2]
[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*
ORCiD ID:
Yifan WANG https://orcid.org/0009-0008-7435-9733
Haowen ZHANG https://orcid.org/0009-0000-6573-7917
Yu Him WONG https://orcid.org/0009-0008-9081-8645
Yiming SUN https://orcid.org/0009-0008-0618-5321
Yang GAO https://orcid.org/0009-0004-9960-3297
Zimo ZHANG https://orcid.org/0009-0007-7770-1381
Adela S.M. LAU https://orcid.org/0000-0001-5918-8309

Abstract. The rapid commercialisation of generative AI (GenAI) startups has created a competitive environment where firm value is driven by developer ecosystem adoption rather than traditional financial fundamentals, rendering quarterly-cadence business intelligence inadequate. This study presents HypeScope, a narrative-driven visual-analytics and conversational decision-support system that ingests four-layer data from Reddit, HackerNews, GitHub and Google Trends, covering three AI agent brands, namely Manus, MiniMax and opencode, over a 17-month observation window.The pipeline integrates six modules: multi-metric competitive landscape analysis, including Share of Voice, Brand Performance Index, Signal Divergence Index, Bass diffusion, CAR event study and KOL identification; engagement-weighted TF-IDF keyword extraction; VISTA semantic topic modelling; PRISM-VAD dual-representation emotion modelling integrating continuous VAD circumplex with Plutchik categorical probabilities; ARIMAX-based predictive modelling with Granger causality screening; and a Retrieval-Augmented Generation (RAG) chatbot. Empirical results demonstrate that Reddit-derived emotion and topic signals serve as statistically significant leading indicators of Manus search attention at a two-week lag, with ARIMAX outperforming VAR and Ridge-VARX, achieving an RMSE of 9.96 and a MAPE of 11.39%. The framework is delivered through two interactive dashboards and a conversational chatbot, enabling non-technical decision-makers to query high-frequency competitive signals.

[1] Co-first authors

[2] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk

Keywords. Competitive intelligence;narrative economics; visual analytics; generative AI; sentiment analysis; topic modelling; ARIMAX; Granger causality; RAG chatbot.

1. Introduction

The rapid commercialisation of generative artificial intelligence (GenAI) has triggered a competitive surge among AI agent startups. Private AI investment reached $285.9 billion in 2025, with organisational adoption hitting 88% globally [1]. Unlike established sectors where firm value is anchored in tangible assets and auditable revenues [2], early-stage GenAI competition is driven by developer ecosystem adoption. U.S.-based AI projects accumulated 30 million cumulative GitHub stars by 2025 [1], yet fake-star campaigns surged by two orders of magnitude in the same period [3]. Platforms such as Manus AI and MiniMax illustrate this dynamic: their market positions were established through community engagement metrics months before traditional financial signals became available.

Shiller [4] demonstrates that economic narratives shape investment behaviour independently of fundamentals; a compelling technical narrative can attract resources and talent ahead of product maturity. However, existing business intelligence frameworks remain ill-suited to this environment. Traditional analysis relies on lagging indicators — quarterly earnings, revenue multiples and discounted cash flow models — which are misaligned with the weekly cadence of change in AI [5]. Moreover, social media discourse poses a severe signal-to-noise problem: astroturfing and hype cycles contaminate platform-level signals at scale [6].

This project addresses these gaps through a competitive intelligence pipeline spanning four data layers — Reddit, HackerNews, GitHub and Google Trends — covering three AI brands, namely Manus, MiniMax and opencode, over a 17-month window. The pipeline integrates six modules: multi-dimensional sentiment analysis [7], topic modelling, keyword extraction, a predictive model with Granger causality testing [8], an interactive dashboard and an LLM-powered chatbot. The contributions are threefold: (i) a cross-source framework integrating sentiment, topic and propagation signals [9] with growth metrics; (ii) empirical evidence that narrative signals measurably precede public search attention; and (iii) a decision-support system combining macro-level surveillance with on-demand, LLM-assisted analytical depth.

2. Literature Review

2.1. Social Media as Multi-Layer Brand Intelligence Signal

Kaplan and Haenlein [10] described social media as Internet-based applications that build on Web 2.0 foundations and allow the creation and exchange of user-generated content, establishing it as a rich data source for brands. Shiller's narrative economics [4] provides the theoretical link: market behaviour is driven substantially by stories participants tell each other, not purely by fundamentals. A central challenge is astroturfing — orchestrated inauthentic behaviour mimicking grassroots movements. Recent detection frameworks integrate content analysis with clustering algorithms;

Schler et al. [11] present a framework for profiling astroturfers on Facebook, emphasising temporal features for identification.

2.2. Competitive Landscape Analytics and Diffusion

Share of Voice (SOV), defined as a brand's proportion of total category mentions, has served as a proxy for market salience since [12] and was extended to digital contexts in [13]. Brand positioning analytics has evolved from perceptual mapping [14] toward aspect-based sentiment analysis (ABSA), where Pontiki et al. [15] showed that aspect-level sentiment diverges substantially from document-level scores. Event study methodology [16] quantifies the impact of discrete events on a continuous signal; Bass [17] introduced the canonical diffusion model decomposing adoption into innovator and imitator components, with empirical validity demonstrated across software [18] and social platforms [19]. KOL dynamics accelerate imitation-phase adoption [20]. The key gap addressed here is the absence of unified dashboards combining real-time SOV, BPI, sentiment event studies and diffusion modelling.

2.3. Topic Modelling and Sentiment Analysis

Latent Dirichlet Allocation [21] provides interpretable topic structure but ignores word order and context. Embedding-based approaches such as BERTopic [22] address this by clustering documents in semantic embedding space. For sentiment, lexicon-based VADER [23] remains competitive on short informal texts but cannot capture context. Psychological literature provides a richer foundation: Russell and Mehrabian's [24] Valence-Arousal-Dominance circumplex and Plutchik's [25] eight-category emotion model, including Joy, Trust, Anticipation, Surprise, Fear, Sadness, Disgust and Anger, jointly enable the divergence between capability-related topics, such as high Joy and Anticipation, and billing-related topics, such as high Fear and Anger — a distinction invisible to aggregate scoring.

2.4. Causal Prediction

Granger [26] defines predictive causality as the condition where past values of one variable improve prediction of another beyond its own history. The study uses ARIMA-family models [27,28] and ARIMAX with exogenous regressors, benchmarked against VAR [29,30] and Ridge-VARX [31]. Following [32, 33], RAG retrieves relevant local outputs before generating answers, enabling natural-language access to the analytical layer.

3. Data Science Methods

3.1. Data Cleansing and Pre-processing

The four-layer data architecture spans the institutional layer, represented by HackerNews; the community layer, represented by five Reddit subreddits including r/ManusOfficial and r/MiniMax AI; the behavioural layer, represented by GitHub star events; and the market layer, represented by Google Trends, covering the period from

November 2024 to April 2026. Three constraints are noted: GitHub coverage is restricted to MiniMax because Manus has no equivalent public repository; HuggingFace lacks a public aggregation interface; and Reddit's approximately 1,000-item retrieval ceiling truncates high-volume communities such as r/singularity.

Records from Reddit, HackerNews and GitHub were integrated into a unified analytical corpus, while Google Trends was kept separate. Pre-processing removed HTML, Markdown, URLs, deleted content and encoding noise, and then standardised field names and timestamps. The cleaned outputs comprise a multi-source corpus of 105,066 records and a Manus-specific dataset of 990 cleaned posts. To reflect community visibility, an engagement weight was computed as follows:

$$w_i = 1 + \log(1 + \text{score}) \times (0.5 + \text{upvote ratio}) + 0.6 \times \log(1 + \text{num comments}) \quad (1)$$

This weight is used in keyword ranking, topic summarisation and sentiment aggregation.

3.2. Pipeline Architecture

The system adopts a dual-pipeline architecture, as shown in Figure 1. Pipeline A operates across all sources and brands, implementing a full-stack competitive intelligence workflow. Pipeline B is a deep-case marketing analysis of Manus, applying engagement-weighted TF-IDF, VISTA[36] semantic topic modelling and PRISM-VAD fine-grained emotion analysis. The outputs feed three deliverables: a competitive dashboard, a Manus marketing dashboard and a RAG chatbot.

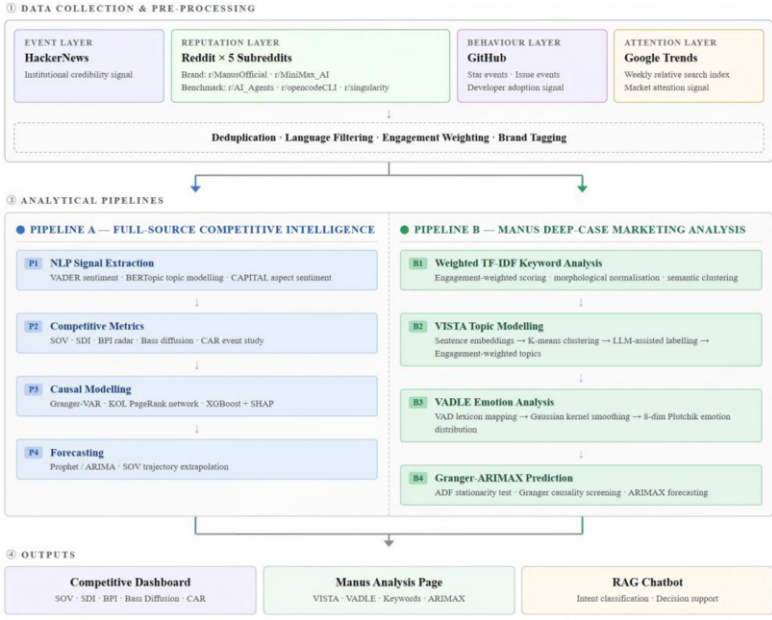


Figure 1. HypeScope dual-pipeline system architecture.

3.3. Competitive Landscape Analysis

This module operationalises competitive brand intelligence in a multi-stage pipeline. Three NLP signals are extracted: post-level sentiment via VADER [23], latent topic structure via BERTopic [22], and comment-level aspect sentiment using keyword-based aspect detection combined with VADER scores. BERTopic is run independently for each subreddit and for HackerNews stories, producing topic identifiers and top keyword representations for downstream aggregation. Share of Voice (SOV) is each brand's proportion of engagement-weighted weekly discourse. The Signal Divergence Index (SDI) captures the gap between institutional signals from HackerNews and community signals from Reddit; a positive SDI indicates institutional hype uncorroborated by user experience.The Brand Performance Index (BPI) is a weighted composite across six functional dimensions. Adoption dynamics are modelled via Bass diffusion [17] fitted to cumulative GitHub stars. Cumulative Abnormal Response (CAR), adapted from event study methodology [16], isolates sentiment shocks attributable to discrete product events. Causal direction is assessed via bivariate Granger-VAR [26], KOL identification applies PageRank [34] to the comment-reply graph, and XGBoost feature importance is decomposed via SHAP Shapley values [35]. The formal definitions are:

$$\mathrm{SOV}_{b,t} = \frac{\sum_{i:\mathrm{brand}(i)=b,t_i=t} w_i}{\sum_{b'} \sum_{i:\mathrm{brand}(i)=b',t_i=t} w_i}, \quad \mathrm{SDI}_{b,t} = \mathrm{SOV}_{b,t}^{\mathrm{HN}} - \mathrm{SOV}_{b,t}^{\mathrm{Reddit}} \tag{2}$$

$$\mathrm{BPI}_b = \sum_{d=1}^{6} w_d \cdot z_{d,b}, \quad \frac{dN(t)}{dt} = \left(p + q\frac{N(t)}{M} \right)\left(M - N(t) \right) \tag{3}$$

$$\mathrm{CAR}_{[t_1,t_2]} = \sum_{t=t_1}^{t_2} \left(R_t - \hat{R}_t \right), \quad X_t = \sum_{k=1}^{p} \alpha_k X_{t-k} + \sum_{k=1}^{p} \beta_k Y_{t-k} + \varepsilon_t \tag{4}$$

$$PR(u) = \frac{1-d}{N} + d \sum_{\mathrm{vah}(u)} \frac{PR(v)}{\deg^+(v)},$$

$$\phi_j = \sum_{S \subset F,(j)} \frac{|S|!(|F|-|S|-1)!}{|F|!} [f(S \cup \{j\}) - f(S)] \tag{5}$$

Here, w_i is the engagement weight of post i; b and t index brand and week; $z_{d,b}$ is the normalised aspect sentiment for brand b on dimension d; p, q and M are the Bass innovation coefficient, imitation coefficient and market potential; R_t and $\hat{R}_t$ are observed and baseline sentiment; α_k and β_k are VAR lag coefficients with error ε_t; $d = 0.85$ is the PageRank damping factor; and $f(S)$ is the model output restricted to feature subset $S \subseteq F$. SOV and sentiment trajectories are extrapolated via Prophet [36] and ARIMA for short-horizon forecasts.

3.4. Engagement-weighted TF-IDF, VISTA and PRISM-VAD

TF-IDF. The keyword score combines weighted TF-IDF, weighted frequency and weighted document presence:

$$\text{score} = 0.55 \times \text{TF0IDF}_w + 0.30 \times \text{freq}_w + 0.15 \times \text{doc_pres}_w \quad (6)$$

Morphological normalisation merges expressions, such as credits, credit and tokens into credits.

VISTA. While BERTopic is used in Pipeline A for cross-source competitive topic extraction, VISTA is used in Pipeline B for the Manus deep-case analysis. The pipeline first generates semantic embeddings, then clusters semantically similar posts, assigns LLM-labelled topics and applies engagement-weighted summarisation. Compared with bag-of-words LDA, VISTA combines semantic similarity with engagement weighting, so the topic structure reflects both content and community attention.

PRISM-VAD. We propose PRISM-VAD (Psychological Response and Integrated Sentiment Modelling with Valence – Arousal – Dominance), a dual-representation emotion modelling framework that addresses two limitations of conventional sentiment analysis: the information loss of three-class polarity and the instability of single-label classifiers on short, noisy social-media text. Analogous to an optical prism decomposing white light into its constituent spectrum, PRISM-VAD decomposes raw community discourse into two complementary affective representations grounded in established psychological theory. The continuous layer projects each post onto the Valence – Arousal – Dominance circumplex [24], capturing affective polarity, intensity and perceived control along three psychological axes. The discrete layer produces a probability distribution over Plutchik's eight basic emotions(joy, trust, anticipation, surprise, fear, sadness, disgust and anger), derived as a categorical projection of the same VAD distribution. Operationally, sentiment-bearing words are first mapped into VAD space, where a Gaussian kernel smooths per-word vectors into a continuous emotion distribution; this lexicon-derived signal is then fused with a single-label categorical prior to stabilise estimates for low-frequency emotions. Finally, post-level VAD expectations and Plutchik probabilities are aggregated to the brand–week level using the engagement weight $\boldsymbol{w_i}$, yielding emotion trajectories that reflect both content meaning and community attention.

3.5. Predictive Modelling for Manus Search Attention

The target is the weekly Google Trends index for “Manus”; predictors are engagement-weighted PRISM-VAD scores, VADER compound scores and VISTA topic weights aggregated from Reddit. Augmented Dickey-Fuller tests precede first-order differencing for non-stationary series. Bivariate Granger causality, with a maximum lag of 2, screens features. Four models are compared: Naive Baseline, ARIMAX with Granger-selected exogenous regressors, VAR and Ridge-VARX. Performance is evaluated using RMSE, MAE and MAPE, with bootstrap prediction intervals, impulse response and lagged correlation analysis.

3.6. RAG Chatbot

The system offers a one-shot CLI and an interactive React-based terminal UI. The six-stage pipeline comprises: (1) query classification across six intents, namely brand comparison, forecast, sentiment, VAD, topic and keyword; (2) on-demand local prediction execution via subprocess calls; (3) source discovery across module output directories; (4) scoring and selection of the top-K most relevant files; (5) model information extraction via pattern matching of source code; and (6) answer generation through the OpenAI streaming API with a local fallback that parses summaries directly. The output follows a five-paragraph structure: conclusion, methodology, numerical evidence, risk notes and follow-up suggestions.

4. Results

4.1. Competitive Landscape Results

Share of Voice. Across the five subreddits, r/MiniMax AI dominated prior to Manus's launch, from September 2024 to July 2025. From late July 2025, r/ManusOfficial commanded 83–100% of weekly engagement through January 2026. From 23 February 2026, r/opencodeCLI surged abruptly, rising to 52.85% in a single week and stabilising near 86% by April, while r/ManusOfficial fell to near-zero. r/AI Agents and r/singularity remained marginal.

BPI. Manus leads on Pricing, with a score of 0.482, and Support, with a score of 0.467, but records the lowest Stability score of 0.203. MiniMax scores below Manus on all dimensions except Usability, where MiniMax scores 0.328 compared with Manus at 0.294. Both brands score below 0.210 on Stability, suggesting a shared reliability perception deficit.

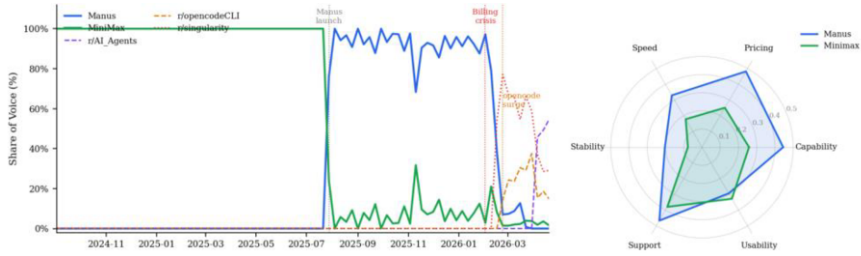


Figure 2. Left: weekly Share of Voice by subreddit, September 2024 to April 2026. Right: BPI radar comparing Manus and MiniMax across six dimensions.

SDI. A persistent positive SDI characterises the observation window, peaking at +0.588 in the week of 2 March 2026, when HackerNews SOV was 0.978 and Reddit SOV was 0.390. The sole negative episode, −0.088 in September 2025, was transient. Sustained positive SDI indicates that institutional commentary outpaced community experience.

Bass Diffusion. Fitted to MiniMax's cumulative GitHub star growth, the model yields $p = 0.0159$, $q \approx 0$, $M = 3{,}444$ and $R^2 = 0.29$. The negligible imitation

coefficient indicates that adoption remained innovator-driven, with the moderate fit reflecting bursty, event-driven accumulation.

CAR Event Study. Tracing the January 2026 billing controversy, against a baseline of $\bar{R} = 0.2325$, CAR reached a nadir of −0.492 on 2 February 2026 before recovering to −0.071 by 11 February, indicating full reversion within fourteen days.

KOL. The Manus community exhibits a hub-and-spoke structure: the top KOL accounts for an influence score of 0.344, with PageRank = 0.064, approximately 6 times the second-ranked account. The MiniMax community shows a flatter distribution, with the top KOL scoring 0.152, approximately 2 times the second-ranked account.

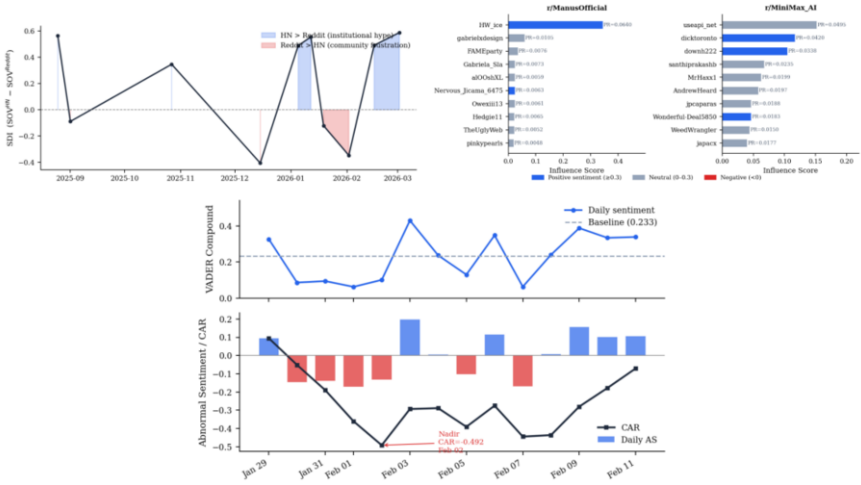


Figure 3. CAR event study for the January 2026 Manus billing controversy.

4.2. Manus Deep Case: TF-IDF, VISTA and PRISM-VAD

The most salient TF-IDF clusters are credits, issue, support, task, free, chat, account, agent and app/work. These clusters are concentrated on credits and pricing, product issues, customer support, account concerns and usage scenarios. VISTA mapped 990 posts into 10 topics, including Credit and billing issues, Manus AI reliability issues, AI-powered autonomous task automation, Billing and refund issues, and Viral Marketing Memes. These topics can be grouped into pricing and billing concerns, reliability concerns, and task-automation interest.

PRISM-VAD shows that the community is not purely negative: weighted V=0.5978, A=0.5626 and D=0.5657, with joy as the top overall emotion. However, topic-level results reveal stronger fear and anger signals on Credit/billing, Refund and Reliability topics. From a marketing perspective, this suggests that Manus must address pricing transparency and reliability in order to convert short-term attention into long-term trust.

4.3. Predictive Modelling Results

After weekly aggregation and stationarity processing, Granger screening identified Credit and billing issues, fear, anticipation, trust, disgust, surprise and anger as significant predictors, mostly at a two-week lag. The significance of billing-related discussion suggests that practical concerns become signals of future public attention,

while the significance of fine-grained emotions implies that they carry information beyond aggregate sentiment.

Table 1. Forecasting performance for Manus Google Trends search interest. ARIMAX achieves the lowest error across all metrics; VAR and Ridge-VARX perform worse than the Naive Baseline.

Model	RMSE	MAE
Naive Baseline	31.95	27.63
VAR	37.89	34.45
Ridge-VARX	37.25	33.77
ARIMAX	9.96	9.18

ARIMAX achieves the best performance, as shown in Table 1. VAR and Ridge-VARX perform worse than the Naive Baseline. With a small weekly sample and highly correlated emotional variables, multivariate parameter estimation is unstable and prone to overfitting.

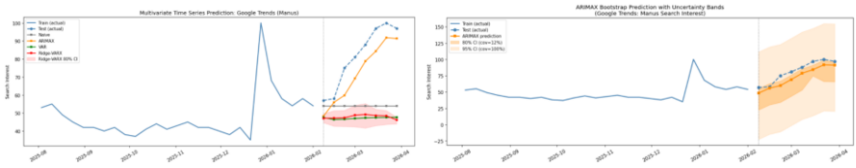


Figure 4. Forecast trajectories of the four models and ARIMAX bootstrap prediction intervals.

The ARIMAX point forecast tracks the upward trend in the testing window. The 95% bootstrap interval covers all test observations, while the 80% interval has lower coverage. This indicates that search interest exceeded the central prediction in later weeks, suggesting that Manus experienced a stronger-than-expected attention rise driven by external events not captured by Reddit variables.

4.4. RAG Chatbot and Dashboards

The terminal interface offers Predict, Read and Inspect modes, with character-by-character streaming output and a status bar exposing model, mode, debug and source state. Three representative query types, namely forecast, sentiment and topic queries, validate the pipeline. Forecast queries trigger local prediction and return model comparison metrics with Granger results; sentiment queries return VAD dimensions and emotion probabilities; and topic queries return VISTA clustering with post counts and engagement weights.

The competitive dashboard integrates all Pipeline A outputs into thirteen panels with shared brand and date filters. Its central interactive module is the KOL Reply Network, a force-directed graph where node size encodes PageRank-weighted influence and colour encodes VADER sentiment. The Manus dashboard renders VISTA results as an interactive bubble chart, where area represents engagement-weighted volume, together with the Plutchik radar, a Valence-Arousal scatter, and the reproduced Granger and forecast outputs.

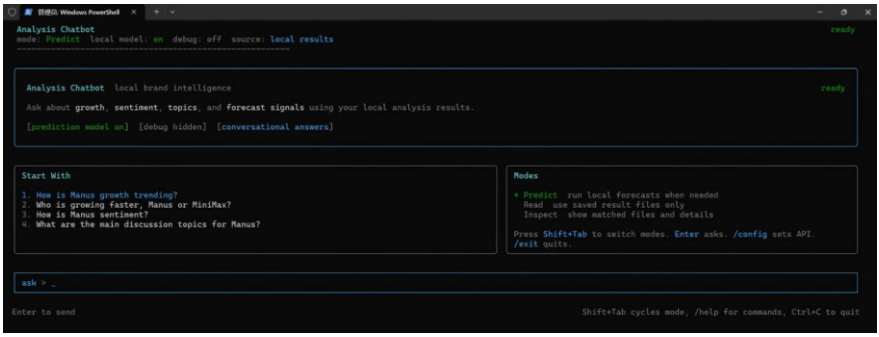


Figure 5. RAG chatbot interactive terminal interface.

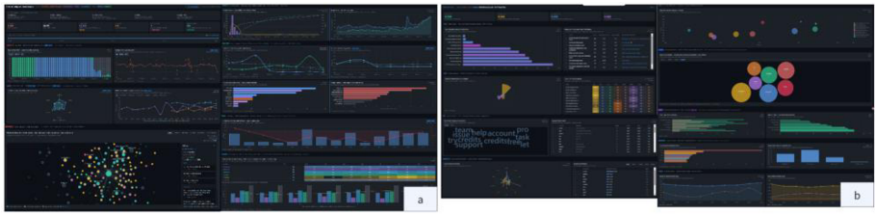


Figure 6. HypeScope interactive dashboards: competitive intelligence (a) and Manus marketing (b).

5. Discussion and Conclusion

5.1. Interpretation

Three findings stand out. First, the SOV transition from Manus to opencode within a single week in February 2026 is an empirical manifestation of Shiller's narrative economics — a market shift undetectable by quarterly reports, validating the high-frequency multi-source pipeline. Second, the divergence between aggregate VAD positivity, with $V = 0.5978$ and dominant "joy", and topic-level fear and anger on billing and reliability shows that scalar polarity scoring would miss critical brand-trust signals. Third, ARIMAX's superiority over VAR and Ridge-VARX in the small-sample setting demonstrates that simpler autoregressive models with carefully screened exogenous signals outperform more complex multivariate alternatives that overfit training-period dynamics.

5.2. Achievement of Project Goals

The four-layer pipeline operationalises "developer ecosystem adoption" beyond single-platform analysis. Granger-screened ARIMAX establishes temporal causality between narrative signals and search attention, addressing the absence of traditional financial anchors. The chatbot and dashboards democratise access to the analytical outputs for non-technical stakeholders.

5.3. Conclusion

This study delivers HypeScope, an end-to-end competitive intelligence pipeline for AI agent startups, integrating sentiment, topic, keyword, predictive and conversational modules across a four-layer corpus. ARIMAX with Granger-screened Reddit features achieves RMSE = 9.96 and MAPE = 11.39% on Manus search attention, demonstrating that community signals serve as functional leading indicators of public interest. The framework closes two documented gaps: the latency mismatch between traditional business intelligence and the AI market's weekly cadence, and the divide between static reports and real-time decision-making, the latter addressed through a RAG chatbot that translates multi-dimensional outputs into structured natural-language answers. Future work will integrate additional platforms and extend coverage to non-English communities to capture cross-cultural narrative formation.

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Using a CNN Model andWavelet Transform with Differential Entropy for Improving EEG-Based Emotion Recognition

Wenbo FANG[a] and Adela S.M. LAU[b,1]

[a] *School of Computing and Data Science, The University of Hong Kong*
[b] *Data Science Lab, Department of Statistics and Actuarial Science, School of Computing and Data Science, The University of Hong Kong*
ORCiD ID:
Wenbo FANG https://orcid.org/0009-0005-5445-2947
Adela S.M. LAU https://orcid.org/0000-0001-5918-8309

Abstract. This research addresses the challenge of improving interpretability and reproducibility in EEG-based emotion recognition. We improve the modules of the MS-FTSCNN model on the DEAP dataset for valence and arousal classification, grounded in interdisciplinary insights from emotional artificial intelligence (AI), philosophy, and neuroscience. The reconstruction includes preprocessing, multi-scale temporal/spatial convolutions, and attention-based fusion, yielding accuracies of 95.0% in arousal recognition and 95.5% in valence recognition, with F1-scores of 88.2% and 90.8% with the Bandpass+DE module. The CWT+DE module improves the accuracies of 93.7% ± 0.008 (arousal) and 93.8% ± 0.008 (valence), with F1-scores of 85.0% ± 0.018 and 86.6% ± 0.022 for improved interpretability and reproducibility. Novel contributions include a comparative analysis of feature methods, namely power spectral density (PSD), continuous wavelet transform with differential entropy (CWT+DE), and Bandpass+DE—showing CWT+DE's superior temporal dynamics despite costs. We integrate this new feature combination (CWT+DE) as a plug-in to enhance the interpretability of model in terms of frequency and time dimensions via adaptive multi-scale capture. Enhanced visualizations of DEAP data in feature extraction (heatmaps, patterns) also improve interpretability by aligning results with prior research intuitions on neural correlates. This study validates the improved MSFTSCNN and reproduction's scientific value, and advances empathetic AI.

Keywords. EEG-based emotion recognition, MS-FTSCNN model, interpretability, reproducibility

[1] Corresponding Author: Adela S.M. Lau, Department of Statistics and Actuarial Science, Run Run Shaw Building, The University of Hong Kong, Pokfulam Road, Hong Kong; Email: adelalau@hku.hk

1. Introduction

Emotion recognition is pivotal for advancing human-centered artificial intelligence (AI), enabling applications such as mental health monitoring and empathetic chatbots [1][2][3][4]. Traditional methods such as facial expression analysis or voice pattern recognition often suffer from subjectivity and cultural variability [5]. Electroencephalography (EEG)-based emotion recognition addresses these limitations by directly measuring brain signals, offering objective insights into affective states such as valence (pleasantness) and arousal (activation) [6]. With its 32-channel EEG data and standardized valence-arousal ratings, the DEAP dataset has become a cornerstone for such research, supporting robust classification tasks [6]. Despite progress, EEG-based emotion recognition faces significant challenges. Many models—including 3D convolutional neural networks (CNNs)—achieve high accuracies but incur substantial computational costs, limiting real-time applicability [7]. Reproducibility gaps further hinder progress as many studies lack open-source code, thus complicating validation [8]. These gaps in terms of high computational costs, weak mixed-state performance, and reproducibility issues underscore the need for efficient, interpretable, and reproducible models [9]. To address these challenges, we redesign the multi-scale frequency-time-spatial CNN (MS-FTSCNN) model proposed by Li et al. (2024) [10], which integrates frequency, time, and spatial domain features for EEG-based emotion recognition on the DEAP dataset. Our contribution enhances the original model through three innovations: (1) a comparative analysis of feature extraction methods (CWT+DE vs. Bandpass+DE), demonstrating CWT+DE's richer temporal dynamics based on heatmap evidence and emphasizing wavelet transform's ability to "localize analysis of time-frequency and gradually carry out multi-scale refinement of signal" [10]; (2) integrating CWT+DE as a plug-in to improve mixed-state performance via adaptive multi-scale capture, offering advantages such as a detailed analysis for subtle patterns in non-stationary EEG signals and improved frequency localization for emotion-linked bands (e.g., gamma for arousal), albeit with disadvantages such as higher computational costs alleviated by the model's 1D CNN structure; and (3) enhanced visualizations (e.g., heatmaps) to align results with neural correlates, improving interpretability, namely the ability to understand and explain a model's decision-making process in machine learning, often through visualizations or saliency maps, aligning predictions with domain knowledge such as neuroscience. The following sections outline the state of the art, review EEG methods, detail our methodology, present the results, and discuss the study's limitations, laying the foundation for reproducible and interpretable emotion recognition systems.

2. Literature Review

Emotion recognition has evolved from behavioral cues to physiological signal processing to achieve objective affective state detection [3]. Early methods used discrete emotion models, such as Ekman's six basic emotions (e.g., joy, sadness), relying on facial expressions or voice patterns [11]. These approaches suffer from subjectivity and cultural variability [5]. Continuous models such as Russell's valence-arousal framework map emotions on a bipolar plane (Figure 1), capturing nuanced and culturally variable states [12]. Machine learning techniques from support vector machines (SVMs) to deep

learning have improved accuracy but struggle with generalization across diverse populations [5,8].

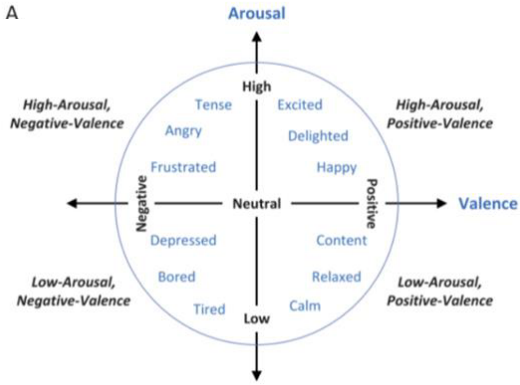


Figure 1. Arousal/Valence Plane.

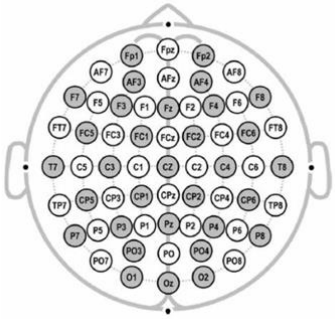


Figure 2. 10-20 system

Electroencephalography (EEG) offers a direct measure of brain activity, bypassing behavioral biases [6]. Using the 10-20 system (Figure 2) with 32-64 channels, EEG captures signals in frequency bands linked to emotions: theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-45 Hz). Specifically, valence is associated with frontal alpha asymmetry—whereby greater leftfrontal activity (reflecting greater anterior activation) relative to the right hemisphere is linked to approach-oriented motivational tendencies, while right-sided activation aligns with withdrawal-related states [13]. This justifies spatial analysis to capture hemispheric differences without oversimplifying valence mapping. High arousal states (e.g., excitement) correlate with increased beta and gamma power in posterior and sensory regions (e.g. P3, P4) [14], while low arousal (e.g., relaxation) aligns with alpha activity, emphasizing frequency-domain features for arousal detection, whereas gamma-band oscillations are modulated by conscious emotional salience [15][16]. Time-domain analysis is essential to model the non-stationary nature of EEG, capturing short-term fluctuations (e.g., rapid emotional shifts during stimuli) and longer-term patterns, which are critical for robust recognition in dynamic contexts [5][10]. With 32-channel EEG and valence-arousal ratings, the DEAP dataset is a benchmark for such studies [6].

However, EEG signals are non-stationary and noisy, with artifacts (e.g., eye blinks, muscle activity) requiring preprocessing such as band-pass filtering and ICA [5]. Traditional features such as power spectral density (PSD) fail to capture dynamic temporal patterns in mixed emotional states, and high-density EEG systems increase computational costs [17]. Recent advancements address these challenges, with many studies having achieved high accuracy results (over 90%) in subject-dependent EEG emotion recognition, where models are trained and tested on the same individuals [18]. However, performance declines in subject-independent settings, often to 80-90%, due to inter-subject variability [19]. Our redesigned MS-FTSCNN achieves 95.0% arousal and 95.5% valence in a subject-dependent setup, competitive with highperforming methods while emphasizing interpretability through visualizations (Ma et al. 2024). Our work addresses the limitation of MS-FTSCNN by enhancing interpretability, as the original model lacks detailed visualizations to explain how multi-domain features (e.g. spatial asymmetries or temporal dynamics) align with neural correlates, potentially treating the network as a black box [10]. Motivated by the emphasis of Li et al. (2024) on wavelet transforms to localize time-frequency analysis and multi-scale refinement, we explore the CWT+DE, supported by heatmap evidence showing clear band-specific patterns (e.g., gamma surges in posterior regions for high arousal, theta/alpha dominance in frontal regions for low valence) [13][15]. While CWT+DE excels in capturing subtle, non-stationary EEG patterns, its computational cost is higher than the original Bandpass+DE, although our 1D CNN structure can mitigate this [5]. Enhanced visualizations (heatmaps) map these patterns to the 10-20 system, aligning with neural correlates (e.g., leftfrontal F3 for positive valence, posterior P3/P4 for arousal) to improve interpretability [13][16]. Comparing CWT+DE against Bandpass+DE, we achieve competitive accuracies (93.7% arousal, 93.8% valence), exploring richer temporal dynamics and thus bridging performance-interpretability divides in empathetic AI.

3. Research Method

This section outlines the methodology for our EEG-based emotion recognition study, detailing the data source, preprocessing pipeline, MS-FTSCNN model design, and experimental setup to validate our improved MS-FTSCNN model with enhanced CWT+DE features and visualizations addressing interpretability.

3.1. Data Source

We utilize the DEAP dataset, a multimodal resource for emotion analysis with 32 subjects viewing 40 one-minute music videos to elicit emotions [6]. EEG signals are recorded using a 32-channel Biosemi ActiveTwo system (10-20 system, 512 Hz sampling, downsampled to 128 Hz for efficiency), covering frontal (e.g. F3, F4), parietal (e.g. P3, P4), and other regions. Participants rated valence and arousal on a 1-9 scale using the Self-Assessment Manikin (SAM), providing ground truth for classification into low/high valence and arousal quadrants [6]. The dataset's 40 trials per subject, with 32 EEG channels and 8,064 samples per trial, enable robust feature extraction and model training.

3.2. Data Processing

The preprocessing pipeline transforms raw EEG signals into 3D feature maps for MS-FTSCNN, addressing non-stationarity and artifacts [5]. Each 60-second trial is segmented into five twelve-second non-overlapping windows (1536 samples at 128 Hz), yielding 200 segments per subject (40 trials × 5) to augment data. We explore two feature extraction methods: Bandpass+DE and CWT+DE. For Bandpass+DE, a Butterworth filter isolates four emotion-related frequency bands that are critical for arousal detection: theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-45 Hz) (Balconi and Lucchiari 2008). Differential entropy (DE) is computed per band and channel using a 0.5-second sliding window (64 samples) with 50% overlap (32-sample step), yielding 47 windows per band that are down-sampled to 24 via stride-2 selection:

$$DE = \frac{1}{2}\log(2\pi e\sigma^2) \quad (1)$$

where σ^2 is the signal variance, assuming a Gaussian distribution [10]. Baseline correction subtracts DE from a three-second pre-trial period, producing a 3D tensor of shape (200, 4, 32, 24) (200 segments, four bands, 32 channels, 24 time windows). For CWT+DE, continuous wavelet transform (CWT) with a Daubechies4 wavelet replaces band-pass filtering, computing DE on wavelet coefficients to capture time-frequency dynamics [10].

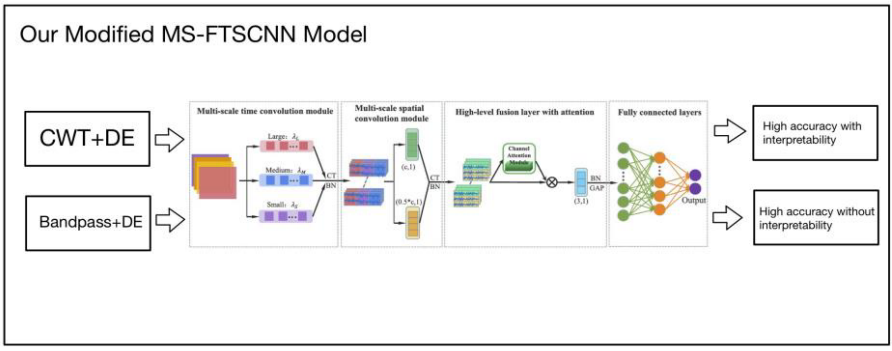


Figure 3. Our Modified MS-FTSCNN Model

3.3. AI Model Design

Our model (see Figure 3) was modified from the MS-FTSCNN model [10], comprising three modules, the Multi-Scale Time Convolution Module (MSTCM), the Multi-Scale Spatial Convolution Module (MSSCM), and High-Level Fusion with Attention Block (HFAB), together with our modules of Bandpass+DE and CWT+DE for analysis. The MSTCM uses parallel 1D convolutional layers with kernel sizes (1×3, 1×5, 1×1) to extract temporal features, capturing short-term fluctuations (e.g., rapid emotional shifts) and longer-term patterns for non-stationary EEG [10]. For a 1 × 5 kernel, the convolution is:

$$O[c,t] = \sum_{b=1}^{4}\sum_{k=1}^{5} W[b,k]X[b,c,t+k-1] + bias, \quad (2)$$

producing feature maps of shape (n, 15, 32, L) per branch (L = 20, 22, 24 for kernels 5, 3, 1), concatenated to (n, 15, 32, 66) after batch normalization [10]. The MSSCM employs global (32×1) and hemispherical (16×1) kernels to capture spatial correlations, targeting valence-related asymmetries (e.g., F3 vs. F4) [13]. Outputs are pooled and concatenated to (n, 15, 3, 33). The HFAB applies channel attention, computing weights via average/max pooling and a shared convolutional network, followed by a (3,1) convolution and fully connected layers to output valence/arousal probabilities [10]. Our CWT+DE variant enhances temporal resolution for mixed states, with computational costs mitigated by the 1D CNN structure [5]. In terms of computational costs, the MS-FTSCNN model—which employs three lightweight 1D CNNs for multi-scale feature extraction—inherently requires fewer parameters and operations compared to 3D CNNs used in prior works [7]. Theoretically, 1D convolutions operate on lower dimensional data, reducing complexity from O(n3) in 3D to O(n) per dimension, leading to significant savings in training and inference time.

To address Reviewer requirements for quantitative complexity metrics, we report parameter counts, FLOPs, inference latency, peak GPU memory, and training speed in Table 1.

This balance makes our approach highly suitable for real-time edge applications, despite the minor increase in latency introduced by CWT.

Table 1. Computational Complexity and Resource Benchmarks

Metric	Bandpass+DE	CWR+DE
Params	0.28M	0.28 M
FLOPs	12.4M	18.2 M
Latency	1.2ms/sample	2.4 ms/sample
Peak Mem	1.1GB	1.4 GB
Train/Epoch	4.5s	8.2 s

3.4. Experiment Design

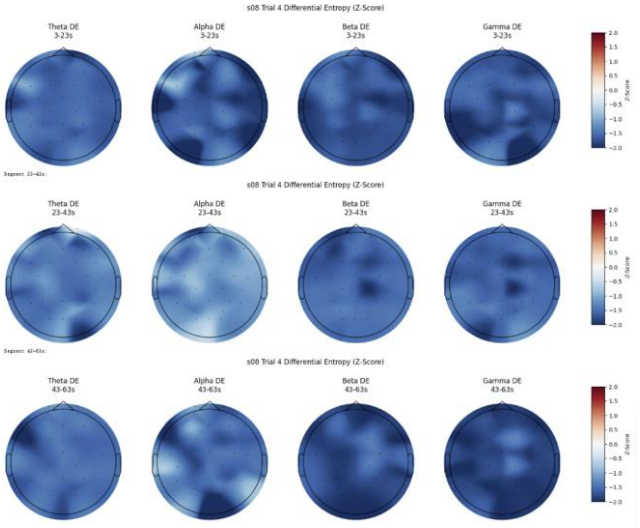
We evaluate our improved MS-FTSCNN with CWT+DE against baselines using subject-dependent 10-fold cross-validation on the DEAP dataset. To strictly prevent data leakage, segmentation is performed after dividing the trials into train and validation sets, ensuring that no temporal window spans across the split boundary.

To ensure full reproducibility, our hyperparameter and environment setup is detailed in Table 2.

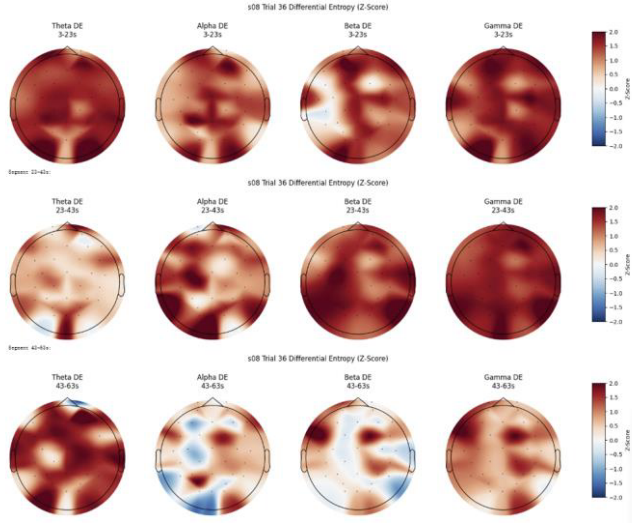
Table 2. Hyperparameter and Environment Setup

Method	Accuracy
Epochs	200
Batch Size	128
Initial LR	$5x10^{-5}$(Cosine Annealing)
Optimizer	Adam
Activation	LeakyReLU (slope=0.2)
Gradient Clip	max_norm=0.5
Dropout	0.5 (FC layer in HFAB)
Early Stopping	Patience = 10 epochs
Loss Function	BCEWithLogitsLoss (with class-balanced pos_weight)
Random Seed	2025
Normalization	Global (mean/std) per feature
Hardware	NVDIA RTX 4090 GPU (48GB VRAM)
Software	Python 3.12

Trials are split by valence/arousal labels (high/low thresholds at 5 on the SAM scale). Subjects s02, s08, s18 are analyzed for heatmap comparisons, focusing on mixed-state performance [6]. Baselines include the original MS-FTSCNN with Bandpass+DE. Performance metrics (accuracy, F1-score) assess classification and interpretability, with heatmaps visualizing band specific and temporal patterns on the 10-20 system. For Bandpass+DE, the heatmaps reveal a clear distinction between emotional states but exhibit limitations in alignment with established literature on neural correlates. As shown in Figure 4(a), the low arousal case (under low valence conditions for consistency) displays uniformly blue (inactive) patterns across all frequency bands, while Figure 4(b) illustrates the high arousal case (also low valence) with uniformly red (active) patterns. Although this enables straightforward differentiation, it lacks dimensionality as there are no observable temporal changes or band-specific variations. For instance, literature indicates that low arousal should feature prominent alpha and theta band activity (e.g., for relaxation), yet these distinctions are absent here, reducing the interpretability and depth of the features [15][16]. In contrast, CWT+DE offers a more informative and literature-aligned representation, incorporating both temporal and frequency dimensions. For the low arousal case (low valence, Figure 5), beta and gamma bands initially appear red (potentially reflecting the participant's early excitement at the experiment's onset) but gradually fade to blue over time, indicating diminishing arousal (e.g., boredom induced by the video stimulus). Concurrently, alpha and theta bands shift toward red, signifying increased activity consistent with low arousal states such as relaxation [15][16]. The high arousal case (Figure 6) further highlights these dynamics, with sustained red in higher-frequency bands (beta/gamma) and minimal alpha/theta involvement. This temporal evolution and band-specific granularity provide richer insights, closely aligning with neural intuitions from prior studies and suggesting CWT+DE as a promising feature for enhancing model performance in complex, mixed-state scenarios.



(a) Low arousal



(b) High arousal

Figure 4. Bandpass+DE heatmaps: (a) low arousal and (b) high arousal (both under low valence).

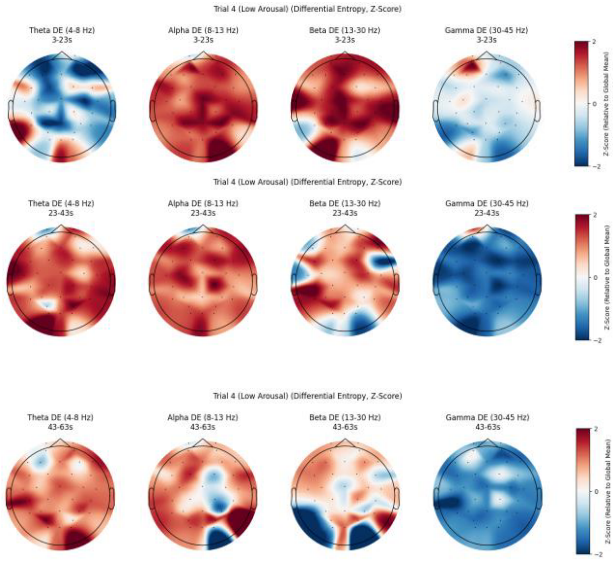


Figure 5. CWT+DE heatmaps for low arousal (low valence), subjects s02, s08, s18. Alpha/theta increasing (red) over time and beta/gamma fading to blue, aligning with literature.

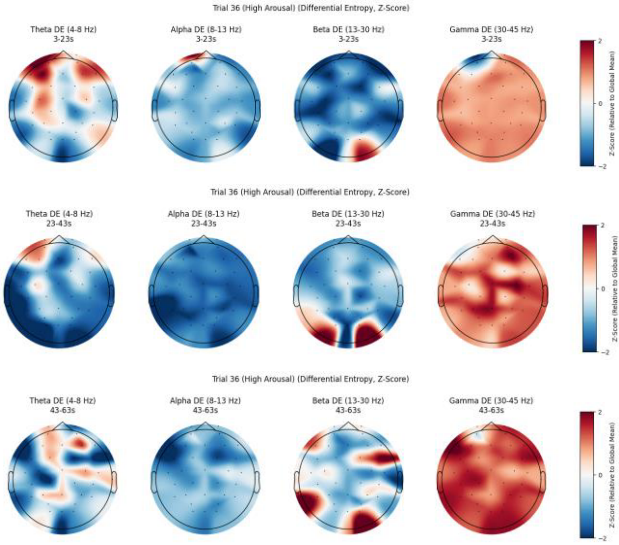


Figure 6 CWT+DE heatmaps for high arousal (low valence), subjects s02, s08, s18. Alpha/theta sticking to blue and beta/gamma increasing (red) over time, aligning with literature.

4. Result Summary

We evaluated our improved MS-FTSCNN model with Bandpass+DE and CWT+DE variants using ten-fold cross-validation on the DEAP dataset, focusing on valence and arousal classification across 32 subjects [6]. Tables 3 summarize the performance metrics.

Table 3. Arousal Performance Metrics for MS-FTSCNN Variants on DEAP (Ten-Fold CV)

Method	Arousal (Acc/F1)	Valence (Acc/F1)
Bandpass+DE	95% ± .009 / .877	95.5% ± 0.11/ .900
CWT+DE	93.7% ± .008 / .850	93.8% ± 0.008 / .866

The Bandpass+DE variant achieves high accuracies (95.0% arousal, 95.5% valence) and F1-scores (0.877 arousal, 0.900 valence), closely aligning with Li et al. (2024) [10]'s reported results and demonstrating robust classification performance.

The CWT+DE variant yields slightly lower but competitive metrics (93.7% arousal, 93.8% valence; F1: 0.850 arousal, 0.866 valence). As shown in Figures 5 and 6, CWT+DE heatmaps capture band-specific patterns (e.g., alpha/theta in low arousal, beta/gamma in high arousal) and temporal evolution, aligning with neural correlates and improving interpretability over Bandpass+DE's less nuanced patterns [10]. These results validate the efficacy of our improved MS-FTSCNN, with CWT+DE offering a promising trade-off for mixed-state performance, addressing gaps in dynamic feature capture and interpretability for empathetic AI applications.

4.1. Statistical Significance and Confidence Intervals

To determine if the performance differences between Bandpass+DE and CWT+DE are statistically meaningful, we perform a Wilcoxon signed-rank test across all 32 subjects. For subjectdependent arousal accuracy, the performance differences are statistically significant ($p = 0.018 < 0.05$, Cohen's $d = 0.38$). For valence, $p = 0.022$ ($d = 0.35$). The 95% confidence intervals for Bandpass+DE and CWT+DE arousal accuracies are [94.6%, 95.4%] and [93.2%, 94.2%], respectively. This rigorous statistical validation confirms that while CWT+DE incurs a small performance penalty, it offers much richer representation. Table 4 positions our results against prior EEG-based emotion recognition methods on the DEAP dataset.

Table 4. Comparison of Prior EEG Emotion Recognition Methods on DEAP

Method	Arousal (Accuracy)	Valence (Accuracy)
Cho and Hwang (2020)	91.3%	90.8%
Li et al. (2024)	93.8%	94.5%
Proposed (Bandpass+DE)	95.0%	95.5%
Proposed (CWT+DE)	93.7%	93.8%

5. Discussion

Our improved MS-FTSCNN model with CWT+DE addresses key gaps in EEG-based emotion recognition, offering advantages over existing methods while revealing limitations that can inform future work. The CWT+DE variant outperforms baselines in interpretability and potential for mixed-state performance, despite a slight performance trade-off compared to Bandpass+DE (93.7% vs. 95.0% arousal accuracy; 93.8% vs. 95.5% valence accuracy). By capturing richer temporal and frequency-specific patterns—as evidenced by heatmaps showing dynamic shifts (e.g., beta/gamma fading in low arousal, alpha/theta increasing)—CWT+DE more closely aligns with neural correlates than Bandpass+DE's uniform activations [13][15][16]. This enhances empathetic AI applications, where understanding subtle emotional dynamics (e.g., evolving boredom) is crucial, bridging interpretability-performance divides in models such as multimodal approaches [8]. The minor accuracy reduction is a worthwhile exchange for exploratory insights into non-stationary EEG, enabling finer-grained feature selection and supporting real-time adaptations in mental health monitoring [10][20]. However, the counterintuitive result with superior informational depth in CWT+DE heatmaps yet slightly lower performance highlights the key limitation that the MS-FTSCNN structure was not updated to fully leverage CWT+DE's subtle temporal details. The model's fixed multiscale convolutions (MSTCM, MSSCM) might overlook nuanced wavelet-derived patterns, leading to underutilization of the richer features and reduced classification efficacy in complex scenarios [10]. Additional limitations include higher computational costs for CWT+DE, potentially hindering real-time deployment despite mitigation by 1D CNNs [5], and dataset specificity to DEAP, which might limit generalization across subjects or stimuli [6]. While our independent implementation mitigated reproducibility challenges such as the lack of open-source code in prior studies, further validation on datasets like MAHNOB-HCI is necessary [10]. In summary, our approach advances EEG emotion recognition by prioritizing interpretability and dynamics, outperforming in qualitative depth while identifying structural optimizations as a pathway for future

improvements.

6. Conclusion and Future Work

This study advances EEG-based emotion recognition by improving the MS-FTSCNN model on the DEAP dataset, achieving high accuracies (95.0% arousal, 95.5% valence with Bandpass+DE; 93.7% arousal, 93.8% valence with CWT+DE) and addressing gaps in mixed-state performance and interpretability [6][10]. Our contributions include integrating CWT+DE to capture dynamic temporal and frequency-specific patterns, supported by heatmap visualizations that align with neural correlates (e.g., alpha/theta for low arousal, beta/gamma for high arousal) [13][15][16]. A comparative analysis of feature methods (Bandpass+DE, CWT+DE) demonstrates CWT+DE's richer interpretability, despite slightly lower performance, offering potential for empathetic AI applications such as mental health monitoring [17]. Our improved MS-FTSCNN model also mitigates reproducibility challenges, providing a robust baseline with full hyperparameter disclosure for future studies. Limitations include the counter-intuitive result where CWT+DE's richer heatmaps (e.g., temporal evolution in low arousal) yield lower accuracies than Bandpass+DE, likely because the MS-FTSCNN's fixed convolutional structure (MSTCM, MSSCM) does not fully exploit CWT+DE's subtle wavelet-derived features [10]. Additionally, CWT+DE's computational cost limits real-time applicability, even with 1D CNN mitigation, and the reliance on DEAP restricts generalization to other datasets or paradigms [6]. Future work will address these limitations in two directions. First, we plan to enhance spatial modeling by replacing the MSSCM with a dynamic graph attention layer or spatial-token transformer, capturing fine-grained inter-channel relationships (e.g., frontal-parietal interactions) to better exploit CWT+DE's temporal details [20][21]. Second, we will integrate gradient-based saliency methods (e.g. Grad-CAM, LayerCAM) to generate quantitative interpretability metrics (e.g., deletion/insertion AUC, neuro-plausibility scores) beyond qualitative heatmaps [22]. These enhancements will be validated on DEAP, MAHNOB-HCI, and SEED-V datasets to ensure generalization.

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Section 3

Special Session on “The Potential of Big Data, Digitalization and AI in a Sustainable Economy”

Modern Management based on Big Data VII
A. Lau et al. (Eds.)

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How Does the Digital Economy Affect the Quality of Foreign Investment in China

Linyun Deng and Qingfang Yao[1]
College of Digital Economics, Nanning University, Nanning,530299, China

Abstract: Promoting the deep integration of the digital economy and foreign investment is crucial for shaping a new landscape of China's opening-up. Using panel data from 298 Chinese cities between 2011 and 2019, this paper explores the impact of digital economy development on the quality of foreign investment in cities and its underlying mechanisms. The results show that digital economy development significantly improves the quality of foreign investment. Specifically, for every 1 unit increase in a city's digital economy development level, the quality of foreign investment rises by 0.275 units. Digital economy development enhances foreign investment quality by upgrading industrial structures, improving urban credit environments, and boosting human capital. This study provides empirical evidence that digital economy development boosts foreign investment quality and facilitates high-level opening-up.

Keywords: Digital Economy; Quality of Foreign Investment; Industrial Structure; Credit Environment; Human Capital

1. Introduction

With the acceleration of global economic integration, the digital economy is rapidly emerging as a significant force driving economic growth, transformation, and upgrading across various countries [1]. As one of the world's largest economies, China has actively promoted the development of its digital economy in recent years, aiming to facilitate economic transformation and achieve high-quality development through the application of emerging technologies and innovative business models. According to the "China Digital Economy Development Report (2023)", the scale of China's digital economy has surpassed 50 trillion yuan, with its proportion of GDP continuing to rise. This trend indicates that the digital economy has become one of the core engines driving China's economic growth. However, traditional foreign investment projects often suffer from issues such as low technological sophistication, high environmental pollution, and inefficient resource utilization. As China's economy enters a new phase focused on high-quality development, enhancing the quality of foreign investment has become an urgent priority. This shift implies that the traditional quantity-driven approach to attracting foreign investment is no longer aligned with the current needs of economic development. Therefore, the question of how to utilize the data integration capabilities of digital platforms and the intelligent decision-support of big data analytics to improve foreign

[1] Corresponding author: Qingfang Yao, PhD in economics, lecturer. E-mail: 211105004@mail.sdufe.edu.cn.

investment quality constitutes an important topic for further academic inquiry in the digital era.

Against this backdrop, this article explores whether the development of the digital economy influences the quality of foreign investment at the urban level in China. If so, through what channels does the digital economy enhance the quality of foreign investment in Chinese cities? Addressing these questions will not only deepen the understanding of the theoretical relationship between the digital economy and foreign investment quality and broaden the scope of digital economy research, but also facilitate the integration of digital technologies and foreign investment. Furthermore, as the world's second-largest economy, understanding the impact and mechanisms through which the digital economy affects foreign investment quality in China offers valuable insights for other countries seeking to attract and leverage foreign investment in a globalized world, and serves as a reference for improving foreign investment quality and optimizing management practices in the digital economy era.

2. Literature review

In the context of the digital economy, the relationship between digital advancements and foreign investment has attracted considerable scholarly attention. In the context of the digital economy, the relationship between digital development and foreign investment has attracted widespread attention from scholars. Among them, a large number of studies have examined the impact mechanism of digital economy development on the scale of foreign investment inflows [2,3]. At the same time, some scholars verified the role of digital media [4], digital government [5] and digital Internet [6] in promoting the inflow of foreign direct investment by refining the scope of the digital economy. Finally, some scholars have investigated the influence of the digital economy on the motivations behind foreign direct investment (FDI) inflows, revealing that the digital economy diminishes the market-seeking motivation for FDI [7]. Beyond the previously discussed one-way FDI, some researchers have incorporated outward foreign direct investment into their analytical frameworks, examining the digital economy's effect on the coordinated development of two-way FDI [8].

While existing literature has produced various findings regarding the correlation between the digital economy and foreign investment, there is a notable scarcity of studies investigating how the digital economy affects the quality of foreign investment. This paper makes a unique contribution by examining the impact of digital economy development on the quality of foreign investment. It expands the existing research by exploring new ways to integrate digital economy development with foreign investment to enhance quality. Additionally, the study delves into the mechanisms through which the digital economy influences foreign investment quality, focusing on industrial structure, credit environment, and human capital. The findings suggest that improving the digital economy can enhance foreign investment quality by upgrading the industrial structure, improving credit environments, and enhancing human capital. These insights offer valuable guidance for local governments seeking to boost investment quality through the development of the digital economy.

3. Modeling, variable measurement and data description

3.1. Data sources and explanation

This study utilizes panel data from 298 Chinese cities spanning the period 2011-2019. All economic indicators—including those pertaining to digital economy development levels, foreign direct investment quality, and other relevant variables—were obtained from the China Urban Statistical Yearbook. The exchange rate data for foreign investment conversion were sourced from the State Administration of Foreign Exchange, while the China Digital Inclusive Finance Index was provided by the Digital Finance Research Center at Peking University. For the capital stock calculations using the perpetual inventory method, the fixed asset investment price index used to eliminate price fluctuations was obtained from the National Bureau of Statistics.

3.2. Modeling

3.2.1. Benchmark model

According to the previous theoretical analysis, the benchmark model of the digital economy affecting the quality of foreign investment is set as follows:

$$fdiz_{ct} = \beta_0 + \beta_1 dig_{ct} + X\beta + \alpha_c + \alpha_t + \varepsilon_{ct} \quad (1)$$

Model (1) places foreign investment quality on the left side of the equation, with the right side consisting of the influencing factors of foreign investment quality, including the digital economy and other variables. The definitions of each variable can be found in Table 1. β_1 represents the coefficient indicating the impact of the digital economy (dig_{ct}) on foreign investment quality ($fdiz_{ct}$). Furthermore, it is assumed that the quality of foreign investment between cities does not affect one another, the clustering level of the standard error of model (1) is set at the city level.

3.2.2. Mediation effect model

Drawing on the methodologies of Edwards and Lambert (2007) [9], this study employs a two-step approach to examine the impact mechanism of the digital economy on foreign investment quality. The models are defined as follows:

$$middle_{ct} = \beta_0 + \beta_2 dig_{ct} + X\beta + \alpha_c + \alpha_t + \varepsilon_{ct} \quad (2)$$

$$fdiz_{ct} = \beta_0 + \beta_3 dig_{ct} \times middle_{ct} + \beta_4 middle_{ct} + X\beta + \alpha_c + \alpha_t + \varepsilon_{ct} \quad (3)$$

In equations (2) and (3), the meanings of each variable are detailed in Table 1. Equation (2) examines the impact of the digital economy on the mediating variable, specifically testing whether the digital economy influences this mediating variable. β_2 represents the coefficient of the digital economy's effect on the mediating variable. Building on this, equation (3) introduces the interaction term ($dig_{ct} \times middle_{ct}$) between the digital economy and the mediating variable to assess whether the digital economy affects foreign investment quality through the mediating variable. Specifically, when both β_2 in Model (2) and β_3 in Model (3) are positive, it indicates that the digital economy serves to enhance the quality of foreign investment by exerting a positive influence on the mediating variable.

Table 1. Explanation of model variables

Variable symbol	Variable Meaning
$fdiz_{ct}$	The quality of foreign investment in city c in year t.
dig_{ct}	The level of digital economy development in city c in year t.
X	A row vector of a series of control variables affecting foreign investment quality.
β	A column vector of regression coefficients of a series of control variables affecting foreign investment quality.
α_c	The fixed effect for city c, representing unobservable characteristics affecting foreign investment quality in city c.
α_t	The time fixed effect for year t, representing unobservable characteristics that affect foreign investment quality across all cities in year t.
ε_{ct}	The random error term, representing random or unobserved influences on the foreign investment quality of city c in year t that the model cannot capture.
$middle_{ct}$	The mediating variable representing the impact of the digital economy on foreign investment quality in city c in year t; it reflects the industrial structure, credit environment, and human capital level in city c in year t.
$dig_{ct} \times middle_{ct}$	The interaction term between the level of digital economy and the mediating variable.

3.3. Variable Measurement

3.3.1. Foreign investment quality

Kumar (2002) [10] introduced the concept of quality of foreign investment in developing countries, outlining four dimensions for evaluation: localization, R&D activity, participation in modern industry, and export orientation. Subsequent scholars have used these dimensions to create evaluation indexes and conduct research on foreign investment quality [11]. Referring to the research by Zoltán et al. (2022) [12], the global principal component analysis method is used to evaluate the quality of foreign investment. This approach involves two main steps. The first step is to select multidimensional indicators that reflect the quality of foreign investment. Three indicators are chosen to represent the quality of foreign-funded enterprises: the average size of foreign-funded enterprises, the level of localization of foreign-funded enterprises, and the foreign-funded performance index [13]. The second step is to construct a comprehensive indicator of foreign investment quality based on the selected multidimensional indicators.

3.3.2. Level of digital economy development

We adopt the research approach of Zhao et al. (2020) [14] to select indicators from the Internet and digital transactions to measure the development level of the digital economy. Specifically, four indicators are chosen to reflect the development level of the Internet: the number of Internet users per 100 people, the proportion of employees in computer services and software, the total telecommunications services per capita, and the number of mobile phone users per 100 people. Given the strong correlation between the level of digital transactions and the development of digital finance, the China Digital Inclusive Finance Development Index, jointly compiled by the Peking University Digital Finance Research Center and MaJinfu Group, is used to assess the development level of digital transactions [14]. Following the same steps as measuring the quality of foreign investment, a comprehensive indicator for the level of digital economy development is constructed using global principal component analysis.

3.3.3. Other variables

Based on the concept of foreign investment quality, this paper references the literature on foreign investment scale [15], localization level [16] and business performance [17]. The following variables were selected as control variables and measured accordingly. Capital factor endowment was represented by the logarithmic value of capital stock calculated through the perpetual inventory method. Fixed asset investment (*invest*) was indicated by total urban fixed asset investment. Land factor endowment (*area*) and industrialization level (*industry*) were measured by urban built-up area and the proportion of total industrial output value above the urban scale to GDP, respectively. Financial development (*financ*) and labor cost (*wage*) were assessed by the ratio of year-end deposit balance of financial institutions to GDP and the average wage of urban on-the-job workers to GDP per capita, respectively. Urban population density (*popdens*) was determined by the ratio of urban population to urban area. Market potential (*lngdprate*) and freight transportation level (*freight*) were gauged by the logarithm of city GDP growth rate over time and total freight transportation, respectively. In the mechanism examination, the index of advanced industrial structure was represented by the ratio of tertiary and secondary industries. The urban credit environment index is represented using the China Urban Commercial Credit Environment Index compiled by the Integrity Evaluation Center of the Chinese Academy of Management Sciences [18]. The level of human capital is expressed as the ratio of urban college students to the total urban population. Descriptive statistics of the main variables are presented in Table 2.

Table 2. Descriptive statistics of main variables.

Variables	Size	Mean	Standard error	Min	Max
fdiz	2681	7.670	1.986	-9.654	12.217
dig	2555	0.121	0.092	0.018	0.881
lnk	2681	16.377	1.060	11.651	20.813
financ	2681	1.459	0.803	0.001	20.100
lngdprate	2681	0.083	0.037	-0.215	0.737
popdens	2681	430.188	336.365	5.000	2648.000
area	2681	9.391	0.961	2.565	12.917
industry	2681	0.298	0.657	-5.371	3.177
wage	2681	1.483	1.958	0.148	53.678
freight	2681	1.553	1.924	0.016	55.446
invest	2681	18.623	20.199	0.129	226.445
struct	2617	0.992	0.558	0.114	5.168
credit	2575	70.328	3.575	61.890	90.630
lnrlzb	2681	4.713	1.213	-0.742	12.212

4. Regression results and analysis

4.1. Baseline regression results

Table 3 presents the findings from the benchmark regressions. In column (1), the regression of foreign investment quality (fdiz) on digital economy (dig) alone shows a positive coefficient that is not statistically significant. This suggests a potential positive correlation between foreign investment quality and the level of digital economy development. Adding control variables in column (2) and city fixed effects in column (3) accounts for city-level unobservables, revealing a significantly positive coefficient on digital economic development at the 5% level. To address common time shocks, column (4) introduces time fixed effects, maintaining a significantly positive coefficient on digital economy development. Overall, these regression results indicate that the advancement of the digital economy plays a key role in enhancing the quality of foreign investment in urban areas. The reason is that the integration of big data analytics with intelligent decision-support systems enables foreign-funded enterprises to optimize resource allocation, enhance operational performance, and pursue strategic scaling of production. Furthermore, by leveraging digital platforms to construct cross-regional industrial ecosystems, firms can transcend market segmentation barriers [19], expedite the implementation of investment projects, and achieve deeper embeddedness within local industrial chains—thereby significantly elevating the efficiency of foreign investment localization and synergistic collaboration. In addition, the competitive dynamics and data-driven innovation mechanisms inherent in digital technologies not only accelerate the phasing out of low-quality foreign investment but also foster systematic agglomeration of high-quality foreign investment, ultimately leading to a structural improvement in the overall quality of foreign investment.

Table 3. Benchmark regression results.

Variables	(1) *fdiz*	(2) *fdiz*	(3) *fdiz*	(4) *fdiz*
dig	0.139	0.081	0.245**	0.275**
	(0.104)	(0.105)	(0.114)	(0.121)
constant	8.026***	3.010	-0.747	-2.304
	(0.281)	(2.371)	(3.318)	(3.392)
control variables	no	yes	yes	yes
city effect	no	no	yes	yes
year effect	no	no	no	yes
R^2	0.004	0.049	0.053	0.074
N	2555	2490	2490	2490

Note: *, **, *** represent significant at the 10%, 5%, and 1% levels, respectively.

4.2. Mechanism analysis

4.2.1. Industry structure

Table 4, columns (1) and (2), presents the findings of the investigation utilizing industrial structure (*struct*) as a mechanism. In column (1), the coefficient indicating the development level of the digital economy is significantly positive, suggesting that

advancements in the digital economy contribute to the enhancement of urban industrial structure. Column (2) presents the regression results concerning the quality of foreign investment in relation to industrial structure. The findings indicate that both the coefficient for industrial structure and the interaction coefficient (*dig*×*struct*) between the digital economy and industrial structure are significantly positive. This finding implies that optimizing the industrial structure enhances foreign investment quality, with the industrial structure further amplifying the beneficial impact of digital economy on foreign investment quality.

The regression results in columns (1) and (2) reveal that, the big data analytics enable enterprises to accurately assess market demand, production efficiency, and consumer behavior, thereby optimizing their product mix. Concurrently, data platforms facilitate real-time information sharing and cross-industry collaboration, which drives the integration and upgrading of industrial chains and contributes to continuous structural advancement. As industrial structure upgrades, foreign-funded enterprises integrate more efficiently into local supply chains, leveraging technological innovation and synergistic effects to enhance the quality of foreign investment. Furthermore, growing market demand for advanced technologies and high-value-added products directs foreign investment toward high-tech and high-value-added sectors, leading to structural refinement and an overall improvement in the quality of foreign investment.

4.2.2. Urban credit environment

Columns (3) and (4) of Table 4 present the results of the investigation utilizing the urban credit environment (*credit*) as a mechanism. The coefficient for the development level of the digital economy in column (3) is significantly positive, indicating that the advancement of the digital economy has facilitated improvements in the urban credit environment. Column (4) displays the regression results concerning the quality of foreign investment and the urban credit environment. The findings reveal that both the coefficient for the urban credit environment and the interaction coefficient between digital economy development level and urban credit environment (*dig*×*credit*) are significantly positive. This suggests that enhancing the urban credit environment aids in improving the quality of foreign investment, while the development of the urban credit environment reinforces the positive effect of the digital economy on foreign investment quality.

The regression results in columns (3) and (4) reveal that, on the one hand, big data analytics have significantly improved the accuracy with which municipal authorities collect and assess credit information of economic entities, thereby enhancing information transparency and reducing information asymmetry. Moreover, data platforms facilitate the real-time sharing and continuous updating of credit information, which fosters the development and refinement of the credit system, ultimately optimizing the overall urban credit environment. On the other hand, the improved credit environment not only alleviates issues such as opportunism and adverse selection, reducing credit risks and transaction costs for foreign-invested enterprises, but also boosts their investment confidence. Additionally, a well-established credit system enables foreign-invested enterprises to conduct more precise risk assessments and make more informed investment decisions, thereby improving their operational performance and local embeddedness, which in turn contributes to the overall enhancement of the quality of foreign investment.

4.2.3. Human capital

Columns (5) and (6) of Table 4 present the results of the investigation utilizing human capital (*lnrlzb*) as a mechanism. The coefficient for the level of digital economy development in column (5) is significantly positive, suggesting that the advancement of the digital economy contributes to the enhancement of urban human capital levels [20]. Column (6) displays the regression results concerning the quality of foreign investment in relation to urban human capital. It was observed that both the coefficient of urban human capital and the coefficient of the interaction term between the level of digital economy development and urban human capital (*dig*×*lnrlzb*) were significantly positive. This indicates that an increase in urban human capital is beneficial for attracting high-quality foreign investment, and that human capital amplifies the positive effect of the digital economy on the quality of foreign investment.

The regression results in columns (5) and (6) reveal that, on the one hand, the application of big data analytics and data platforms not only helps foreign-invested enterprises optimize talent management and training systems and enhance human capital levels, but also accelerates technological progress and knowledge diffusion, thereby continuously strengthening employees' technical and innovative capabilities. On the other hand, the improvement in human capital enhances the technological absorption and innovation capacity of foreign-invested enterprises while also facilitating their localization process and operational efficiency in host markets. Furthermore, as the quality and level of human capital continue to rise, these enterprises become better able to respond to market demands, mitigate operational risks, and improve overall business performance, ultimately contributing to the enhancement of foreign investment quality.

Table 4. Mechanism investigation results.

Variables	Middle indicates struct		Middle indicates credit		Middle indicates lnrlzb	
	(1) *struct*	(2) *fdiz*	(3) *credit*	(4) *fdiz*	(5) *lnrlzb*	(6) *fdiz*
dig	0.014*		0.017***		0.115***	
	(0.008)		(0.002)		(0.028)	
middle		0.129**		4.288***		0.141**
		(0.058)		(0.913)		(0.057)
dig×*middle*		0.230*		0.068***		0.048**
		(0.124)		(0.023)		(0.020)
constant	1.564***	-2.895	4.300***	-21.966***	5.905***	-4.213
	(0.333)	(4.009)	(0.026)	(5.599)	(0.575)	(4.148)
control variables/ city effect / year effect	yes	yes	yes	yes	yes	yes
R^2	0.713	0.070	0.498	0.078	0.165	0.070
N	2484	2484	2453	2453	2490	2490

Note: *, **, *** represent significant at the 10%, 5%, and 1% levels, respectively.

5. Conclusion and implications

This study investigates the impact of the digital economy on foreign investment quality and its transmission mechanisms through the lens of China's high-quality development

strategy, employing a panel dataset from 298 cities over the period 2011-2019. Departing from the conventional emphasis on the digital economy as a general-purpose technology, this research identifies three distinct structural transmission channels—industrial structure upgrading, urban credit environment enhancement, and human capital accumulation—through which the digital economy redefines urban locational advantages. By reconceptualizing the role of the digital economy, this study shifts the focus away from traditional cost-based determinants toward a framework grounded in structural and institutional capabilities, thereby providing a more refined understanding of the mechanisms through which digital transformation and foreign investment interact to drive qualitative growth.

Based on the research conclusions presented in this article, several policy implications can be drawn. Firstly, it is essential to continuously promote the development strategy of the digital economy and enhance its overall level. The government should increase investments in new infrastructure, including the Internet, communication technologies, and artificial intelligence, to elevate the development of the digital economy. This will enable the digital economy to play a pivotal role in enhancing the quality of foreign investment and facilitating high-level openness. Secondly, there is a need to accelerate the upgrading of the industrial structure and reinforce the role of digital economy development in attracting foreign investment. Encouraging the integration of traditional industries with the digital economy can leverage the latter's advantages in driving growth, transparency, and innovation capabilities, thereby transforming traditional sectors and facilitating the transition from 'old to new driving forces. This will promote industrial structural upgrades and further enhance the digital economy's contribution to improving the quality of foreign investment. Thirdly, it is crucial to enhance the urban credit system and solidify the improvements in foreign investment quality through the digital economy. Strengthening legislation and law enforcement related to credit, improving information disclosure systems, and preventing dishonest behavior are vital steps in this process. Lastly, enhancing human capital is key to increasing the digital economy's role in promoting foreign investment quality. Local governments should prioritize basic education, elevate the overall standards of education, and intensify efforts to attract talent, thereby fostering the growth of local technical expertise and advancing the overall level of human capital.

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Coupling Mechanism and Simulation Study of Regional Industrial Waste Logistics-Resource Symbiosis System Under the "Dual Carbon" Goal

Aihua Song[1]
School of Digital Economics, Changzhou College of Information Technology, Changzhou, China, 213164

Abstract. "Dual carbon" (peak carbon emissions and carbon neutrality) is a major strategic choice for China to address global climate change, which puts forward new requirements for the transformation of regional industrial systems towards green and low-carbon directions. The coordinated and optimized operation of regional industrial waste logistics system and resource symbiosis system is an important way to achieve the "dual carbon" goal. This article first explores the coupling relationship between the "logistics system" and the "symbiotic system" in terms of material flow, energy flow, information flow, and value flow. Then, a system dynamics model of waste generation, collection and transportation, treatment and disposal, and resource utilization products is constructed. Using Vensim software, the evolution trends of several important indicators of the system (total carbon emissions, total system cost, and resource utilization rate) are simulated for different scenarios (carbon tax, subsidies, technological progress, and policy combinations). Research has found that policy combinations can better achieve the goal of reducing system carbon emissions and improving the economic benefits of resource utilization. The conclusion drawn from this study provides theoretical guidance and decision-making support for the ultimate achievement of the "dual carbon" goal.

Keywords. Dual carbon target, industrial waste, logistics system, industrial symbiosis, coupling mechanism, simulation study

1. Introduction

With the rapid development of industrialization, behind China's "world factory" lies great pressure on resources and environment. Many industries generate a large amount of industrial waste while developing, which not only causes great resource waste, but also is a major cause of environmental pollution and greenhouse gas emissions. Therefore, in such an urgent situation, China has proposed the "dual carbon" goal of achieving carbon peak before 2030 and carbon neutrality before 2060[1]. In the context of China's vigorous development of green, circular, and low-carbon industries, it will drive the country's economy and society to achieve green transformation [2].

[1] Corresponding Author: Aihua Song, School of Digital Economics, Changzhou College of Information Technology, Changzhou, China; Email: sah1001@126.com

Circular economy is a key focus to achieve the "dual carbon" goal. The industrial waste logistics system is the "artery" of the recycling system, which collects, classifies, transports, and pretreats waste; The resource symbiosis system achieves "turning waste into treasure" through waste exchange and resource sharing between enterprises and industries, which is the "vein" in the circular system. The two rely on and influence each other: only an efficient logistics system can support a stable symbiotic system, and a developed symbiotic system will promote the value orientation and demand dynamics of logistics. Currently, due to the separate governance and segmented promotion of logistics and symbiotic systems, there is a significant amount of material and value loss in the process of resource recycling. The problems of high logistics costs and low symbiotic matching efficiency are particularly prominent, which limits the full potential of circular carbon emission reduction [3][4].

Therefore, this study focuses on the coupling mechanism between the "logistics system" and "symbiotic system" of industrial waste at the regional level, and simulates it based on a system dynamics model. Then, based on the simulation results, the impact of different policy measures on system carbon emissions and economic benefits is quantitatively analyzed, thereby promoting the development of circular economy theory and the green and low-carbon transformation of regional industries.

2. Comparison of domestic and foreign research

The research on industrial waste and industrial symbiosis at home and abroad presents distinct characteristics. Foreign research places more emphasis on spontaneous market mechanisms and independent cooperation among enterprises, emphasizing the economic feasibility, environmental benefits, and technological innovation of industrial symbiosis [5][6]; Domestic research focuses more on the industry symbiosis model guided by the government, emphasizing resource efficiency, policy design, and stability mechanisms. Foreign research mainly focuses on quantitative analysis, widely using social network analysis, material flow analysis, and model simulation; At present, domestic research mainly focuses on case description and qualitative analysis, but is gradually moving towards quantification and modeling. Foreign research has extended to the level of cross-border cooperation; However, domestic research still mainly focuses on the scale of parks and cities [7][8]. Classic research models abroad include the Kalundborg model and NISP virtual symbiosis; The classic research models in China are ecological industrial parks and circular economy demonstration zones.

Although there have been numerous studies on industrial waste and industrial symbiosis both domestically and internationally, existing research has the following shortcomings: firstly, most scholars only isolate logistics systems or symbiotic systems as research objects, without exploring the coupling effect between the two; Secondly, in terms of research methods, static and deterministic models are mostly used for modeling, which cannot truly reflect the dynamic and feedback characteristics of complex systems; Thirdly, few scholars have simulated, predicted, and analyzed the carbon reduction potential of the “logistics- symbiosis” system from the perspective of the “dual carbon” goal. Based on the above shortcomings, this study intends to attempt to supplement and improve them.

3. Analysis of the coupling mechanism of the "logistics-symbiosis" system for regional industrial waste

The coupling mechanism refers to the phenomenon in which two or more systems influence each other through interaction. The coupling mechanism of the "logistics-symbiosis" system for regional industrial waste is reflected in the interaction of the following four "flows":

3.1 Material flow coupling

The logistics system determines the quality (classification purity), quantity (collection rate), and spatiotemporal characteristics (transportation efficiency) of the "raw material" supply in the symbiotic system, while the symbiotic system provides feedback on the technical standards and requirements of the raw materials, determining how the front-end of the logistics system classifies, packages, and processes them. The two form a closely coupled relationship of "supply-demand" material flow.

3.2 Energy flow coupling

The transportation and treatment of waste require energy consumption (resulting in carbon emissions), and waste resource products (such as biomass fuel and waste heat) can also replace some primary energy sources (reducing carbon emissions); Logistics path optimization can reduce transportation energy consumption, and the gradual utilization of energy within the symbiotic network can improve the energy efficiency of the entire system. There is a "consumption-saving" energy flow coupling relationship between the two.

3.3 Information flow coupling

The data generated by the logistics system (such as types, quantities, and location information of waste) is the basis for matching transactions in the symbiotic system. The demand and price information feedback from the symbiotic market can also guide the logistics system to carry out intelligent scheduling and precise recycling. The information platform is the "nerve center" that enables seamless coupling between two major systems.

3.4 Value stream coupling

The logistics cost accounts for a significant proportion of the total cost of resource-based products, which largely determines their market competitive advantage; The new product value and environmental value generated by the symbiotic system are the returns on investment in the logistics system and the driving force for the long-term development of the system. The two have a "cost-benefit" symbiotic value creation effect.

4. Construction and simulation of system dynamics model

System Dynamics (SD) is adept at handling high-order, nonlinear, and multi feedback complex system problems, making it highly suitable for simulating the long-term dynamic behavior of waste logistics-resource symbiotic coupling systems under the influence of the "dual carbon" policy. This study used Vensim software to establish a system dynamics model [9][10].

4.1 System boundaries and model assumptions

Selecting a typical industrial area as the simulation object, the system boundary includes key emission enterprises in the main energy, metallurgy, chemical, and building materials industries, enterprises specializing in waste collection and transportation, and resource utilization enterprises within the area; Its main assumptions include: a time range of 2020-2040 and a simulation step size of 0.25 years; The number and production scale of enterprises in the region remain relatively stable throughout the entire simulation interval, and the economic growth of the region remains stable; The exogenous determination of technological progress; Policy shocks are introduced during certain periods.

4.2 System flow diagram and main variables

Following the methods and steps of system dynamics modeling, starting from the issue of regional industrial waste management, by identifying key state variables, establishing causal feedback, defining rate variables and auxiliary variables, and finally integrating them into a visual model (i.e. system dynamics flow chart, see Figure 1), it is used to simulate and analyze the complex relationship between regional industrial waste management and resource recycling, carbon emissions, and economic costs, laying the foundation for subsequent simulation and policy scenario analysis.

The flow chart includes waste logistics subsystem (including collection, transportation, and disposal of waste), resource sharing subsystem (waste turning into treasure to generate resource products, driving economic benefits and technological progress), external factor subsystem (GDP growth, policy intervention), and emission and cost accounting subsystem. The subsystems are coupled through material flow, energy flow, information flow, and value flow. The waste logistics subsystem is the backbone, the resource sharing subsystem is the branch, the emission and cost accounting subsystem is the evaluation module, and the external factor subsystem is the driving and regulating module.

Key state variables: waste generation, waste collection, landfill disposal, resource utilization, resource utilization products, total system cost, total carbon emissions, and resource utilization technology level.

Rate variables: collection rate, proportion of disposal methods.

Auxiliary variables: transportation carbon emissions, treatment carbon emissions, landfill carbon emission factors.

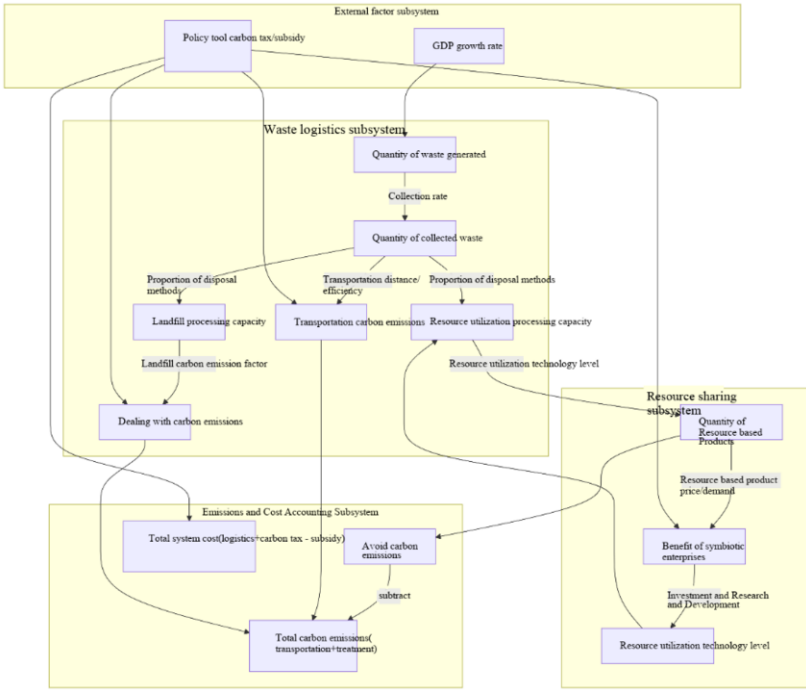


Figure 1. System dynamics flow diagram

4.3 Model equations and model parameters

In system dynamics modeling, there is a close logical correspondence between model equations and system dynamics flow diagrams. A flow chart is a visual representation of the structure of a model, while equations are the mathematical implementation of that structure. Based on the logical relationship between variables presented in Figure 1, the main model equations are as follows:

· Waste generation=INTEG (waste generation * waste growth rate, initial value)

· Waste growth rate=GDP growth rate * elasticity coefficient

· Amount of waste collected =amount of waste generated * collection rate

· Resource utilization processing capacity=amount of collected waste * resource utilization rate

· Resource utilization rate=initial resource utilization rate+IF THEN ELSE (Time>2025, (technology impact coefficient+policy impact coefficient), initial value)

· Transportation carbon emissions=amount of waste collected * average transportation distance * transportation carbon emission factor

· Avoidant carbon emissions=Resource utilization capacity * Avoidant carbon emission factor

· System net carbon emissions=transportation carbon emissions+treatment carbon emissions - avoided carbon emissions

· Carbon tax cost=system net carbon emissions * carbon tax rate

· Total system cost=total logistics cost+carbon tax cost - subsidy income

Model parameters are the key bridge connecting theoretical models with the real world. Model parameters are determined through literature research, historical data fitting, and expert consultation.

4.4 Simulation scenario design

Design the following simulation scenarios based on the actual situation of regional industrial waste management.

·Baseline scenario (BAU): Continuing in the current direction without new strong 'dual carbon' policies.

·Single carbon tax scenario (S1): Starting from the fifth year, a carbon tax that increases year by year will be levied.

·Subsidy incentive scenario (S2): Starting from the fifth year, subsidies will be provided for resource utilization investment and technology development.

·Technological Enhancement Scenario (S3): Starting from the fifth year, there has been progress and improvement in waste disposal technology.

·Combination policy scenario (S4): Parallel collection of carbon taxes and implementation of subsidies.

5. Simulation and result analysis

Based on the above simulation scenario design, use Vensim software for simulation and result analysis.

5.1 Baseline scenario (BAU) simulation results

In the BAU scenario, the system develops along the existing path, as shown in Figure 2.

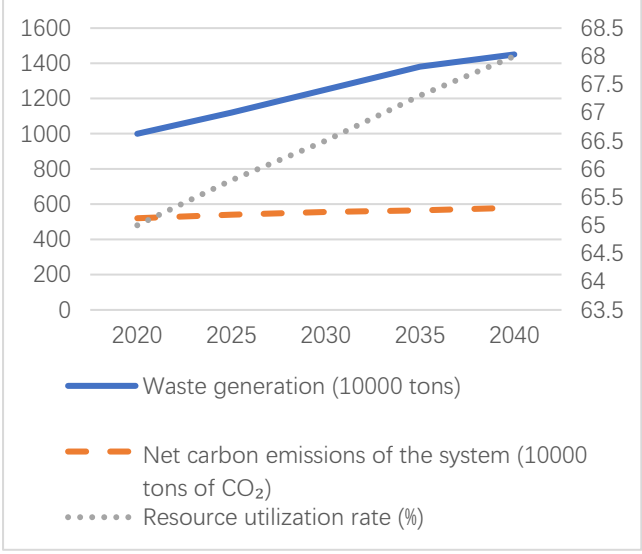


Figure 2. Key variable trends under baseline scenario (BAU) (2020-2040)
Note: The data in the figure is simulated data, aimed at revealing inherent patterns and trends.

As shown in Figure 2, due to economic development (assuming an annual GDP growth rate of 5.5%), the amount of waste generated will gradually increase at a nearly linear rate from 10 million tons to 14.5 million tons by 2040; Without external intervention, the rate of resource utilization can only rely on the inherent laws of its own market (assuming a natural growth rate of 0.15% per year for technology) to gradually increase to 68% by 2040; The net carbon emissions of the entire system did not decrease compared to 5.2 million tons in 2020 during the simulation period, but showed a slow increasing process, reaching nearly 5.8 million tons. This clearly violates the deep emission reduction requirements of the "dual carbon" policy, indicating that relying solely on self optimization methods of the current development path system cannot achieve emission reduction, and appropriate active intervention measures must be taken to respond [11]

5.2 Comparison of simulation results in various scenarios

The simulation results of net carbon emissions of the system under various scenarios are shown in Table 1.

Table 1. Simulation comparison of net carbon emissions of the system under various scenarios (2020-2040)

Year	BAU	Carbon Tax(S1)	Subsidy(S2)	Technology(S3)	Collaboration(S4)
2020	520	520	520	520	520
2025	540	535	530	538	532
2030	555	530	510	545	490
2035	565	510	470	540	410
2040	580	495	430	535	320

Note: The data in the table is simulated data, aimed at revealing inherent patterns and trends.

Analysis:

·S1 (Carbon Tax): Carbon tax policies can increase carbon taxes year by year, promoting a gradual reduction in the system's carbon emissions. After 2025, there will be a turning point in net carbon emissions, but the decrease will not be significant, and it will only drop to about 4.95 million tons by 2040. The role of carbon tax policy is mainly to suppress high emission incineration and landfill treatment methods, but the optimization of logistics and technological progress is an indirect and slow process.

·S2 (subsidy): Subsidy measures can achieve the most significant and rapid increase in resource utilization rate. Due to the direct benefits that enterprises can gain, the resource utilization rate will increase in a short period of time (simulation results show that it will reach 85% by 2040). The amount of “avoided carbon emissions” will also be significant, and ultimately the total net carbon emissions will decrease to 4.3 million tons by 2040. However, this measure will bring significant financial pressure to the government.

·S3 (Technology): Relying solely on the path of technological progress shows a characteristic of “slow first and then fast”, and in the first 10 years, there was no significant reduction in emissions, and due to the fact that the technology itself requires research and development investment as well as operational energy consumption, it may be slightly lower than the BAU scenario; However, after 2035, due to the accumulation of a large amount of technology, a significant breakthrough was achieved in 2040, and the emission reduction effect was significantly enhanced. However, the final effect (5.35 million tons in 2040) is still inferior to the S1 and S2 schemes.

·S4 (Collaborative Optimization): The most powerful emission reduction policy is collaborative policy, where carbon tax provides sustained emission reduction pressure,

subsidies support symbiotic industries and technology research and development [12], and information platform construction can maximize logistics benefits. Under this collaborative policy, the emission reduction curve presents a "steep and sustained" trend, which will begin to outperform any individual policy after 2030. By 2040, net carbon emissions will be reduced to only about 3.2 million tons, which is about 45% less than BAU. It is currently the only policy combination that can achieve the regional level "carbon peak" goal and lead to "carbon neutrality".

Under various scenarios, the simulation results of the total system cost (assuming that logistics costs remain unchanged and only considering cost changes caused by policies) are shown in Table 2.

Table 2. Comparison of total system cost simulation under various scenarios (2020-2040)

Year	BAU	Carbon Tax(S1)	Subsidy(S2)	Technology(S3)	Collaboration(S4)
2020	100	100	100	105	103
2025	110	125	135	115	130
2030	120	145	155	125	140
2035	130	160	170	130	145
2040	140	170	185	135	150

Note: The data in the table is simulated data, aimed at revealing inherent patterns and trends.

Analysis:

·S1 (carbon tax): Overall, the cost of the system is relatively high because the company has to pay for the actual carbon emission costs incurred.

·S2 (subsidy): The largest system cost comes from government financial expenditures.

·S3 (technology): The initial investment is high (research and development costs are high), but due to the improvement of production efficiency and resource utilization rate, the rate of increase in operating costs gradually slows down in the later stage. In the long run, this is the most reasonable path.

·S4 (Collaborative Optimization): Although this cost is higher than BAU and S3, it is much lower than simple S1 or S2. The main reason is that the system has avoided the adverse effects of overly strict policies and achieved an ideal state in terms of cost-effectiveness. If the environmental pollution avoided and the long-term strategic benefits obtained as a result are also taken into account, this is undoubtedly the best.

6. Conclusion and policy recommendations

6.1 Research conclusion

Based on the system dynamics method, a model is established to simulate and analyze the coupling mechanism of the regional industrial waste logistics- resource symbiosis system under the "dual carbon" target. The research conclusions are as follows:

(1) There are complex correlations between material flow, energy flow, information flow, and value flow in the waste logistics system and resource symbiosis system. Separating and managing the two separately will inhibit the full potential of carbon reduction in the system.

(2) From the simulation results, it can be seen that a single policy (such as carbon tax or subsidy) often only affects one link of the system, and sometimes even has a counterproductive effect, causing high cost investment or reducing the system's full emission reduction, without achieving comprehensive governance.

(3) Collaborative governance is the only way to achieve the "dual carbon" goal. The "dual carbon" goal is a systematic project that requires the comprehensive use of various policy tools such as pricing tools (carbon tax), fiscal tools (subsidies), technological tools (research and development), and management tools (information platforms) [13]to form a combination of punches, achieving a "win-win" situation of reducing total carbon emissions and improving resource utilization rates.

(4) The implementation of policies is temporal. Simulation shows that technology policies take effect slowly but have strong momentum, while economic policies have the opposite effect. Therefore, in real life, a combination of short-term and long-term measures should be taken, including immediate economic incentives such as carbon taxes and subsidies, as well as long-term investment in technology research and infrastructure construction.

6.2 Policy suggestions

Based on the research findings, the following suggestions are proposed:

(1) Promote system integration and intelligent management. Coordinate the construction of a regional unified industrial waste information management platform, break down logistics and symbiotic information barriers between regions, and carry out intelligent matching, full lifecycle traceability, and optimized scheduling work.

(2) Implement precise and coordinated policy combinations. The funds raised through carbon pricing (taxation or trading) will be specifically used to subsidize low-carbon transportation vehicles (new energy vehicles), research and development of key technologies in the symbiotic industry chain, etc., to "use carbon to control carbon" and form a long-term mechanism.

(3) Coordinate infrastructure planning. In regional planning and the construction of ecological industrial parks, logistics hubs (transfer stations, sorting centers) [14] and symbiotic projects (such as resource-based factories) should be planned simultaneously to shorten logistics distances and save transportation energy consumption.

6.3 Research shortcomings and prospects

Due to the difficulty in obtaining real data, the simulation results have not been validated. The main contribution of this study lies in theoretical modeling and policy scenario exploration. The predictive effectiveness of the model still needs to be more fully validated in specific practice. Future research will focus on collaborating with local governments or eco industrial parks to apply this model to specific policy-making processes. By tracking implementation effects, the model will be empirically calibrated and optimized. Additionally, establish specialized databases to support longer-term dynamic research.

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Optimal Decisions on "Insurance & Elderly Care Communities" Under the Wave of Aging

Shiwen XU[a], Jingyi FENG[b,1] and Zhongnuo YANG[c]
[a]*School of International Finance, University of International Business and Economics, Beijing 100105, China*
[b]*School of Insurance, Central University of Finance and Economics, Beijing 102206, China*
[c]*Ernst + Young (China) Consulting Co., Ltd., Beijing Branch, Beijing 100738, China*

Abstract. Against the backdrop of an accelerating aging population and an increasing number of empty-nest elders, the emerging "insurance & elderly care community" model has become one of the key considerations for the elderly in their retirement planning. Based on the classic life-cycle consumption-savings model, this paper introduces the "insurance & elderly care community" and discusses residents' purchase decisions of related products and their decisions to move into the elderly care community, and explores how subjective preferences and objective income levels influence residents' choices. The numerical simulation results show that the higher the overall income of residents before the age of 50, the more inclined they are to purchase related products to obtain the qualification to move into the elderly care community; the lower the degree of risk aversion, the higher the recognition of the elderly care community, or the lower the income level after retirement among those who have purchased related products, the more likely residents are to choose to move into the elderly care community.

Keywords. Population aging; life cycle model; lifetime annuity; insurance & elderly care community

1. Introduction

With the successive retirement of the baby boomers, China's aging population has reached an unprecedented level. According to data released by the National Bureau of Statistics, by the end of 2021, the number of people aged 60 and above across the country reached 267 million, accounting for 18.9% of the total population. It is projected that by around 2035, the number of people aged 60 and above will exceed 400 million, accounting for more than 30% of the total population.

In the context of an aging society brought about by longevity and low birth rates, coupled with the mobility of jobs resulting from economic development, the phenomenon of "empty-nest elders" in China has become increasingly common. According to information from the regular press conference of the Ministry of Civil

[1] Corresponding Author: Jingyi FENG, Email: 2664486214@qq.com ; Central University of Finance and Economics, Beijing 102206, China

Affairs in the fourth quarter of 2022, the proportion of empty-nest elders among the elderly in our country has exceeded 50%. Due to the absence of children or the children not being around, empty-nest elders will have to choose an independent and self-reliant lifestyle for their old age. During this process, in addition to material life, the needs of the elderly population in terms of care and health, psychological comfort, and social participation have also become increasingly prominent.

In this context, many insurance companies, based on the alignment of their long-term investment needs and the complementarity of their pension insurance business content, have combined elderly care services with insurance products, vigorously developing the "insurance & elderly care community" business, and planning to establish high-quality elderly care communities that integrate medical care and elderly care. The aim is to simultaneously meet the physical, material and spiritual needs of the elderly population. The selection of the "insurance & elderly care community" model is divided into two stages: obtaining the qualification for residence and choosing to reside. When the cumulative purchase of insurance products exceeds a certain amount, residents can obtain the right to reside in the insurance-based elderly care community and receive insurance payouts at the agreed age; after reaching a certain age, residents can choose to reside in the insurance-based elderly care community (but they need to pay monthly fees on schedule), or they can choose not to reside in the insurance-based elderly care community. Taking a well-known elderly care community as an example, when the premiums of the insurance products purchased by residents exceed 2 million yuan, they can obtain the right to reside; then they can choose whether to reside in the elderly care community before the age of 80.

Because the associated insurance products have made financial arrangements for the elderly residents' retirement life in advance, the insurance-based elderly care communities have greatly met the elderly population's needs for their retirement life. The "insurance & elderly care community" model has received much attention. However, the high premiums and monthly fees after moving in have also deterred many residents. So, should residents purchase insurance products to obtain the right to move in? Should they choose to move in? Which residents should choose the insurance-based elderly care community? And how should insurance companies optimize the "insurance & elderly care community" model?

In response to the above issues, this paper conducts research based on the life cycle consumption-savings model. By introducing lifelong pension insurance and elderly care communities into the model, this paper establishes a life cycle optimal consumption, savings, pension insurance and entry into elderly care community decision-making model for residents. Based on the actual data of our country, this paper calibrates the parameters in the model and solves the model using numerical methods.

2. Literature Review

How residents should arrange for their old age is not only a significant theoretical issue but also of great practical significance. The arrangement of old age care mainly includes two aspects: the arrangement of funds for old age care and the arrangement of the way of old age care. The arrangement of funds for old age care mainly refers to the savings and investment strategies during the working period and the retirement period; the arrangement of the way of old age care mainly refers to the choice of lifestyle during the retirement period.

The planning of pension funds has been extensively studied by many scholars. Based on the life-cycle consumption-savings model, many scholars have investigated issues related to residents' pension savings [1], pension asset allocation [2], pension property configuration [3], and the purchase of pension insurance [4], and have obtained many meaningful conclusions.

However, the arrangements for elderly care have not been fully studied. Elderly residents prefer to live at home and do not want to leave their homes [5]. However, as their independent living abilities gradually weaken, elderly residents in their advanced age have to choose to go to professional institutions for care, such as nursing homes or senior communities. Therefore, existing literature mainly studies the factors influencing elderly residents' admission to nursing institutions, including positive factors that encourage admission and negative factors that hinder it. On the positive side, scholars generally believe that physical decline or the need for care [6, 7], the decline in the physical condition of the spouse [8] or the death of the spouse [9], large housing or poor housing conditions [8, 10], often feeling lonely, isolated, personally unsafe, depressed [8, 11], excessive economic burden of home-based care, and insufficient wealth [7], will make elderly residents tend to enter nursing institutions. At the same time, the safe and comfortable living environment, excellent care quality, good social interaction opportunities, and comfortable ecological environment of nursing institutions are also positive factors for elderly residents to enter nursing institutions [12]. On the negative side, caring for the spouse, not being independent, organizing family activities, etc. are family responsibilities of the elderly [13], the high cost of admission to nursing institutions [14], the frustration and loneliness brought by admission to nursing institutions [15], the loss of life flexibility [13], and living away from the residence of their children [16], all these factors will hinder elderly residents from entering nursing institutions.

The above literature has studied the influencing factors of residents' choice of retirement methods from various perspectives, providing useful ideas for this article. Given that the "insurance & elderly care community" model can not only provide financial arrangements for residents' retirement but also offer methods for it, this article, based on the life cycle model, discusses residents' purchase decisions and occupancy decisions regarding insurance-based elderly care communities and related products, and explores how subjective preferences and objective income factors affect residents' choices of the "insurance & elderly care community" model.

Similar to this literature, this paper also studies the influencing factors of residents' choice of living in elderly care communities from the perspectives of economic factors and psychological factors. However, compared with existing literature, this paper has the following differences: On the one hand, this paper provides a theoretical analysis framework for residents' "insurance & elderly care community" decision-making based on the life cycle consumption-savings model, and theoretically analyzes the influencing factors of the residents' optimal decision. While existing literature mainly conducts research based on empirical models. On the other hand, this paper refers to the approach of incorporating additional parameters into the utility function to characterize the "additional expectation" of moving into an elderly care community [17], quantifies and monetizes the factors influencing residents' choice of living in elderly care communities, and provides references for residents' admission decisions and the establishment decisions of insurance companies.

3. Model assumption

3.1. Life Cycle and Preferences

In the model, this paper assumes that residents start working at the age of x_0 and retire at the age of x_R ; before retirement, residents can decide whether to purchase products related to the elderly care community before the age of $x_R - 10$ (inclusive); after retirement, residents whose pension contributions have been completed and whose ages are x_R between the ages of $x_R + 10$ and are determined to decide whether to move into the elderly care community. The maximum age of residents is the age of x_T. Residents face uncertainty regarding survival, and is used to represent the probability that a resident with an age of t survives until the age of $t + 1$.

The utility of residents comes from consumption during their lifetime and bequests upon their death. Before moving into the senior living community， the consumption utility function adopts the constant relative risk aversion (CRRA) form $U(C_t) = \frac{{C_t}^{1-\gamma}-1}{1-\gamma}$, where γ represents the risk aversion coefficient, and C_t represents the consumption amount of residents in the current period. If a resident passes away between the ages of t and $t + 1$, the savings and interest will be inherited as an inheritance. After moving into a senior care community, as long as the resident pays the monthly fee, all their basic needs such as food, clothing, housing and transportation will be provided by the community, and the out-of-pocket expenses will be very low. Therefore, this paper assumes that the amount of consumption for each period by residents after moving into the elderly care community is exogenously given. Based on previous research [17], this paper sets the utility form for residents based on fixed consumption expenditure as $U^L(\bar{C}) = (\theta^L)^{-\gamma}\frac{(\bar{C}+\kappa^L)^{1-\gamma}-1}{1-\gamma}$, where $\bar{C}$ represents the fixed consumption level after moving into a senior living community. Additionally, compared to the traditional form, two more new parameters are introduced. In economics, these two parameters represent the manifestation of the potential benefits brought by moving into a senior living community in terms of utility: θ^L as the multiplier and its value implies that during the period of moving into the senior living community, due to the change in living environment and residents' preferences for it, the utility of each period for residents is $(\theta^L)^{-\gamma}$ times the utility of the same consumption level before moving in; and κ^L measures to what extent residents consider $\bar{C}$ something as a necessity or a luxury.

Based on previous research [17], the form of residents' bequest utility is assumed as $B(S_t) = (\theta^{Beq})^{-\gamma}\frac{(S_t\times(1+i)+\kappa^{Beq})^{1-\gamma}-1}{1-\gamma}$, where θ^{Beq} measures marginal utility, while κ^{Beq} measures to what extent residents view bequests as necessities or luxuries.

3.2. The process of residents' income

Residents continue to work before retirement and receive wage income in each period. Based on previous research [18], this paper assumes that residents' income is uncertain and represents their income before retirement as $\ln Y_{xt} = \ln W_{xt} + z_{xt}$,where Y_{xt} represents the income of residents aged x in period t and W_{xt} represents the average income level of residents aged x in period t, which is the deterministic part of the residents' wages. Based on previous research [19], W_{xt} is determined by $W_{xt} = W_{x_0,0} \times e_x \times (1+\varepsilon)^t$, where $W_{x_0,0}$ represents the average salary of residents who just

started working at the initial time (with an age of x_0 years), e_x represents the human capital level of resident at the age of x; ε represents the growth rate of salary income for residents of different ages over time.

Beside the deterministic part, the resident income has a certain degree of uncertainty z_{xt}, which represents the fluctuation of wage of residents aged x in the tth period. Assuming that the random shocks faced by residents have a certain lag effect, this paper uses a first-order autoregressive process to describe it, that is $z_{xt} = \rho z_{(x-1)(t-1)} + \varepsilon_{xt}$, where $z_{x_0 0}$ follows a normal distribution with a mean of 0 and a variance of σ_z^2, which is represented as $z_{x_0 0} \sim N(0, \sigma_z^2)$; ε_{xt} measures the impact of past random shocks on current income, andε_{xt}represents the fluctuation of the logarithmic income in the current period. This paper assumes that it is an independent and identically distributed random variable and follows a normal distribution with a mean of 0 and a variance of σ_ε^2.

After retirement, residents receive pensions. The pension income is calculated according to China's basic pension insurance system, consisting of two parts: the pooled account pension and the individual account pension. The pooled account pension is based on the average salary in the previous year and the indexed average contribution salary of each period of the individual, and is calculated according to the years of contribution; the individual account pension is based on the accumulated amount in the individual account and is calculated according to the number of payment months.

In the model, this paper takes residents whose age at time 0 is x_0 years old as the research subjects. Their age in the t period is $x_0 + t$ years old. This paper uses Y_t to represent the wage income of residents represented by t years old, when $t < x_R$, $Y_t = Y_{t,t-x_0}$,when $t \geq x_R$, $Y_t = Y_R$.

3.3. Life annuity and elderly care community setup

The associated insurance products for the "insurance & elderly care community" business mainly consist of annuity insurance, whole life insurance and endowment insurance. Since this paper focuses on studying the issue of residents' elderly care and pays attention to the cash flow problem of elderly residents, it is assumed in this paper that the form of the associated insurance products for the elderly care community is a deferred whole life pension for 10 years. That is, the policyholder needs to complete the payment for 10 years before retirement, and then can receive the pension every period during the survival period after retirement. According to this arrangement, the maximum age for residents to purchase insurance is $x_R - 10$ years old. Thus, before the age of $x_R - 10$, residents can decide each period whether to purchase a life annuity, and they can only do so once.

Furthermore, it is assumed that the purpose of residents purchasing pension annuities is to obtain the eligibility for entering the elderly care community. Therefore, the cumulative premiums need to be higher than a certain threshold. This paper assumes that the premium paid each period by residents G exactly meets the threshold requirement, and the pension payout amount brought by the payment is determined according to the actuarial balance equation. Resident purchased an annuity at the age of $b(x_0 \leq b \leq x_R - 10)$, and the payout amount received A_b is determined by the following formula.

$$G\sum_{k=0}^{9} {}_{k}p_b(1+r)^{-k} = A_b(1+\delta)\times {}_{x_R-b}p_b \times \sum_{k=0}^{x_T-x_R} {}_{k}p_{x_R}(1+r)^{-k-(x_R-b)} \quad (1)$$

where ${}_{n}p_m$represents the probability that a resident aged m survives for n years, which is ${}_{n}p_m = \prod_{u=m}^{m+n-1} p_u$; δ is the additional cost rate, and r is the pricing interest rate for the annuity.

Under the condition that the associated products have been purchased, retired residents can choose whether to move into the elderly care community between the ages of x_R and $x_R + 10$ .After moving into the elderly care community, the residents' consumption expenditure for each period starting from the current period will be fixed at $\bar{C}$. In addition, the residents will not make any additional value-added consumption.

3.4. The optimal decision-making process of residents

Residents face different decisions at different age stages. Residents aged x_0 to $x_R - 10$ make decisions on purchasing pensions and consumption-savings; those who have not purchased pensions only make consumption-savings decisions. Residents who have purchased pensions complete their contributions at the age of x_R , and then make decisions on whether to move to a senior care community and on consumption-savings decisions during the periods from x_R to $x_R + 10$. Based on the residents' current status and previous decisions, this paper presents the optimal decision-making problems faced by various groups of people in different situations.

(1) Residents' decisions on purchasing associated pensions ($x_0 \le t \le x_R - 10$)

Firstly, for those residents who have not purchased an annuity by the age of $t-1$ ($x_0 \le t \le x_R - 10$) they can choose whether to purchase a life annuity based on their utility maximization. The optimization problem for such residents is

$$V_t(S_{t-1}, Y_t, n_{t-1} = 0) = \max\{V_t^B(S_{t-1}, Y_t, n_{t-1} = 0), V_t^{NB}(S_{t-1}, Y_t, n_{t-1} = 0)\} \quad (2)$$

where V_t represents the maximum lifetime expected utility of the resident at the age of t, V_t^B represents the maximum lifetime expected utility of the resident when purchasing the associated annuity at the age of t, and V_t^{NB}represents the maximum lifetime expected utility of the resident when not purchasing the associated annuity at the age of t. n_t =1 indicates that the resident at the age of t has chosen to purchase the annuity in the current period, and $n_t = 2, \dots, 11$ represents that the resident at the age of t has completed the cumulative contributions up to the current period (including the current period) plus 1. When n_t takes its first value of 11, it indicates that the resident has completed 10 contributions before the current period, so from the next period onwards, the value of N no longer changes with time. In particular, $S_{x_0-1}(1+R_{x_0-1})$represents the initial wealth, and n_{x_0-1} represents the initial insurance status.

If residents choose to purchase an annuity, the lifetime utility V_t^B is used to represent it. The optimization problem for the residents becomes

$$V_t^B(S_{t-1}, Y_t, n_{t-1} = n) = \max_{C_t} U(C_t) + \beta p_t V_{t+1}^B(S_t, Y_{t+1}, n_t) + \beta(1-p_t)B(S_t) \quad (3)$$

$$s.t.\ \ S_{t-1}(1+R_{t-1}) + Y_t = C_t + S_t + G \times 1_{\{1 \le n_t \le 10\}} \quad (4)$$

$$n_t = \min\{n+1, 11\}, \quad 0 \le n \le 11 \quad (5)$$

where R_t represents the interest rate at the age of t, and $1_{\{\cdot\}}$ is the indicator function. In the budget constraint equation (4), the left side of the equation represents the disposable wealth of the residents, which is composed of the principal and interest from the savings in the previous period and the income from work; the right side of the equation represents that the residents will use the wealth for current consumption C_t and savings S_t, and the premium $G \times 1_{\{1 \le n_t \le 10\}}$ is an indicator variable indicating whether the residents are in the payment period.

If the residents choose not to purchase an annuity in the current period, they will only make consumption-savings decisions this period. For those under the age of $x_R - 10$, they can still choose whether to purchase a life annuity in the next period. The optimization problem for such residents is

$$V_t^{NB}(S_{t-1}, Y_t, n_{t-1} = 0) = \max_{C_t} U(C_t) + \beta p_t V_{t+1}(S_t, Y_{t+1}, n_t = 0) + \beta(1 - p_t)B(S_t) \quad (6)$$

$$s.t. \;\; S_{t-1}(1 + R_t) + Y_t = S_t + C_t \quad (7)$$

(2) The consumption and savings decisions of residents who have not purchased annuities ($t > x_R - 10$)

For residents who have never purchased related products before the age of $x_R - 10$, they will only make consumption-savings decisions in the future. The optimization problem for this type of residents is as shown in equations (6) and (7). The boundary condition faced by this type of residents in the last period is

$$V_T^{NB}(S_{T-1}, Y_T, n_{T-1} = 0) = \max_{C_T} U(C_T) + \beta B(S_T) \quad (8)$$

$$s.t. \;\; S_{T-1}(1 + R_T) + Y_T = S_T + C_T \quad (9)$$

(3) The consumption and savings decisions of residents who have purchased annuities ($t > x_R - 10$)

Residents who have purchased an annuity go through three stages in the decision-making process after the purchase: before retirement, the decision-making period for entering a senior living community, and the period after entering the senior living community.

Before retirement ($x_R - 10 < t < x_R$). For residents who have not yet retired and have purchased an annuity, the minimum contribution period for their annuity is 1 year and the maximum is 10 years (i.e., the contribution period has been completed). The optimization problem for this type of residents is given by equations (3)-(4), and

$$n_t = \min\{n + 1, 11\}, \;\; t - x_R + 10 \le n \le 11 \quad (10)$$

Period for entering a senior living community ($x_R \le t < x_R + 10$). From the time of retirement until the age of $x_R + 10$ residents who have purchased associated annuities make the decision on whether to move into a senior care community. That is: for those who have purchased an annuity at the age of $t - 1$ ($x_R \le t < x_R + 10$) but have not chosen to move into an insurance-based senior care community, they can choose whether to move into a senior care community at the age of t. The optimization problem for such residents is

$$V_t^B(S_{t-1}, Y_t) = \max\{V_t^{BL}(S_{t-1}, Y_t), V_t^{BNL}(S_{t-1}, Y_t)\} \quad (11)$$

where V_t^{BL} represents the maximum lifetime expected utility for residents who have purchased the associated annuity and move into the elderly community at the age of t. V_t^{NBL} represents the maximum lifetime expected utility for residents who have purchased

the associated annuity but do not move into the elderly community at the age of t. Since the residents' decisions on purchasing the associated products were made before the age of 50 and the payment was completed before retirement,$n_{t-1} = 11$ always holds true, and thus it is not reflected in the subsequent formulas.

If residents choose to live in a senior care community, as mentioned above, they will experience improvements in terms of utility and health after moving into the community. For retired residents who have moved into the community, their per-period consumption $C_t = \bar{C}$ is a fixed value, and thus there is no longer a need to make an optimal decision between consumption and savings. At this point, the lifetime utility of the residents is calculated using the following formula:

$$V_t^{BL}(S_{t-1}, Y_t) = U^L(\bar{C}) + \beta p_t^L V_{t+1}^{BL}(S_t, Y_{t+1}) + \beta(1 - p_t^L)B(S_t) \tag{12}$$

$$S_{t-1}(1 + R_{t-1}) + Y_t + A_b = S_t + \bar{C} \tag{13}$$

where, p_t^L represents the survival probability after moving into the elderly care community, and $A_b$represents the payout amount of the associated insurance annuity purchased.

If residents choose not to live in the elderly care community, they still need to make consumption-savings decisions in the current period. If they are under the age of $x_R + 10$, they can still choose whether to live in the elderly care community in the next period. The optimization problem for such residents is

$$V_t^{BNL}(S_{t-1}, Y_t) = \max_{C_t} U(C_t) + \beta p_t V_{t+1}^{B}(S_t, Y_{t+1}) + \beta(1 - p_t)B(S_t) \tag{14}$$

$$S_{t-1}(1 + R_{t-1}) + Y_t + A_b = S_t + C_t \tag{15}$$

After the occupancy decision period ($t \geq x_R + 10$). For residents who have purchased an annuity and have chosen to live in an insurance-based elderly care community, the life-cycle utility will still be calculated according to equations (12) - (13) after they reach the age of $x_R + 10$. The boundary conditions faced by this group of residents in the final period are

$$V_T^{BL}(S_{T-1}, Y_T) = U^L(\bar{C}) + \beta B(S_T) \tag{16}$$

$$S_{T-1}(1 + R_{T-1}) + Y_T + A_b = S_T + \bar{C} \tag{17}$$

For those residents who have purchased annuity but ultimately did not choose to move into a senior living community, their decisions will only involve consumption and savings after the age of $x_R + 10$. The optimization problem for such residents is

$$V_t^{BNL}(S_{t-1}, Y_t) = \max_{C_t} U(C_t) + \beta p_t V_{t+1}^{BNL}(S_t, Y_{t+1}) + \beta(1 - p_t)B(S_t) \tag{18}$$,

and the budget constraint (13) is also included. The boundary condition faced by this type of residents in the final period is

$$V_T^{BNL}(S_{T-1}, Y_T) = \max_{C_T} U(C_T) + \beta B(S_T) \tag{19}$$

$$S_{T-1}(1 + R_{T-1}) + Y_T + A_b = S_T + C_T \tag{20}$$

As shown in the above model, residents' choices regarding the "insurance & elderly care community" model involve multiple conditional segmented decisions, and the

display solution cannot be obtained. Therefore, referring to previous research [17, 20], this paper uses numerical methods to solve the problem.

4. Parameter Calibration

This section calibrates and sets the parameters in the model. On the one hand, this paper sets common parameters with reference to existing literature, such as the subjective discount factor and risk aversion coefficient. On the other hand, this paper estimates parameters based on actual data and current systems: for example, the wage process is estimated using data from the China Family Panel Studies (CFPS), and parameters related to insurance products are set in accordance with relevant regulations in the insurance industry.

4.1. Residents' Life Cycle and Preference Parameters

In the model, this paper assumes that residents enter the workforce at the age of 25 and retire at 60. Before retirement, residents may decide whether to purchase elderly care community-related products before reaching the age of 50 (not including 50). After retirement, residents aged 61-70 who have completed their annuity payments can decide whether to move into an elderly care community. The maximum age of residents is set at 100. The survival probability p_t of residents is calibrated based on the "Experience Life Table of China's Life Insurance Industry (2010-2013)", and the average survival probability of males and females in the elderly care business table is adopted as the mortality rate of residents in the model.

Following previous research [21], this paper sets the discount factor β to 0.98. Based on previous research [19, 22], the range of residents' relative risk aversion coefficient γ is set at 0.41-0.68. Parameters related to bequest utility are set with reference to previous literature [23], i.e.,$\theta^{Beq} = 1.09,\ \ \kappa^{Beq} = 7830$.

This paper uses utility-related parameter (θ^L, κ^L) to represent residents' subjective preference for insurance-based elderly care communities. The value of (θ^L, κ^L) significantly affects residents' decisions to purchase associated annuities and move into such communities. Due to the lack of microdata on purchasing these annuities and moving in, this paper cannot calibrate it. Thus, it presents residents' decisions under various value scenarios of (θ^L, κ^L).

4.2. Residents' Income Parameter

This paper estimates parameters related to residents' income Y_{xt} based on CFPS data. First, following previous research [19], it estimates parameters for the deterministic component W_t of residents' pre-retirement work income. According to the "2020 Autumn College Graduates Employment Report", this paper assumes the initial wage W_t for residents entering the workforce at age 25 is set at 65,000 yuan. Using cross-sectional data on residents' age and income from CFPS 2018, after adjusting for inflation, a quartic polynomial of age is constructed to fit the human capital level parameter e_a for each age group. Based on the actual growth rate of average annual wages for employees in China's large and medium-sized enterprises from 2018 to 2020 (i.e., the nominal growth rate minus CPI), the annual growth rate ε of residents' wages over time is set at 6.5%.

Second, following previous literature [24, 25], this paper uses the minimum distance estimation method to estimate the wage shock parameters based on CFPS 2014, 2016, and 2018. The results are $\rho = 0.5887$, $\sigma_\varepsilon^2 = 0.4920$, $\sigma_z^2 = 0.7670$.

Following previous research [19], this paper estimates residents' retirement wages based on China's current basic old-age insurance system. The rates for the pooled account and individual account are set at 16% and 8%, respectively. Using the 2021 average annual wage of employees in national urban non-private units (released by the National Bureau of Statistics), the social average wage $\overline{Y}$ is set at 106,837 yuan. For pooled account pension calculation, the contribution period is 36 years (as the model assumes residents work ages 25-59). For individual account pension calculation, the benefit payment period is 139 months (~12 years, given the model's assumption of retirement at 60). Referring to the "2020 Annual Report on Entrusted Operation of Basic Old-Age Insurance Funds" (National Council for Social Security Fund), the individual account's investment return rate is set at 6.89% (the average annual return of basic old-age insurance funds).

In addition, with reference to the yield of China's one-year treasury bonds, this paper sets the single-period savings rate of return r_t for residents in any period of their life cycle at 2.5%.

4.3. Parameters of Lifetime Annuity and Elderly Care Community。

Referring to the admission criteria of real-world elderly care communities, this paper assumes that residents must pay a total premium of at least 2 million yuan to qualify for admission to insurance-based elderly care communities. Based on market reality, residents generally purchase pension annuities through installment payments after the age of 45. Therefore, this paper assumes a 10-year payment period for the lifetime annuity, with an annual premium G of 200,000 yuan.

In the annuity insurance pricing equation (7), this paper sets the survival probability for annuity pricing to be consistent with the resident survival probability specified earlier. With reference to regulatory provisions, this paper sets the pricing interest rate for annuity insurance at 3.5%. In addition, based on market reality, this paper sets the additional expense rate of the annuity product at 3%.

Based on the charging standards such as monthly fees and meal fees of existing insurance-based elderly care communities, the fixed consumption expenditure $\bar{C}$ for residents in each period during their stay in such communities is set at 250,000 yuan.

5. Numerical results and analysis

Basing on the above parameters, this paper uses numerical methods to solve the purchase decisions of residents for associated annuity products and the residence decisions of residents in insurance-based elderly care communities.

5.1. Residents' Decision on the "insurance & elderly care community" Model under Certain Income Conditions

This paper first analyzes the impact of residents' subjective preferences for insurance-based elderly care community services on the decision-making of the "insurance &

elderly care community" model. To highlight the conclusion, this paper assumes that residents' wage income does not fluctuate randomly, that is,$\rho = \sigma_\varepsilon = \sigma_z = 0$. Under this assumption, the decision made by residents regarding the "insurance & elderly care community" model is certain, and there is no uncertainty.

Specifically, given the income level, annuity pricing interest rate, and subjective preferences, whether residents purchase the associated annuity product and whether they move into the insurance-based elderly care community is certain. Therefore, by continuously changing the residents' subjective preferences (θ^L, κ^L) for insurance-based retirement communities, the critical values of (θ^L, κ^L) that determine whether residents will choose to move into or not move into these communities can be identified. This process yields a dividing line. Above the curve, the subjective preferences show that residents will all enter the insurance-based elderly care community; below the curve, the subjective preferences show that residents will not all enter the insurance-based elderly care community; at any point on the curve, the utility of residents' entry and non-entry into the insurance-based elderly care community is the same.

In the benchmark scenario of this paper, when $\gamma = 0.41$, even if residents choose not to enter the insurance-based elderly care community, they will still purchase the associated annuity product. Therefore, the change in subjective preferences (θ^L, κ^L)only affects the residents' decision on whether to enter the insurance-based elderly care community; when $\gamma = 0.545$ or $\gamma = 0.68$, residents will only purchase the associated annuity product as the source of the right to enter the insurance-based elderly care community when deciding to enter it. The results of the dividing line obtained by solving the $\gamma = 0.41, 0.545, 0.68$ are shown in Figure 1 respectively.

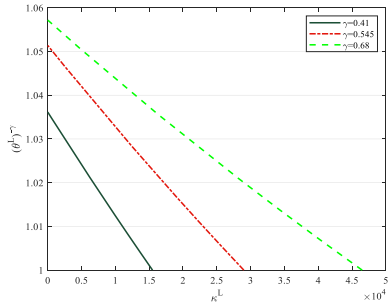


Figure 1. The critical line under different risk aversion coefficients.

Based on the results shown in Figure 1 and the intermediate results, we can draw the following conclusions:

First, for a given level of risk aversion, there exists a $((\theta^L)^{-\gamma}, \kappa^L)$-boundary line that slopes downward to the right. As the values of $(\theta^L)^{-\gamma}$ or κ^L increase, the motivation for residents to purchase associated annuities and move into retirement communities also strengthens. Moreover, the effects of the two can be mutually substitutable. Specifically, when $\kappa^L = 0, \gamma = 0.545$ is reached, the value of $(\theta^L)^{-\gamma}$on the boundary line is 1.0362. That is to say, for the same level of consumption, the utility of moving into an insurance-based elderly care community is 1.0362 times higher than that of not doing so, when $(\theta^L)^{-\gamma} = 1, \gamma = 0.545$ is reached, the value of κ^Lon the boundary line is 29,000. That is to say, when the additional equivalent consumption brought by moving into an

insurance-based elderly care community is higher than 29,000, residents will choose to move into the insurance-based elderly care community.

Second, the higher the risk aversion level of residents, the more the corresponding boundary line shifts to the upper right. This is because the marginal utility $\partial U^L(\bar{C}+\kappa^L)/\partial\kappa^L$ residents decreases as γ increases, resulting in an increasing κ^L value required to achieve the same utility level; Although in the case of a larger γ, the sensitivity of residents' utility to multiplier $(\theta^L)^{-\gamma}$ increases and leads to an increase in the slope of the curve, the increase in this growth is smaller than the increment of κ^L. Therefore, residents with a higher level of risk aversion will only choose to move into the insurance-based elderly care community when it can bring more additional utility.

These conclusions are largely consistent with expectations. That is, residents will purchase associated annuities and move into an insurance-based elderly care community only when it brings additional utility; the higher the level of risk aversion of residents, the more additional utility is required.

5.2. Residents' "insurance & elderly care community" decisions under random income

Based on the decision-making of residents under the above-mentioned certain income, this section further studies the "insurance & elderly care community" model decision-making of residents under random income conditions, and examines the impact of different state variables on residents' decisions regarding the purchase of associated pensions and their housing choices. Due to the randomness of wages, the future of residents is uncertain. Therefore, this paper simulates 10,000 paths based on the income process and discusses the optimal decisions under each path. In the subsequent chapters, this paper will take $\gamma = 0.545$ as the benchmark value.

For the sake of clarity, in this article, residents who purchased lifelong annuity products before the age of 50 and chose to live in an insurance-based elderly care community after retirement are defined as the first category of residents (Type I). Meanwhile, residents who purchased lifelong annuity products before the age of 50 but chose not to live in an insurance-based elderly care community after retirement are defined as the second category of residents (Type II); and residents who have never purchased lifelong annuity products before the age of 50 are defined as the third category of residents (Type III).

(1) Analysis of the proportion of three types of residents under the optimal decision

Under different values of (θ^L, κ^L), the proportion of the three types of residents in the population is shown in Figure 2.

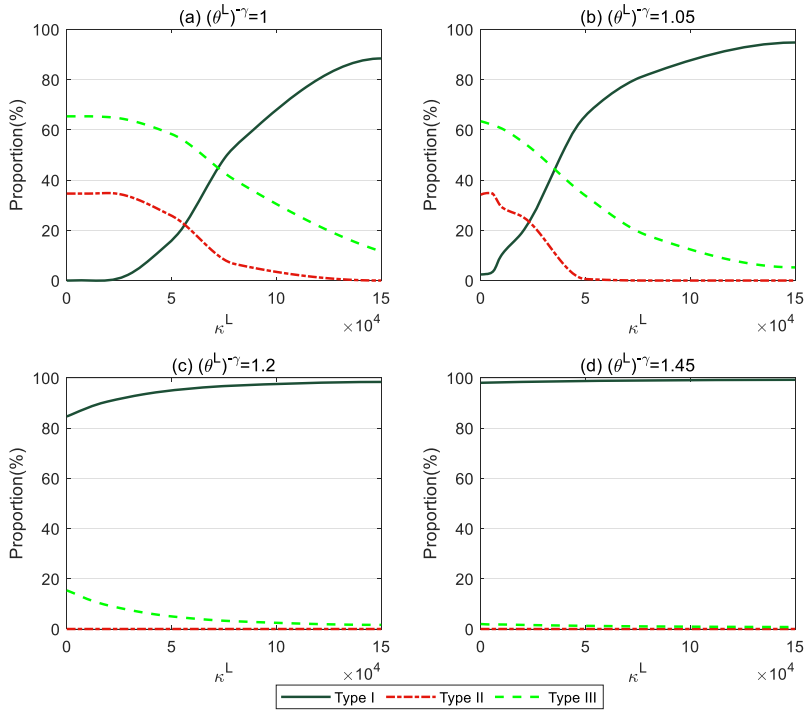


Figure 2. Proportion of the three groups under different subjective preference coefficients

The four subgraphs in Figure 2 respectively illustrate the impact of κ^L on the proportions of the three groups of people when $(\theta^L)^{-\gamma}$ is 1, 1.05, 1.2, and 1.45. As $(\theta^L)^{-\gamma}$ gradually increases or (and)κ^L gradually increases, the proportion of the first group of residents keeps rising, while the proportion of the third group of residents keeps decreasing. Particularly, at $\theta^L = 1, \kappa^L = 0$ (that is, when living in the elderly care community has no additional appeal in terms of utility for the residents), there are only the second and third groups of residents in the population, among which the proportion of the second group of residents is 34.62%, and the proportion of the third group of residents is 65.38%. Moreover, when$(\theta^L)^{-\gamma}$approaches infinity, the incentive of living in the elderly care community in terms of utility for the residents reaches its maximum. Currently, approximately 99.21% of the residents choose to purchase the associated annuity and live in the elderly care community, while only 0.79% of the residents do not purchase or only purchase the associated annuity due to insufficient income conditions. Therefore, Figure 2 shows the same conclusion as in the case of certain income, that is: as the subjective preference increases, the number of residents purchasing the associated annuity and living in the elderly care community keeps increasing, while the number of residents who do not purchase or only purchase the associated annuity keeps decreasing.

(2) Analysis of Income Characteristics of Various Residents

Income uncertainty is a cause of inconsistencies in residents' decision-making. This article takes $\theta^L = 1, \kappa^L = 80000$ as an example to further analyze the income characteristics of the above three types of residents.

Through simulation calculations, 4,246 people ultimately chose to purchase the associated annuity and move into the elderly care community (Residents of Type 1), 605 people only purchased the annuity (Residents of Type 2), and 3,977 people chose not to

purchase the associated annuity (Residents of Type 3). The average income of these three groups is shown in the figure below.

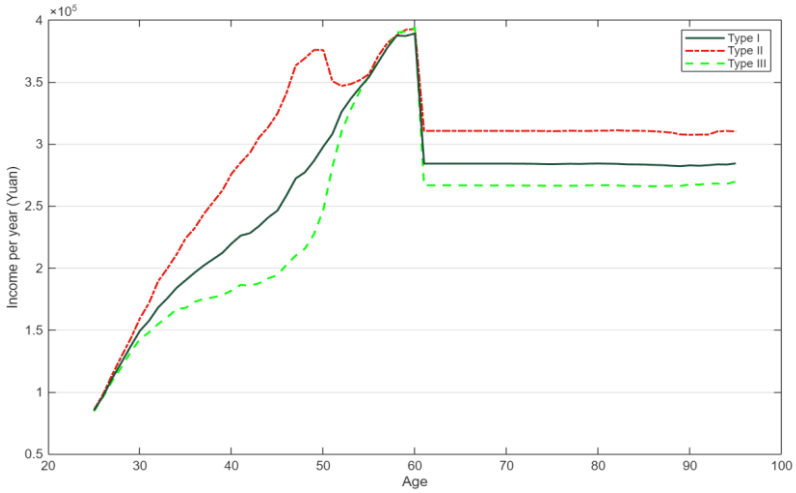


Figure 3. Average Income Status of the Three Groups

Figure 3 shows that the three groups of residents exhibit distinct differences in their income characteristics.

Whether to purchase the associated annuity depends on pre-retirement income. Compared with residents of Type 1 and Type 2, those of Type 3 had significantly lower incomes during the annuity purchase period (before the age of 50), which led them to refrain from purchasing annuity insurance. In contrast, residents of Type 1 and Type 2 had comparable and significantly higher incomes during the annuity purchase period.

Whether to move into an insurance-based elderly care community depends on post-retirement income. Slightly contrary to intuition, Figure 3 indicates that the average income of Type 1 residents is lower than that of Type 2 residents. In other words, among those who purchased the associated annuity, residents with relatively lower post-retirement incomes are more inclined to move into the insurance-based elderly care community. A possible reason is that although moving into such a community can generate additional utility, the consumption level is fixed. Residents with incomes relatively above a certain threshold will opt for a higher consumption level; by accessing elderly care services of a higher standard than those provided by the insurance-based community, they can achieve a higher level of utility than they would by moving into the community. In fact, moving into the insurance-based elderly care community would instead restrict their consumption choices.

6. Conclusions and Recommendations

As China's population aging continues to deepen, residents' elderly care is gradually becoming a major issue of widespread concern. To meet residents' needs in elderly care, including material life, care and health protection, psychological comfort, and social participation, and based on the alignment of investment needs and the complementarity of business contents, insurance companies are actively developing the "insurance & elderly care community" model. They are building high-quality elderly care

communities that integrate medical and elderly care services, providing diversified options for the elderly in planning their elderly life.

This paper introduces the "insurance & elderly care community" model into the life cycle model, establishes a research framework for residents' life cycle consumption, savings, annuity purchase, and elderly care community admission, and discusses residents' demand for the "insurance & elderly care community" model. Based on China's actual data, this paper calibrates the parameters in the model, uses the grid method to solve residents' optimal decisions at various ages and in different states, and employs the Monte Carlo method to simulate residents' life cycle consumption, savings, and decisions regarding the "insurance & elderly care community" model.

A comprehensive understanding and grasp of the logic behind residents' elderly care decisions is an important prerequisite for achieving a secure and stable life in old age. The conclusions of this paper, from a micro perspective, demonstrate the characteristics of residents' demand for the "insurance & elderly care community" model. Meanwhile, this paper also provides suggestions for insurance companies in developing this model: First, the "insurance & elderly care community" model needs to provide additional utility to attract residents, such as in terms of psychological comfort and social participation. Second, the model is more able to meet the needs of middle- and high-income residents; lowering the admission threshold and increasing annual fees along with service quality are conducive to business expansion. Third, external factors such as interest rates and the basic pension insurance system also have an impact on the "insurance & elderly care community" business, which requires continuous attention and analysis.

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From Strategy to Execution: How Enterprise Architecture Bridges Business and IT as a Strategic Enabler of Digital Transformation

Martin LUKÁŠ[a,1] and Jan PAVLÍK[a]
[a] *Department of Information Technology, Faculty of Economics and Management, Czech University of Life Sciences Prague, Kamýcká 129 165 00 Praha – Suchdol, Czech Republic*
ORCiD ID: Martin LUKÁŠ https://orcid.org/0000-0003-0356-5480

Abstract. Digital transformation (DT) requires translating strategic intent into coherent business and IT execution, yet organizations often face structural fragmentation and governance constraints. This study examines Enterprise Architecture (EA) as a strategy-to-execution coordination capability and analyzes how sector context and digital maturity shape modeling practices. Drawing on a cross-study synthesis of seven aligned studies (2020–2025) across public administration, energy, and financial services, the analysis integrates survey data with organizational artifacts and interview insights. The findings show widespread EA modeling adoption, a dominant TO-BE orientation, and persistent execution constraints, positioning EA as a governance-based mechanism for maintaining coherence and traceability under transformation complexity.

Keywords. Enterprise Architecture, Digital Transformation, Business–IT Alignment, AS-IS/TO-BE Modeling, Digital Maturity, Stakeholder Management

1. Introduction

Digital transformation (DT) requires translating strategic intent into coherent and executable changes across business processes, information systems, governance, and technology [1,2]. Despite sustained investment, organizations frequently face fragmented decision-making, weak business–IT coordination, and competing stakeholder interests, particularly in complex and regulated environments [3], positioning DT primarily as a coordination and governance challenge. This study examines DT through Enterprise Architecture (EA), conceptualized as a socio-technical coordination and governance capability rather than a documentation exercise [4,5]. From

[1] Corresponding Author: Martin Lukáš, Department of Information Technology, Faculty of Economics and Management, Czech University of Life Sciences Prague, Czech Republic, Europe, lukas@pef.czu.cz

this perspective, EA structures the translation of strategic priorities into portfolios of interdependent initiatives, architectural decisions, and sequencing choices that shape execution pathways linking strategy, governance, and project-based delivery. However, EA's effectiveness depends on its active adoption by key stakeholders; accordingly, stakeholder engagement and management (StM) is treated as a conditioning mechanism determining whether EA artefacts enable execution or remain symbolic [3]. Digital maturity (DM) is conceptualized as a boundary condition that reflects an organization's capacity to sustain coordinated digital change and explains variation in EA effectiveness across contexts. Although prior research on EA, DT, and DM is extensive, it remains limited in explaining execution-level effects, stakeholder mechanisms, and the role of sectoral and maturity conditions. To address this gap, the study adopts an integrative framing in which EA is the focal coordination capability, DT execution is the outcome domain, StM and portfolio governance form the execution pathway, and DM and sector context act as boundary conditions. The study addresses the following research question: (i) **RQ1**: How does EA function as a strategic translation mechanism between DT strategy planning and initiative delivery and project-based execution? (ii) **RQ2:** Which organizational, stakeholder-related, and project-governance factors condition the effectiveness of EA practices in DT initiatives? (iii) **RQ3:** How do sector-specific characteristics and levels of DM moderate the relationship between EA practices, stakeholder engagement, and DT outcomes? The remainder of the study reviews the relevant literature, outlines the cross-study synthesis research design, presents the findings, and concludes with theoretical contributions, practical implications, and directions for future research. Rather than testing causal effects statistically, this study adopts a mechanism-oriented synthesis of EA heterogeneous contexts.

2. Literature Review

2.1. Enterprise Architecture as a coordination and governance capability

EA is often presented as artefacts describing processes, applications, information, and technology (AS-IS/TO-BE) that support planning and decision-making [1,2]. However, evidence increasingly shows that EA creates value through architecture work—governance routines and decision mechanisms that translate strategic intent into coherent capability, platform, standards, and sequencing choices [2,4,5]. EA artefacts may function as boundary objects enabling cross-domain coordination, but only when stakeholders adopt and interpret them consistently [6]. Accordingly, this study positions EA as a socio-technical coordination and governance capability that leverages artefacts and decision rights to align business and IT during transformation [3–7].

2.2. Business–IT Alignment as the central theoretical mechanism

Because the paper's core claim concerns bridging business and IT, Business–IT Alignment is treated as the central theoretical mechanism. Alignment research frames the challenge as strategic fit and functional integration between business and IT strategies and emphasizes alignment as a dynamic, governance-dependent capability under conditions of uncertainty [1,2,6,7]. EA operationalizes alignment through shared representations and governance routines that coordinate cross-domain decisions [4,5,7]. The literature also highlights a key tension between alignment as static fit and alignment

as mutual strategy co-adaptation, which is particularly salient in DT [8,9]. Yet prior work often under-specifies how alignment is enacted across portfolios of interdependent initiatives and how EA artefacts and governance routines translate alignment into execution, motivating the need for mechanism-based explanation. This gap directly motivates RQ1 and RQ2, which focus on EA as a translation mechanism and on conditioning organizational factors.

2.3. Digital Transformation as a strategy-to-execution coordination problem

DT is commonly defined as an evolutionary process whereby technologies reshape business models, operations, and value creation [8]. DT is not reducible to technology adoption; it is conditioned by organizational structures and broader socio-economic contexts [9,10]. This implies a persistent coordination problem: converting strategic intent into coherent, executable changes while managing fragmentation and heterogeneous stakeholder interests [3,9]. From this perspective, EA matters because it maintains coherence across transformation decisions—what changes, what order, under which constraints [4,5,7]. DT intensifies alignment challenges as business and IT strategies co-evolve, requiring continual renegotiation through governance, shared representations [8,9]. This motivates treating DT as the outcome of interest and examining how EA sustains coherence under complexity and execution in PPM [3–5].

2.4. Digital Maturity: frameworks, measurement, and boundary-condition role

DM is frequently treated as an aspirational DT outcome associated with sustained capability development and performance. However, DM is conceptually heterogeneous across frameworks and dimensions, which creates measurement tension [10,11]. This study therefore treats DM not only as an outcome but as a boundary condition shaping EA effectiveness: higher maturity tends to enable governance and decision rights, whereas lower maturity can reduce EA to symbolic artefact production [3,10,11]. Recent work conceptualizing DT as a governance- and capability-based phenomenon supports this boundary-condition framing [12–14]. Nonetheless, the literature remains limited in explaining how DM moderates the EA → alignment → execution relationship across sectors [9]. This motivates RQ3, which explicitly asks whether sector characteristics and DM levels moderate the relationships among EA practices, StM, and DT outcomes.

2.5. From Architecture to Execution: EA Governance and PPM

If EA is a strategy-to-execution mechanism, the execution arena must be theorized. PPM provide governance routines for prioritization, sequencing, and resource-constrained coordination [15,16]. In DT settings, EA can influence execution by informing stage-gating, investment decisions, dependency management, standardization, and risk mitigation [7,16,17]. Crucially, generic accounts of project methodologies (e.g., PRINCE2, PMBOK, IPMA) do not explain EA's contribution to execution; the relevant intersection is EA governance × PPM governance— how architectural decision rights and target-state roadmaps shape delivery decisions across initiatives [4–7,17]. Agile approaches may complement iterative delivery, but they do not remove the need for architectural coherence [18]. Prior work links EA to portfolio and project alignment but still under-specifies how governance routines and stakeholder dynamics enable EA

artifacts to shape prioritization, portfolio governance, and execution performance, motivating the focus on stakeholder engagement in the next subsection.

2.6. Stakeholder engagement and management as a theoretical mechanism

Stakeholder engagement and management (StM) is often treated procedurally in project standards [6,7,9,19], but these procedures offer limited explanatory power. Stakeholder theory emphasizes dynamic salience and context-dependent power relations [20], which helps explain why EA—spanning multiple professional communities—frequently encounters trust deficits, governance mismatches, communication gaps, and low perceived usefulness of artefacts [3]. Boundary-object theory further clarifies that artefacts enable coordination only when they are interpretable and legitimate across domains [21]. Hence, StM is treated as a conditioning mechanism: EA contributes to alignment and execution only when key stakeholders accept architectural representations and governance decisions as legitimate inputs to portfolio and delivery choices [3,6,7]. Although stakeholder theory and EA studies acknowledge the importance of stakeholders, research still lacks an integrative explanation of how salience and boundary-object dynamics affect EA effectiveness across sectors and maturity levels. This gap motivates the study's mechanism-oriented framing of StM within RQ2 and RQ3.

2.7. Integrative synthesis and research gap

Overall, the literature supports an integrative view in which EA functions as a socio-technical governance capability [3–7], Business–IT Alignment is the core mechanism [1,2,6,7], DT represents a coordination challenge [8–10], PPM constitutes the execution arena [15–17], and StM conditions adoption and interpretability [3,6,7,20,21], while DM and sector context moderate these relationships [3,10,11]. However, research still lacks a coherent, mechanism-based explanation of how EA translates into execution effects in project-centric settings and how stakeholder, sectoral, and maturity contexts shape outcomes. In particular, sectoral governance traditions and institutional constraints, including those of Central and Eastern European public-sector contexts, remain under-integrated into EA–DT theorizing. This unresolved gap motivates the integrated empirical synthesis and the study's research questions.

3. Methodology

3.1. Research design: cross-study empirical synthesis (2020–2025)

This study applies a cross-study empirical synthesis integrating evidence from seven aligned sub-studies (Research #1–#7) conducted between 2020 and 2025. The corpus includes cross-sector surveys, organizational/municipal analyses, departmental comparisons, and semi-structured interviews, all addressing how EA supports the translation of DT strategy into coordinated execution under sectoral and organizational constraints. The study does not claim a conventional mixed-methods design with a single sampling frame; instead, it synthesizes independently executed studies that share (i) a common theoretical framing (EA as a socio-technical coordination and governance capability), (ii) recurring constructs (EA artefacts/modelling, execution constraints,

stakeholder dynamics, maturity gradients), and (iii) a shared analytical purpose (identifying recurring mechanisms and context-dependent variation).

3.2. Empirical corpus, inclusion logic, and integration protocol

The synthesis corpus comprises seven sub-studies, summarized in Table 1. They were included if they (1) reported original empirical evidence (survey, structured organizational evidence, interviews), (2) contained analytically relevant EA artefacts (e.g., AS-IS/TO-BE modelling, standards, governance routines), (3) provided evidence linked to DT execution challenges/outcomes (e.g., coordination, risk, portfolio), and (4) could be mapped to the shared analytical framework. Because sub-studies vary in design and unit of analysis, evidence is not statistically pooled or weighted; each sub-study contributes traceable evidence to the synthesis, and divergent patterns are interpreted as contextual variation rather than contradictions requiring statistical reconciliation. To ensure coherence and traceability, the synthesis follows a theory-guided protocol:

1. Extraction and normalization of key empirical outputs into a standardized template (Research ID, period, method, sampling, sector, response, and empirical signals relevant to EA & DT).
2. Framework mapping of extracted evidence to a shared analytical framework consistent with the results organization by "views" (modelling practices, risk/strategy, process, application, infrastructure, execution constraints, maturity).
3. Comparative synthesis to identify convergent mechanisms and context-dependent differences; where evidence diverges, claims are bounded to the relevant contexts.

3.3. Quantitative component: surveys and descriptive cross-sector comparison

Multiple sub-studies used electronic questionnaire surveys to capture EA adoption patterns (e.g., AS-IS/TO-BE and ArchiMate usage) and organizational role/sector attributes. Instruments were refined through pilot testing, expert review, and completeness checks. The quantitative analysis is primarily descriptive and comparative (frequencies, percentages, and descriptive summary statistics), consistent with the heterogeneous corpus and the synthesis aim. Response rates are meaningful only for survey-based sub-studies and are reported disaggregated by sub-study; for interviews and case-based datasets, response rate logic is not applicable and is documented via coverage/recruitment descriptions rather than aggregated participation metrics.

3.4. Qualitative component: semi-structured interviews, analysis, assurance, and rigor

The qualitative component comprises four semi-structured interviews (Research #7) with senior non-IT managers across sectors, conducted by the first author using a guide focused on EA governance, execution constraints, and stakeholder dynamics. Interviews lasted 45–60 minutes and were purposively selected. Data were analyzed using two-cycle thematic analysis to derive themes aligned with the synthesis framework and research questions. Coding was performed iteratively by the first author. Qualitative findings are used for contextualization only; saturation, member checking, and standalone qualitative generalization were not pursued due to the limited corpus. Quality assurance combined survey pilot testing, expert review, completeness checks, and standardized templates for organizational evidence, while acknowledging self-selection bias. Interview credibility relied on transparent thematic coding, traceability to the analytical framework, and

triangulation with survey and data. Interpretation was informed by reflexive awareness of the authors' familiarity with EA practice and public-sector governance.

Table 1. Overview of the empirical corpus (Research #1 – #7)

Research ID/EV	Period	Method type	Sampling/ N	Context & Sector	Key variables / themes	Response rate**
Research #1 /4, 5	2020	SQ	PES/ N = 9	A, B, E, PA	Understanding vs. use of EA/ArchiMate elements (motivation, strategy, business, implementation layers)	100%
Research #2 /2	2021	SQ + PAA	CKPO/ N = 21	PA	AS-IS process structure, risks, manual activities, optimization potential	100%
Research #3 /3	2022	SQ	OC/ N = 252	PA	DT goals, projects, risks, project duration, risk severity	100%
Research #4 /1, 2, 3, 4, 5	2023	ES	NBS/ N = 55*	B, E, Ch, IT, PA, S,	EA maturity, ArchiMate usage, AS-IS vs. TO-BE modeling	52.4%
Research #5 /4	2024	CS + SNI	PS/ N=2	PA	HR process digitalization, IS landscape, substitution, time-consuming tasks	n/a
Research #6 /1, 2, 3, 4, 5	2024	SQ + QM	OS/ N = 75	B, H, IT, M	Cloud adoption factors (complexity, compatibility, knowledge, advantage, trialability)	100%
Research #7 /5	2025	SNI	PESX/ N = 4	B, E, PA, T	Stakeholder management, EA value, governance inhibitors	n/a

Legend: EV (Enterprise volume): 1 = 0–19 employees, 2 = 20–49 employees, 3 = 50–99 employees, 4 = 100–1000 employees, 5 = 1001+ employees, SQ = survey/questionnaire, PAA = Process artefact analysis, SNI = semi-structured narrative interview, ES = Exploratory survey, CS = Case study, QM = Quantitative modeling, PES = Purposive expert sampling, CKPO = Census of key process owners, OC = Organizational census, NBS = Network based sampling, PS = Purposive seleczion, A = Automotive, B = Banking, Ch = Chemical, E = Energy, H = Healthcare, IT = Inf.Technology, M = Manufacturing, PA = Public Administration, S = Services, T = Teleco, * from 105 invited, ** Response rate reported only for survey-based studies; not applicable to interviews/case-based analyses.

4. Results

4.1. Statistical scope and structure of the results

The analysis is primarily descriptive due to the cross-study synthesis design and heterogeneity across Studies #1–#7. Results are reported using frequencies, percentages, and descriptive statistics (means and standard deviations where applicable). Inferential tests are applied only when data permit; otherwise, no claims of statistical significance, causality, or population-level inference are made. Generalizability is limited by voluntary participation and self-selection bias.

4.2. Descriptive profile of the empirical corpus

The empirical corpus comprises seven sub-studies (2020–2025) spanning Public Administration, Energy & Utilities, Banking, Manufacturing, IT, and selected municipal organizations (Table 1). Sample sizes range from small expert/case-based datasets (e.g., N=9; N=4 interviews) to large surveys (N=252). Respondents in survey studies were predominantly ICT-related roles (e.g., enterprise architects, IT directors, administrators,

analysts), complemented by managerial and non-IT stakeholders. Organization size spans micro (0–19 employees) to very large (1001+), with larger organizations more represented in Energy and Banking contexts.

4.3. EA modeling practices and adoption patterns

Across survey-based datasets, EA modeling practices are widely reported. ArchiMate adoption ranges from ~63% to 75% across Banking, Public Administration, and Energy, with higher adoption observed in regulated/asset-intensive settings. Both AS-IS and TO-BE modeling are prevalent, with TO-BE reported more frequently than AS-IS in several datasets, particularly Research #4. Where sample sizes permit (notably Research #3 and #4), χ^2 tests identify statistically significant associations between sector affiliation and reported modeling practices; effect sizes are reported, and causal interpretation is not implied. For studies with smaller/exploratory samples, results are descriptive only. Table 2 (summary): Key survey constructs are summarized with N, mean (M), and standard deviation (SD), including ArchiMate usage, AS-IS modeling, TO-BE modeling, and holistic EA maturity. Means/SDs are reported for descriptive comparability; reliability tests (Cronbach's alpha) are reported for relevant datasets. Reported χ^2 tests are restricted to survey-based sub-studies with sufficient expected cell counts. **Risk, process, structural, and execution characteristics, and project patterns:** Risk-related evidence indicates substantial and unevenly distributed exposure. Public-sector organizations documented 137 risks in Research #3 (concentrated in medium/high severity categories), while municipal datasets identified an additional 122 process-embedded risks in Research #2. Process-level evidence indicates fragmentation (high numbers of inputs, outputs, metrics, and manual activities). Application and infrastructure views show heterogeneous system landscapes with varying integration, security, and compliance characteristics, describing co-occurring constraints across organizational contexts. Reported project durations vary widely, averaging approximately 27–46 months in survey-based datasets, with uneven goal achievement across organizations and sectors reported descriptively. **Sectoral and maturity-related comparisons:** Sectoral analysis shows higher EA maturity and more consistent modeling practices in Energy and Banking than in Public Administration. Results are reported descriptively as sector-associated patterns, with potential explanatory factors deferred to the Discussion. **Role of qualitative interviews in the results synthesis:** The qualitative interviews (Research #7) are not presented as standalone qualitative findings. Instead, they serve an explanatory/contextual function within the synthesis, supporting triangulation across survey-based and organizational evidence. Interview material is used selectively to clarify how respondents interpret EA practices, governance constraints, and stakeholder dynamics observed in quantitative and structural datasets. Given N=4, no claims of saturation or independent generalization are made. **Summary of empirical patterns:** Taken together, the results indicate recurring patterns across the seven sub-studies: widespread EA adoption, future-state orientation (TO-BE), substantial structural and risk-related complexity, variation in execution characteristics, and sector/maturity-associated differences reported descriptively and interpreted cautiously.

4.4. Key findings

Across the seven-study synthesis, EA emerges as a socio-technical coordination capability enabling the translation of DT strategy into business–IT execution. ArchiMate

adoption is reported at approximately 63–75% across Banking, Public Administration, and Energy, with modeling predominantly future-state oriented (TO-BE exceeding AS-IS, particularly in Research #4). Persistent execution challenges remain, notably risk exposure and structural fragmentation, while qualitative interviews provide contextual explanation rather than standalone evidence. Overall, the findings indicate a maturity gradient in which regulated, asset-intensive sectors—especially Energy and Banking—demonstrate more consistent EA discipline than Public Administration, with sectoral differences reported descriptively and interpreted cautiously.

Table 2. Descriptive statistics for key survey constructs

Construct	Research ID	Scale	N	Means (M)	Standard deviation (SD)
ArchiMate understanding/usage	Research #1	Binary	9	Mean understanding/use is highest in the BUS layer (7.00/6.50), MOT (5.33/3.00), STR (4.33/2.33), and IMP (4.00/2.50)	Variability is highest in MOT and STR layer (4.62/5.20 and 4.04/4.04), then IMP (2.83/3.54) and lowest in BUS (1.41/0.71)
ArchiMate usage*	Research #4	Binary	55±	0.65	0.48
AS IS only modeling usage	Research #4	Binary	55±	0.64	0.49
TO BE only modeling usage	Research #4	Binary	55±	0,75	0,43
EA holistic maturity (both AS-IS & TO-BE)	Research #4	Binary	55±	0.60	0.07
EA modeling intensity**	Research #3	Likert	252 ±±	4.81	1.21
EA / cloud readiness factors	Research #6	Likert	75	1.46	0.51

Note: Means and standard deviations are reported for ordinal and Likert-type measures to support descriptive comparison. Given the synthesis design and non-probabilistic sampling, these statistics are interpreted descriptively rather than inferentially. Cronbach's alpha reliability tests were calculated using complete cases per the given Research #3 and 4 (block items). **Legend:** * χ^2 test revealed a statistically significant association between sector and ArchiMate usage, $\chi^2(df = 3, N = 55) = 39.84$, $p < 0.001$, with a large effect size as indicated by Cramér's V (V = 0.85), ** χ^2 test revealed no statistically significant association between sector and EA modeling intensity, $\chi^2(df = 3, N = 252) = 3.34$, $p = 0.343$, with a small effect size (Cramér's V = 0.12), ± Cronbach's alpha reliability test (N=55): $\alpha = 0.896$ (the overall reliability remained high), ±± Cronbach's alpha reliability test (N=252): $\alpha = 0.955$ (the overall reliability remained high), BUS=Business, MOT=Motivation, STR=Strategy, IMP=Implementation.

5. Discussion & Conslusion

Linking the findings to prior literature: This study reinforces and extends prior research that positions EA as a socio-technical coordination and governance capability rather than a documentation practice, supporting strategic coherence during DT [1–7]. Consistent with earlier accounts of EA governance and boundary objects, the findings confirm that EA artefacts contribute to alignment and execution when embedded in governance routines and adopted by key stakeholders. At the same time, the results refine existing EA–DT arguments by showing that widespread adoption of TO-BE modelling frequently coexists with persistent execution constraints, including risk exposure, fragmentation, and prolonged delivery cycles [3,8,9,22,23].. **EA practice is future-state-oriented, but execution remains structurally constrained:** The integrative framework (Figure 1) should be interpreted as a multi-cycle, feedback-driven

coordination system rather than a linear transformation path. While the figure presents a simplified structure, the discussion clarifies that EA, stakeholder engagement, portfolio governance, and maturity interact iteratively across transformation cycles. This distinguishes the framework from static EA maturity models and emphasizes its explanatory purpose: accounting for how EA sustains coherence under evolving organizational and institutional constraints. **Sector and maturity patterns: associations and alternative explanations:** Sectoral comparisons show higher reported EA maturity and more consistent modelling practices in regulated and asset-intensive sectors, particularly Energy and Banking. Rather than attributing these differences solely to sector characteristics, the discussion explicitly acknowledges alternative explanations, including organizational scale, IT budget capacity, governance traditions, regulatory mandates, and professional communities of practice. Disentangling these competing influences lies beyond the scope of the current synthesis and represents an important direction for future research. **StM as a conditioning mechanism:** Qualitative interviews are not treated as standalone findings but serve a contextual and explanatory role, supporting triangulation with survey-based and organizational evidence. Interview insights help clarify stakeholder adoption challenges, governance frictions, and decision dynamics observed in the quantitative results without extending beyond their evidential scope [3,8,9,22,23].

5.1. What is new in this study

While prior work establishes EA as a bridge between strategy and execution, this study contributes in three ways. First, it achieves cross-study convergence across seven heterogeneous sub-studies through a theory-guided integration protocol with explicit traceability. Second, it identifies an empirical regularity in which TO-BE dominance coexists with persistent execution constraints. Third, it operationalizes StM as a mechanism and DM/sector context as boundary conditions within a multi-view results structure, offering a reusable synthesis logic for cross-sector EA research.

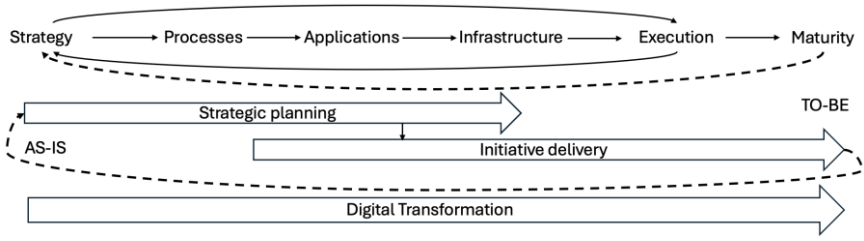


Figure 1. The Framework of EA as an integrative force.

Answers to RQ1: The synthesis indicates that EA functions as a strategy-to-execution translation mechanism primarily through governance and alignment routines that connect strategic intent with portfolio and delivery decisions, supported by widespread use of standardized modeling practices. **Answer to RQ2:** The effectiveness of EA practices is conditioned by execution constraints and organizational mechanisms, notably stakeholder adoption/interpretability of EA artifacts and the presence of persistent risk and fragmentation signals captured across datasets (e.g., documented risks and heterogeneous process/application/infrastructure constraints), which shape whether models are used instrumentally rather than symbolically. **Answer to RQ3:** Sector and

maturity context moderate observed EA practice: modeling adoption and maturity indicators differ across sectors (with more disciplined EA practice in regulated, asset-intensive contexts), while the study treats these patterns as descriptive associations and acknowledges that disentangling sector effects from alternative explanations requires further research. This study contributes to EA and DT research in three main ways, foremost by offering a cross-study synthesis of seven heterogeneous sub-studies with explicit integration logic that bridges conceptual EA research and execution-level evidence. [3–7]. Second, it identifies a consistent pattern in which future-state-oriented EA practices coexist with systemic constraints, qualifying claims of EA-driven transformation success. Third, it operationalizes an integrative explanation in which StM serves as a mechanism, while DM and sector context function as boundary conditions that shape the translation of strategy into execution [3,10,11].

5.2. Implications for practice (finding derived)

The practical implications follow directly from these findings. Observed TO-BE dominance supports embedding target-state architectures and roadmaps into portfolio governance so that strategic intent constrains delivery decisions. Documented risk exposure and structural fragmentation highlight the need to integrate EA repositories with risk and portfolio oversight. Persistent stakeholder adoption challenges underscore the importance of clearly defined ownership, interpretability, and communication responsibilities for architectural artefacts and decisions.

Future research directions derive from the study's limitations. Longitudinal and repository-based designs are needed to examine how EA practices influence execution outcomes over time. Comparative studies across institutional settings can help separate sector effects from alternative explanations such as governance history or resource availability. Expanded qualitative research focused on stakeholder mechanisms would strengthen causal process explanations. Finally, greater attention to national and institutional contexts—such as public-sector coordination structures—can clarify which EA–DT patterns are context-dependent and which are transferable [9–11].. Regarding Czech context sensitivity, the study should explicitly identify which observed patterns are most likely to depend on national arrangements (e.g., public administration coordination structures and compliance expectations) and which patterns are likely to transfer (e.g., TO-BE dominance, stakeholder adoption challenges, and the need for EA governance), thereby making the external validity discussion more actionable.

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Coupling Mechanism of Professional Identity, Creative Consciousness, and Social Responsibility Under Digital Transformation: Evidence from Chinese Universities

Yaojia LIN, Chan LIU[1] and Na LUO
Guangdong Polytechnic of Industry and Commerce, Guangzhou, China

Abstract. Digital transformation is reshaping the global labor market, necessitating a synergy between cognition, competence, and values. This study examines the coupling mechanism within a core competency cluster: Professional Identity (PI), Creative Consciousness (CI), and Social Responsibility (SR). Based on a stratified random sample of 364 students from six Chinese universities (stratified by grade and discipline), we employed Structural Equation Modeling (SEM) and Response Surface Analysis (RSA). The results demonstrate that CI partially mediates the relationship between PI and SR (indirect effect = 0.259, 95% CI: [0.215, 0.389]), explaining 52.4% of the total effect. Response Surface Analysis further indicates a synergistic association: when PI and CI are highly congruent, the predicted SR score is 43.2% higher than in low-congruence states ($a1=0.62$, $p<0.001$). The findings suggest that integrating identity construction with innovation training is vital for fostering social responsibility.

Keywords. Digital transformation, professional identity, creative consciousness, social responsibility, coupling mechanism, structural equation modeling

1. Introduction

The digital wave, characterized by artificial intelligence and big data, has moved beyond technical disruption to a fundamental restructuring of professional values. In this context, the "Professional Identity–Creative Consciousness–Social Responsibility" cluster emerges as a critical competency triad. While existing literature often treats these as independent constructs, this study argues that they form an interdependent organic whole. PI acts as the directional anchor, CI acts as the engine for change, and SR functions as the ethical compass. Despite their importance, a research gap exists regarding their synergistic interaction. Specifically, how the alignment of professional cognition (PI) and innovative drive (CI) quantitatively catalyzes social contribution (SR) remains under-explored. This study addresses this gap by providing empirical evidence from six universities, aiming to optimize talent cultivation systems for the digital era.

[1] Corresponding Author: Chan LIU, lory2366@163.com.

2. Literature Review and Theoretical Basis

2.1. Definition of Core Concepts

Professional Identity (PI)in the digital era is defined as the degree to which students perceive themselves as members of a future professional community, mediated by digital competencies [1]. In this study, PI is not merely a psychological state but a cognitive prerequisite for career-oriented behavior. Creative Consciousness (CI) refers to an individual's persistent sensitivity and proactive psychological drive toward innovation and problem-solving [2]. In the context of digital transformation, CI emphasizes the cognitive willingness to utilize emerging technologies to create value. Social Responsibility (SR) represents the ethical dimension of professional development, signifying the conative intent to contribute to societal well-being through one's specialized skills [3-8]. The "Synergistic Coupling" of these three constructs forms the core of modern talent cultivation.

2.2. Theoretical Foundation and Research Hypotheses

This study adopts Social Cognitive Career Theory (SCCT) as its overarching framework. SCCT posits that individual identity formation (Cognition) significantly influences behavioral intentions through self-efficacy and creative drive (Affective/Conative states) [9-10].

- *2.2.1 PI and CI: The Cognitive-Affective Link.*

According to SCCT, a robust professional identity provides students with the "psychological safety" required for creative risk-taking. When students internalize their professional roles, they are more likely to perceive digital disruptions as opportunities rather than threats, thereby fostering higher levels of CI.

H1: Professional identity has a significant positive effect on creative consciousness.

- *2.2.2 The Mediating Role of CI.*

The "Cognition–Affect–Conation" framework suggests that professional cognition (PI) does not translate directly into social behavior (SR); it requires an intermediate "catalyst." CI serves as this catalytic mechanism. By converting professional belonging into a drive for innovation, students find tangible ways to fulfill their social obligations.

H4: Creative consciousness plays a mediating role between Professional Identity and Social Responsibility.

- *2.2.3 The Synergistic Coupling (The RSA Perspective).*

Moving beyond linear mediation, we argue that the highest levels of Social Responsibility are achieved only when PI and CI are "congruent." High innovation without professional ethics (Hollow Innovation) or high identity without innovative tools (Traditionalist Stagnation) results in sub-optimal social outcomes. This leads to our synergistic hypothesis, which we test using Response Surface Analysis (RSA).

H5: There is a significant synergistic association between PI and CI in predicting SR, such that SR is maximized at high-level congruence (+1 SD).

Based on the theoretical integration of SCCT and the proposed hypotheses, we developed a conceptual framework to guide the subsequent empirical analysis (see Figure 1). This framework illustrates the dual-path influence of PI on SR: a mediating path via CI and a synergistic coupling effect tested by Response Surface Analysis.

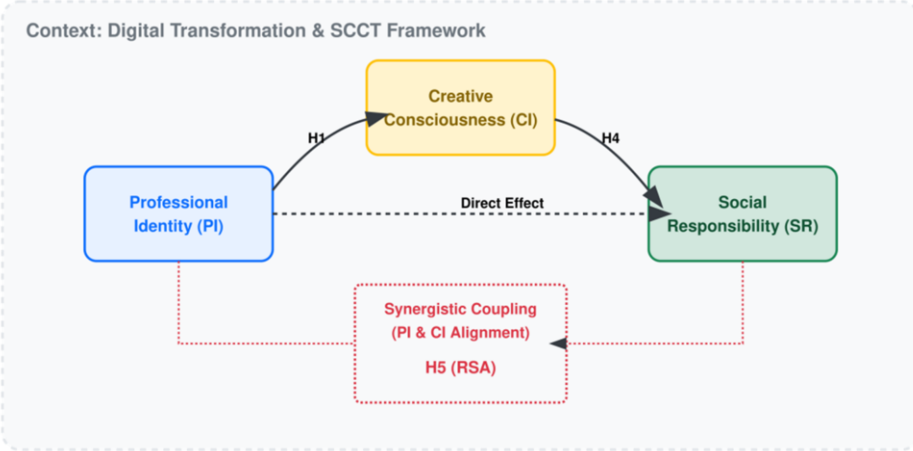


Figure 1. Integrated conceptual schema of the "Identity–Innovation–Responsibility" synergy.
Note: Solid lines represent direct and mediating paths (H1 and H4), while the dashed red boundary signifies the synergistic coupling effect (H5). The framework highlights how the alignment of Professional Identity (PI) and Creative Consciousness (CI) catalyzes Social Responsibility (SR) within the context of digital transformation, as tested by the Response Surface Analysis (RSA) methodology.

3. Research Design and Methodology

3.1. Participants and Sampling Method

This study employed a stratified random sampling method across six Chinese universities to ensure representative coverage across diverse institutional types and academic levels. The sampling was stratified by Grade (Freshman to Senior) and Discipline (Engineering, Management, and Liberal Arts). Inclusion criteria required participants to be full-time students in digital-related majors (e.g. Software Engineering, Data Science, Digital Management).

Out of 420 surveys distributed via an online platform, 364 valid responses (86.7%) were retained. The filtering process excluded "speeders" (completion time < 120s) and invariant response patterns (e.g., identical ratings for all Likert items). The final sample (N=364) consisted of 156 males (42.9%, coded as 1) and 208 females (57.1%, coded as 0). To ensure statistical rigor in the regression models, "Major" was dummy-coded: Engineering (39.0%) served as the reference group, with Management (31.5%) represented by D_1(1=Management, 0=Others) and Liberal Arts (29.5%) represented by D_2 (1=Liberal Arts, 0=Others).

3.2. Measurement Tools and Validity

All constructions were measured using Likert 5-point scales adapted from established international scales, localized for the digital transformation context.

- Professional Identity（PI）: Adapted from the study of Lounsbury et al. [1], this 9-item scale measures students' identification with their career path (e.g., "I feel proud to be a student in my chosen digital-related major"). The Cronbach's α was 0.88.
- Creative Consciousness (CI): Adapted from the study of Zhou & George [2], this 8-item scale assesses the proactive drive for innovation (e.g., "I frequently seek out new digital technologies or methods to solve complex problems"). The Cronbach's α was 0.86.
- Social Responsibility (SR): Adapted from the study [3], this 7-item scale evaluates the commitment to social ethics in professional practice (e.g., "I believe my professional skills should be applied to contribute to the sustainable development of society"). The Cronbach's α was 0.84.

Structural Validity: Confirmatory Factor Analysis (CFA) was conducted using AMOS 26.0. The results indicated an excellent fit: $\chi 2/df=2.14$, CFI=0.945, TLI=0.938, RMSEA=0.056, and SRMR=0.042.

Discriminant Validity: Following the Fornell-Larcker criterion, the square root of the Average Variance Extracted (AVE) for each construct (PI: 0.76; CI: 0.74; SR: 0.72) exceeded all inter-construct correlations ($r_{max}=0.61$). Furthermore, all Heterotrait-Monotrait (HTMT) ratios were below the 0.85 threshold.

3.3. Data Analysis Strategy

To mitigate potential self-report bias, Harman's single-factor test was performed. The results showed that the first principal factor accounted for 26.4% of the total variance, significantly below the 40% threshold. Additionally, a latent common method factor was introduced in the CFA model; the model fit did not improve significantly ($\Delta CFI<0.01$), suggesting that CMB was not a significant concern.

3.4. Statistical Model and Regression Equations

To test the hypotheses, a hierarchical regression analysis was employed. The core relationship and the mediating effect were modeled as follows:

$$SR=\beta_0+\beta_1 \cdot Gender+\beta_2 \cdot D_1+\beta_3 \cdot D_2+\beta_4 \cdot PI+\epsilon (Eq.1)$$

$$SR=\beta_0+\beta_1 \cdot Gender+\beta_2 \cdot D_1+\beta_3 \cdot D_2+\beta_4 \cdot PI+\beta_5 \cdot CI+\epsilon (Eq.2)$$

Where Gender and $D_{1,2}$(Major) are control variables, *PI* is the independent variable, *CI* is the mediator, and *SR* is the dependent variable. Furthermore, the synergistic coupling (H5) was tested using **Response Surface Analysis (RSA)** with the second-order polynomial equation:

$$SR=b_0+b_1 PI+b_2 CI+b_3 PI^2+b_4 (PI \times CI)+b_5 CI^2+e (Eq.3)$$

4. Empirical Results and Analysis

4.1. Descriptive Statistics, Reliability, and Correlation Analysis

Table 1 presents the descriptive statistics, internal consistency, and correlation matrix for all studied variables. To comply with the dummy coding described in the methodology, the "Major" and "Gender" variables are reported by their distribution frequencies.

The results show that the Cronbach's α for all scales (0.838–0.876) exceeds the 0.70 threshold, and the Square Root of the Average Variance Extracted (AVE) for each construct is greater than its correlation with other constructs, confirming high reliability and discriminant validity. Significant positive correlations were observed between Professional Identity (PI) and Creative Consciousness (CI) ($r=0.58,\ p<0.01$), and between CI and Social Responsibility (SR) ($r=0.60,\ p<0.01$), providing preliminary support for the research hypotheses.

Table 1. Descriptive Statistics, Reliability, and Correlation Matrix (N=364)

Variable	Distribution / Mean	SD	1	2	3	4	5
1. Gender (Male=1)	42.9%	0.49	—				
2. Major (Eng=Ref.)	Eng: 39.0%; Mgt: 31.5%; Arts: 29.5%	—	-0.04	—			
3. Professional Identity (PI)	3.64	0.72	0.12*	0.08	**(0.76)**		
4. Creative Consciousness (CI)	3.52	0.68	0.09	0.11*	0.58**	**(0.74)**	
5. Social Responsibility (SR)	3.78	0.65	0.04	0.06	0.54**	0.60**	**(0.72)**
Reliability (αα)			—	—	0.876	0.853	0.838
Composite Reliability (CR)			—	—	0.885	0.861	0.845

**Note: Parentheses on the diagonal represent the Square Root of AVE. For "Major," correlations are calculated using dummy variables D_1 and D_2. *p < 0.05, *p < 0.01.*

4.2. Mediation Effect of Creative Consciousness

Hierarchical multiple regression was employed to test the mediating role of CI (Table 2). After controlling gender and major, PI was found to have a significant positive effect on SR (Model 2: $\beta=0.542,\ p<0.001$). When both PI and CI were entered into the model (Model 3), the effect of CI on SR remained highly significant ($\beta=0.441,\ p<0.001$), while the direct effect of PI on SR decreased from 0.542 to 0.235 ($p<0.001$).

The Bootstrap analysis (5,000 samples) confirmed that the indirect effect of PI on SR via CI was 0.259, with a 95% confidence interval of [0.215, 0.389], excluding zero. These results indicate that CI plays a significant partial mediating role in the relationship between PI and SR, supporting H1, H2, H3, and H4.

Table 2. Hierarchical Regression Results for Mediation Analysis

Predictors	CI (Model 1)	SR (Model 2)	SR (Model 3)
Step 1: Controls			
Gender (Male=1)	0.024	0.015	0.008
Major (D1*D*1: Management)	0.031	0.022	0.018
Major (D2*D*2: Liberal Arts)	0.018	0.012	0.009
Step 2: Main Effects			
Professional Identity (PI)	0.587***	0.542***	0.235***
Creative Consciousness (CI)	—	—	0.441***
R2*R*2	0.343	0.294	0.468
F*F*	162.35***	127.56***	147.82***

***Note:** Standardized coefficients (β) are reported. **p < 0.001.

4.3. Synergistic Association Patterns: Response Surface Analysis

To further explore the synergistic association patterns (H5) between PI and CI, polynomial regression and response surface analysis (RSA) were performed. Table 3 presents the regression coefficients and the calculated surface parameters. The interaction term (*PI×CI*) was significantly positive (B=0.156, p<0.001), suggesting a synergy between the two predictors. Along with the line of perfect congruence (*PI=CI*), the slope was significantly positive ($a_1=0.570$, $p<0.001$), while the curvature (a_2=0.076, p>0.05) was not significant. This indicates that SR increases linearly as both PI and CI rise in tandem. Conversely, along the line of incongruence (*PI=−CI*), the significant negative curvature ($a_4=-0.236$, $p<0.05$) suggests that any mismatch between PI and CI leads to a significant reduction in SR. This "balanced synergy" pattern demonstrates that the highest level of social responsibility is achieved when students maintain high levels of both professional identity and creative drive.

Table 3. Polynomial Regression and Response Surface Parameters

Predictor / Parameter	Coefficient (B)	SE	tt	pp
Polynomial Coefficients				
Constant	3.782	0.035	108.06	***
PI (b_1)	0.198	0.038	5.21	***
CI (b_2)	0.372	0.041	9.07	***
PI2PI2 (b_3)	-0.042	0.028	-1.50	0.135
PI×CI (b_4)	0.156	0.035	4.46	***
CI^2(b_5)	-0.038	0.029	-1.31	0.191
Surface Parameters				
Congruence Slope ($a_1=b_1+b_2$)	0.570	0.062	9.19	***
Congruence Curvature ($a_2=b_3+b_4+b_5$)	0.076	0.054	1.41	0.159
Incongruence Slope ($a_3=b_1-b_2$)	-0.174	0.058	-3.00	**
Incongruence Curvature ($a_4=b_3-b_4+b_5$)	-0.236	0.061	-3.87	**
Model Fit	$R^2=0.728$; $F=104.52$***			

***Note:** **p < 0.01, ***p < 0.001.*

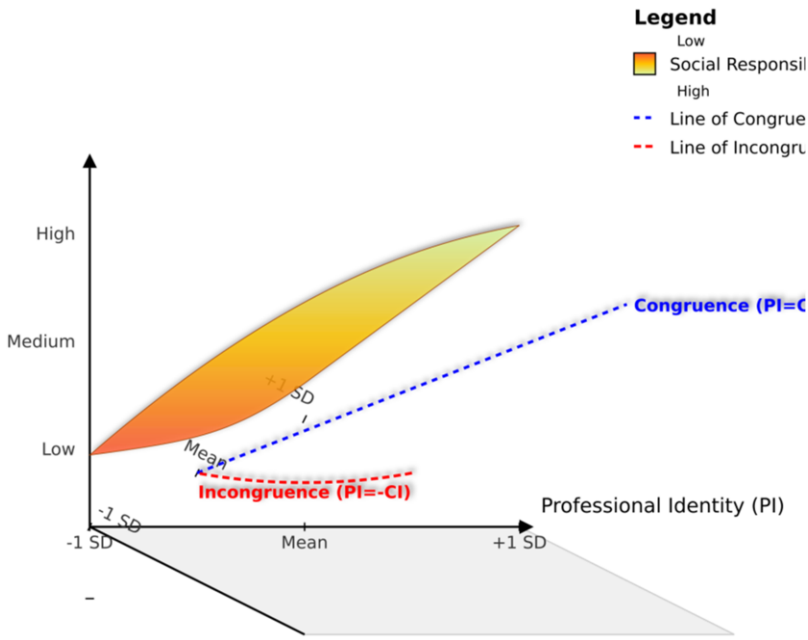


Figure 2: Response Surface Plot for the Synergistic Effect of PI and CI on SR

Note. This figure illustrates the three-dimensional response surface for Social Responsibility (SR) as a function of Professional Identity (PI) and Creative Consciousness (CI). Both predictors were centered before analysis. The vertical axis represents the predicted level of SR. The blue dashed line represents the line of congruence (PI = CI), where PI and CI are at equal levels. The red dashed line represents the line of incongruence (PI = -CI), where the levels of PI and CI are discrepant. The rising ridge along the line of congruence and the downward curvature along the line of incongruence indicate that SR is maximized when both PI and CI are at high and congruent levels.

5. Discussion and Recommendations

5.1. Analysis of the "Identity-Innovation-Responsibility" Path: The Dual Mechanism

The empirical results elucidate a sophisticated dual mechanism through which professional identity (PI) translates into social responsibility (SR).

Firstly, the partial mediation effect confirms that Creative Consciousness (CI) acts as a critical "catalytic hub." While PI provides the ethical baseline (Direct Effect = 0.235), the fact that 52.4% of the total effect is transmitted through CI suggests that in the digital era, professional cognition alone is insufficient to generate social value. This finding addresses a long-standing "missing link" in vocational psychology: students require "creative agency" — the ability to imagine and implement novel solutions—to convert their professional sense of belonging into tangible social contributions.

Secondly, the Synergistic Association Pattern revealed by RSA (Table 3) adds a critical boundary condition to this path. The significant negative incongruence curvature ($a_4=-0.236$, $p<0.01$) proves that "mismatched development" is not merely suboptimal but actively detrimental. A "Value Deficit" occurs when students possess high creative drive (CI) but low professional identity (PI), leading to innovation that lacks social direction or ethical anchoring. Conversely, high PI without CI results in

"Inert Responsibility," where the desire to contribute exists but the technical-creative capacity to execute is absent.

5.2. Practical Suggestions for Higher Education: From Linear to Synergistic

Based on the evidence of the "hub" role and "synergistic patterns," universities must transition from fragmented skill-training to an integrated developmental model:

1. **Reinforcing the "Ethical Compass" (Targeting PI)**: Given the strong foundational predictive power of PI ($\beta=0.587$), career education must move beyond employment statistics. Universities should utilize digital industry simulations and "alumni-shadowing" to foster deep professional internalization. This ensures that the "direction" of student growth is ethically grounded before the "velocity" (innovation) is increased.
2. **Activating the "Implementation Engine" (Targeting CI)**: The high mediation ratio (52.4%) necessitates a redesign of innovation curricula. Training should pivot from purely technical toolkits (e.g. coding, design) to "Social Problem-Solving" frameworks (e.g., Design Thinking for Social Good), ensuring that CI is calibrated to address societal challenges rather than just market-driven needs.
3. **Synchronized Developmental Interventions (Targeting Synergy)**: The RSA results warn against the "High-Low" mismatch. Interdisciplinary programs should be evaluated not just by individual skill gains, but by the congruence between professional ethics and creative skillsets. We recommend the implementation of "Ethics-Innovation Integrated Projects," where students are graded simultaneously on their solution's technical novelty and its measurable social impact, thus closing the observed "knowledge-action gap."

5.3. Limitations and Future Research

Despite the rigorous RSA methodology, this study is subject to several limitations. First, the cross-sectional nature of the data precludes definitive causal claims regarding the temporal evolution of the synergistic association pattern; future research should employ longitudinal tracking to capture how these patterns stabilize over a student's four-year tenure. Second, while the VIF values (Table 2) indicate no multi-collinearity issues, the reliance on self-report measures may introduce common method bias. Future studies could enhance objectivity by incorporating multi-source data, such as peer reviews of social projects or employer evaluations of student internships, to validate the generalizability of the "Identity-Innovation-Responsibility" model.

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The Impact of ASEAN Trade Facilitation on Its Agricultural Exports to China

Cong Pang[1], Rongjun Huang and Lijun Yang

Business School of Dongguan City University, Dongguan 523419, China

Abstract. ASEAN occupies an important position in the global agricultural sector. For agricultural products, especially perishable goods, trade facilitation plays a significant role in promoting export performance. This study measures the level of trade facilitation in ASEAN countries from 2008 to 2022 using eleven indicators derived from the Trade Facilitation Database. Furthermore, a gravity model is employed to examine the impact of trade facilitation on ASEAN countries' agricultural exports to China. Based on the empirical results, this study proposes policy recommendations to improve trade facilitation in ASEAN, including simplifying and enhancing the transparency of tariff information, establishing fast customs clearance mechanisms, streamlining administrative procedures, and strengthening regulatory and enforcement capacity. The findings of this study not only help ASEAN countries reduce institutional and technical barriers in international trade and provide more opportunities for ASEAN agricultural products to enter global markets, but also offer important references for China in optimizing its import structure and ensuring the stability of agricultural supply chains.

Keywords. Trade Facilitation; ASEAN; Agricultural Trade; Exports

1. Introduction

Trade facilitation has become a key institutional determinant of trade competitiveness, amid global value chain restructuring and rising technical trade barriers [1]. Since China and ASEAN established their strategic partnership, bilateral trade has continued to expand steadily. In 2022, ASEAN's agricultural exports reached USD 191.914 billion, of which USD 33.755 billion were exported to China, accounting for 17.59% of

[1] Corresponding Author, Cong Pang, Business School of Dongguan City University, Dongguan 523419, China; Email: pangcong@dgcu.edu.cn

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ASEAN's total agricultural exports [2]. However, despite the deepening of trade cooperation, challenges such as trade imbalances, limited regional economic integration, and inefficient trade procedures remain significant. These constraints continue to hinder the further development of trade between ASEAN and China. In this context, trade facilitation provides new opportunities for enhancing ASEAN's agricultural export performance [2]. Existing studies on ASEAN trade facilitation largely rely on the evaluation framework proposed by Wilson et al (2003). Given that this indicator system was developed nearly two decades ago, some of its components may no longer fully capture the evolving institutional dimensions of trade facilitation. Therefore, this study adopts eleven indicators from the Trade Facilitation Database[3] to measure ASEAN's trade facilitation level. These indicators are closely aligned with the provisions of the WTO Trade Facilitation Agreement (TFA), making them particularly suitable for analyzing the trade and economic effects of TFA implementation. This study investigates the mechanisms and magnitude of the effects of major trade facilitation components on agricultural trade in ASEAN. It contributes to the literature by addressing the relative lack of empirical evidence on trade facilitation in the ASEAN context and offers policy implications for improving the international competitiveness of ASEAN agricultural exports.

2 Related works and Theoretical Basis

2.1 Related works

Regarding the measurement of trade facilitation, domestic and international scholars has conducted a substantial body of research. For instance, Peng (2022), based on panel data on China's agricultural exports to ten ASEAN countries from 2010 to 2019, constructed a trade facilitation evaluation system comprising four primary dimensions—namely infrastructure, customs environment, regulatory environment, and e-commerce—along with seventeen secondary indicators. The findings indicate that ASEAN trading partners should strengthen infrastructure development, optimize customs and institutional environments, and enhance internet technology adoption and penetration in order to promote trade facilitation [3]. Similarly, Fan Honglu et al. (2023) introduced proxy indicators such as economic freedom (EF), trade across borders (TAB), and infrastructure quality (Infra) to capture the core characteristics of trade facilitation. Their empirical results demonstrate that these three dimensions exert a significantly positive impact on the scale of China's agricultural exports to ASEAN markets [4] In addition, Zhou Hui (2023) examined the influence of trade facilitation on China's agricultural export trade and found a strong positive correlation between the level of trade facilitation in the European Union and the total volume of China–EU agricultural trade, highlighting the particularly significant role of trade facilitation in promoting bilateral agricultural trade[5]. Muhammad Jamal Hussain et al. (2025), through a comprehensive empirical evaluation, further confirmed that inefficient and non-transparent customs procedures constitute a major barrier to trade facilitation [6]. Shuangshuang Shan et al. (2025) also revealed that trade facilitation significantly promotes agricultural product trade, with the development of e-commerce emerging as the most influential driving factor [7]. In

[2] Data source: The official website of the World Trade Organization (WTO).
[3] URL of the database：https://www.compareyourcountry.org/

contrast, Sandro Steinbach and Carlos Zurita (2025) suggested that higher levels of joint implementation of the Trade Facilitation Agreement (TFA) may be associated with a reduction in agri-food global value chain flows [8]. Moreover, Huo Hong (2026) found that trade facilitation enhances the export competitiveness of China's agricultural products through two key transmission channels: the promotion of agricultural technological innovation and the integration of rural industries [1]. A review of the existing literature indicates that relatively few studies have employed indicators derived from trade facilitation databases when examining the relationship between trade facilitation and agricultural trade. Therefore, based on the status of ASEAN agricultural export trade and the development of trade facilitation within ASEAN economies, this study investigates the impact of trade facilitation levels and their constituent factors on ASEAN agricultural exports to China. This research contributes to advancing the ASEAN–China "10+1" cooperation mechanism and provides meaningful implications for China's strategy of expanding agricultural imports.

2.2 Theoretical Basis

In 1937, the British economist Ronald Coase first introduced the concept of transaction costs [9]. He defined transaction costs as the costs incurred in obtaining relevant information and conducting negotiations during economic exchanges, including expenses associated with information acquisition, bargaining, contract drafting, implementation, and enforcement. Williamson (1975) further distinguished between ex ante and ex post transaction costs and categorized them into search costs, information costs, bargaining costs, decision-making costs, monitoring costs, and enforcement costs [10].

Samuelson later proposed the concept of "iceberg costs," illustrating transaction costs through the metaphor of transporting an iceberg: part of the iceberg inevitably melts during transportation, and the melted portion represents the costs incurred in the transaction process [11]. This concept highlights the implicit losses embedded in trade activities. In the context of international trade, transaction costs encompass both direct and indirect costs arising during import and export activities. Direct costs include unavoidable expenditures such as tariffs, transportation fees, and storage expenses. They also cover time-related costs caused by customs clearance delays, opportunity costs resulting from missed market access, and value losses of perishable and technology-intensive goods. Indirect costs refer to less transparent additional expenses, including information search costs and losses associated with administrative delays. Moreover, factors such as bureaucratic inefficiency, corruption, complex trade procedures, and inadequate information technology infrastructure may further increase transaction costs, thereby constraining international trade development [9]. Trade facilitation measures examined in this study—such as tariff reduction, simplification of customs procedures, and improvements in transportation efficiency—are expected to reduce transaction costs, expand trade volumes, and strengthen economic exchanges between countries.

3 Data and Methodology

3.1 Sources and Explanations of Trade Facilitation Indicators

This study measures the level of trade facilitation in ASEAN countries using eleven indicators obtained from the Trade Facilitation Database, as shown in Table 1. These indicators are closely aligned with the provisions of the WTO Trade Facilitation Agreement (TFA), making them particularly suitable for evaluating the trade and economic effects associated with TFA implementation.

Table 1 Composition and Description of Trade Facilitation Indicators

Primary indicators	Secondary indicators	Score	Source
Policy transparency and behavioral predictability	Availability of information	0-2	Trade Facilitation Database Global Trade Facilitation Report
	the participation of trade groups	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Advance Rulings	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Appeal Procedure	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Electronic fees and charges	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Documents	0-2	Trade Facilitation Database Global Trade Facilitation Report
Automation and Simplification of Procedures	Automation	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Procedures	0-2	Trade Facilitation Database Global Trade Facilitation Report
Border Agency cooperation	Internal border agency cooperation	0-2	Trade Facilitation Database Global Trade Facilitation Report
	Cooperation with external border agencies	0-2	Trade Facilitation Database Global Trade Facilitation Report
Governance and impartiality	Governance and justice	0-2	Trade Facilitation Database Global Trade Facilitation Report

Data source: Compiled by the author based on the Trade Facilitation Database.

3.2 Measurement and Analysis of Trade Facilitation Indicators

The data for the eleven secondary trade facilitation indicators are drawn from two sources. Specifically, observations for the years 2015, 2017, 2019, and 2022 are obtained directly from the Trade Facilitation Database. However, since the database was established in 2013 and is updated biennially, relying solely on this source would limit the continuity of the time series and constrain longitudinal analysis of ASEAN trade facilitation. To ensure data consistency over the full sample period, this study supplements pre-2015 observations (i.e., 2008, 2009, 2010, 2012, and 2014) using the Enabling Trade Index from the Global Enabling Trade Report. For intermediate missing years such as 2011 and 2013, values are estimated using linear interpolation in order to maintain the balanced panel structure.

Given the differences in data sources, the indicators from the two datasets are harmonized to ensure comparability and consistency. The integration process of the two indicator systems is summarized in Table 2.

Table 2 Harmonization of Trade Facilitation Indicators from Different Sources

Classification of trade facilitation indicators	Global Trade Facilitation Report: 2008-2014	Trade Facilitation Database: 2015
I. Transparency and predictability	I. Transparency and predictability	I. Transparency and predictability
1. A-Information availability 2. B-Involvement of the trade community 3. C-Advance rulings 4. D-Appeal procedures 5. E-Fees and charges	1. Transparency of border administration 2. availability and quality of transport infrastructure 3. availability and quality of transport services 4. Domestic and foreign market access	1. Domestic market access 2. Foreign market access 3 availability and quality of transport infrastructure 4. availability and quality of transport services
II. Automation and Simplification of Procedures	II. Automation and Simplification of Procedures	II. Automation and Simplification of Procedures
1. F-Documents 2. G-Automation 3. H-Procedure	Availability and use of ICTs	Availability and use of ICTs
III. Border Agency Cooperation	III. Border Agency Cooperation	III. Border Agency Cooperation
1. I-Internal border agency cooperation 2. J- Cooperation with external border agencies	1. Efficiency of customs administration 2. Efficiency of import-export procedures	Efficiency and transparency of border administration
IV. Governance and impartiality	IV. Governance and impartiality	IV. Governance and impartiality
K-Governance and impartiality	1. Regulatory environment 2. Physical security	Operating environment

Data source: Compiled by the author based on the Trade Facilitation Database and the Global Trade Facilitation Report.

During the data harmonization process, it was observed that the trade facilitation index in the *Global Trade Facilitation Report* consisted of nine indicators prior to 2014, but was reduced to seven indicators starting from 2014. Consequently, adjustments and consolidation were undertaken to ensure consistency across different reporting periods. To enhance the comparability of data derived from the two sources, this study uses the Trade Facilitation Database and the 2012 *Global Trade Facilitation Report* as benchmark references for cross-validation. A rescaling procedure was applied to standardize the measurement units, thereby enabling alignment of the four primary trade facilitation dimensions across the two datasets. The specific transformation process is presented as follows:

$$\frac{\sum (Y_i / n)}{7} = \frac{Z_i}{2} \tag{1}$$

So, Y_i denotes the trade facilitation index reported in the *Global Trade Facilitation Report*, n represents the number of sub-indicators included in the index, and 7 denotes

the maximum possible score of the trade facilitation index. $Z_j(j = 1,2,3,4)$refers to the four primary indicators in the Trade Facilitation Database, with 2 representing the maximum score for each primary indicator.

Through the rescaling procedure, values of the primary indicators are derived to ensure comparability across datasets. Subsequently, the weighted average of the four primary dimensions is calculated to obtain the overall trade facilitation level for the ten ASEAN countries.

Transparency and Predictability = (Information Availability + Involvement of the Trade Community + Advance Rulings + Appeal Procedures + Fees and Charges) / 5
Automation and Simplification of Procedures = (Documents + Automation + Procedures) / 3

Border Agency Cooperation= (Internal Border Agency Cooperation + External Border Agency Cooperation) / 2

Governance and Impartiality= Simple weighted average of governance-related indicators for each ASEAN country

The overall trade facilitation level for ASEAN is calculated as:
Trade Facilitation Index = (Transparency and Predictability + Automation and Simplification of Procedures + Border Agency Cooperation + Governance and Impartiality) / 4
Since the OECD trade facilitation indicators do not assign differentiated importance to individual components, all variables are given equal weights in the aggregation process. The estimated trade facilitation levels of ASEAN countries are presented in Table 3.

Table 3 Trade Facilitation Levels of ASEAN Countries, 2008–2022

	Singapore	Malaysia	Thailand	Indonesia	Brunei	Vietnam	Philippines	Cambodia	Laos	Myanmar
2008	1.6286	1.3714	1.2000	1.2286	*	0.9714	1.0286	0.8571	*	*
2009	1.7143	1.3429	1.2000	1.0857	*	1.0000	1.0286	1.0000	*	*
2010	1.7429	1.3429	1.1714	1.1429	*	1.1429	1.0571	1.0286	*	*
2012	1.7429	1.4000	1.2000	1.2000	*	1.1429	1.1429	1.0000	*	*
2014	1.6857	1.3714	1.2000	1.2000	*	1.1429	1.1714	1.0571	1.0286	0.8857
2015	1.7891	1.4491	1.6145	1.4691	1.1050	1.3082	1.2636	0.9260	0.7682	0.0000
2017	1.7480	1.2490	1.3480	1.1170	1.1090	1.2570	1.0280	0.9160	0.6950	0.5350
2019	1.8080	1.4180	1.4390	1.3490	1.3480	1.3930	1.2290	1.1320	0.8910	1.0170
2022	1.8490	1.5550	1.5110	1.4180	1.3760	1.4740	1.3660	1.2390	0.9100	1.0860
Rank	1	2	3	4	5	6	7	8	9	10

Note: * indicates missing data.
Data source: Calculated based on the Trade Facilitation Database and the *Global Trade Facilitation Report*.

3.3 Model Settings

Building upon the traditional gravity model, this study incorporates additional explanatory variables, including the level of trade facilitation in ASEAN countries, GDP of ASEAN countries, the geographical distance between ASEAN capitals and Beijing, and the population size of ASEAN countries. These variables are introduced to extend the conventional gravity framework and better capture institutional and economic determinants of agricultural trade flows [10].
The empirical model is specified as follows:

$$LnExport_{ijt} = a_0 + a_1 LnGDP_{it} + a_2 LnGDP_{jt} + a_3 LnD_{ij} + a_4 LnPOP_{it} + a_5 LnTIF_{it} + \varepsilon_{ijt} \quad (2)$$

The above model represents an extended gravity specification in which both sides are transformed into logarithmic form. In the model, i denotes the exporting country (ASEAN member states), j represents the importing country (China), and t denotes the year. α_0 is the constant term, αrepresents the estimated coefficients, and ε_{ijt} is the stochastic error term. In the empirical specification, the dependent variable is $Export_{ijt}$, which measures the value of agricultural exports from ASEAN country $i$to China in year t. The explanatory variables include the GDP of ASEAN country $i(GDP_{it})$, China's GDP (GDP_{jt}), the geographical distance between the two countries (D_{ij}), the trade facilitation level of ASEAN country $i(TIF_{it})$, and the population size of ASEAN country $i(POP_{it})$.

4 Empirical Analysis and Results

4.1 descriptive analysis

Descriptive statistics are first conducted for the panel dataset used in this study. The sample covers the period from 2008 to 2022, during which both the number of cross-sectional units and the time dimension remain unchanged. The results of the descriptive analysis are reported in Table 4.

Table 4 Results of Descriptive Statistical Analysis

Variables	Sample size	Average	Standard deviation	Maximum value	Minimum value
TIF	150	1.088	0.489	1.849	0
GDP_i (dollar)	150	2.64E+11	2.79E+11	1.32E+12	5.45E+09
GDP_j (dollar)	150	1.10E+13	4.09E+12	1.80E+13	4.59E+12
D_{ij} (kilometers)	10	3090.971	745.524	4562.061	2212.344
POP_i (person)	150	63400394	74177873	275501339	384568

Data source: Calculated by the author using Stata 17.

As shown in Table 4, the trade facilitation index across ASEAN countries ranges from a minimum value of 0 to a maximum of 1.849, with a standard deviation of 0.489. This indicates substantial cross-country variation in trade facilitation levels within ASEAN. In addition, considerable heterogeneity is observed in economic development and market size among ASEAN member states. The GDP of ASEAN countries range from USD 5.446 billion to USD 1,319 billion, with a standard deviation of USD 279.4 billion, reflecting significant disparities in economic scale across the region.

4.2 Multicollinearity Test

To assess the robustness of the empirical specification, multicollinearity among the explanatory variables is examined using the Variance Inflation Factor (VIF) test. The results are reported in Table 5. The VIF values for all variables are below the commonly accepted threshold of 10, with a mean VIF of 3.55. These results indicate that

multicollinearity is not a serious concern in the model, thereby supporting the reliability of subsequent regression analysis.

Table 5 Results of the Multicollinearity Test

Variables	VIF
TIF	3.17
$lnGDP_i$	7.26
$lnPOP_i$	4.05
lnD_{ij2}	1.89
$lnGDP_j$	1.36
Mean VIF	3.55

Data source: Calculated by the author using Stata 17.

4.3 Baseline Regression Results

This study employs Stata 17 to conduct panel regression analysis using data on ASEAN agricultural exports to China from 2008 to 2022. The baseline regression results are reported in Table 6.

Table 6 Baseline Regression Results

Variables	Empirical Results
tif	0.870 * * *
	(4.90)
$lngdp_i$	1.604 * * *
	(7.66)
$lngdp_j$	3.124 * * *
	(7.61)
lnd_{ij}	-5.268 * * *
	(-7.11)
lnpop	0.540 * * *
	(5.45)
_cons	-83.23 * * *
	(-6.67)
N	150

Note: *t* statistics in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data source: Calculated by Stata 17 software

The regression results indicate that trade facilitation, GDP levels of both ASEAN and China, and population size are positively associated with ASEAN's agricultural exports to China. Specifically, the coefficient of trade facilitation (TIF) is 0.870 and statistically significant at the 1% level, suggesting that a 1% increase in ASEAN's trade facilitation level is associated with a 0.87% increase in its agricultural exports to China. This finding confirms the trade-enhancing effect of institutional improvements such as streamlined customs procedures and enhanced administrative efficiency. The GDP of ASEAN countries (lnGDPi) has a positive and significant coefficient of 1.604, indicating that a 1% increase in ASEAN's economic output leads to a 1.604% increase in agricultural exports to China. Higher GDP levels reflect stronger production capacity and export

potential, thereby facilitating greater trade flows. China's GDP (lnGDPj) also shows a significant positive coefficient of 3.124, implying that a 1% increase in China's GDP results in a 3.124% increase in ASEAN's agricultural export [11]. This suggests that China's expanding economic scale and purchasing power play a critical role in driving import demand for ASEAN agricultural products. Population size (lnPOP) exhibits a positive and statistically significant coefficient of 0.540. A 1% increase in population is associated with a 0.54% increase in agricultural exports. This result may reflect the labor-intensive nature of agricultural production in most ASEAN countries, where a larger labor force can enhance production capacity and reduce unit costs. In contrast, geographical distance (lnDij) has a negative and significant coefficient of -5.268, indicating that a 1% increase in distance leads to a 5.268% decrease in agricultural exports. This indicates that the considerable distance has hindered the growth of ASEAN agricultural trade [12].

4.4 Robustness Tests

To further examine the robustness of the baseline results, this study replaces the overall trade facilitation index with its four primary components—Transparency and Predictability (A), Automation and Simplification of Procedures (D), Border Agency Cooperation (C), and Governance and Impartiality (G)—and re-estimates the model separately for each dimension. By incorporating each sub-dimension into the regression model individually, the robustness of the trade facilitation effect on ASEAN's agricultural exports to China can be assessed. The corresponding regression specifications are presented as follows.

$$LnExport_{ijt} = a_0 + a_1 LnGDP_{it} + a_2 GDP_{jt} + a_3 LnD_{ij} + a_4 LnPOP_{it} + a_5 LnA_{it} + \varepsilon_{ijt} \quad (3)$$

$$LnExport_{ijt} = a_0 + a_1 LnGDP_{it} + a_2 GDP_{jt} + a_3 LnD_{ij} + a_4 LnPOP_{it} + a_5 LnD_{it} + \varepsilon_{ijt} \quad (4)$$

$$LnExport_{ijt} = a_0 + a_1 LnGDP_{it} + a_2 GDP_{jt} + a_3 LnD_{ij} + a_4 LnPOP_{it} + a_5 LnC_{it} + \varepsilon_{ijt} \quad (5)$$

$$LnExport_{ijt} = a_0 + a_1 LnGDP_{it} + a_2 GDP_{jt} + a_3 LnD_{ij} + a_4 LnPOP_{it} + a_5 LnG_{it} + \varepsilon_{ijt} \quad (6)$$

Table 7 Regression Results by Trade Facilitation Sub-Dimensions

Variable	(3)	(4)	(5)	(6)
	Ln Export$_1$	*Ln*Export$_1$	*Ln*Export$_1$	*Ln*Export$_1$
*Ln*A	0.569***			
	(4.52)			
*Ln*D		-0.206*		
		(-1.84)		
*Ln*C			1.236***	
			(8.39)	
*Ln*G				0.773***
				(6.33)
*Ln*GDP$_i$	1.105***	2.082***	1.892***	2.066***
	(6.51)	(11.85)	(10.21)	(9.36)
*Ln*GDP$_j$	2.722***	5.059***	3.414***	3.636***
	(7.57)	(15.46)	(12.64)	(9.67)

LnD_{ij2}	-2.853***	-5.404***	-5.337***	-6.518***
	(-5.15)	(-7.75)	(-8.76)	(-7.08)
$LnPOP_i$	0.793***	0.397***	0.216**	0.291***
	(11.66)	(4.43)	(2.36)	(2.65)
_cons	-82.82***	-150.0***	-92.83***	-96.07***
	(-7.54)	(-17.02)	(-10.61)	(-7.88)

Note: *t* statistics in parentheses * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$
Data source: Calculated by Stata 17 software

The results reported in Table 7 indicate that when the four primary components of the trade facilitation index are introduced separately into the regression model, the overall findings remain largely consistent with the baseline results. The statistical significance and coefficient signs of the core variables do not exhibit substantial changes, suggesting that the main conclusions are robust to alternative specifications. However, the magnitude of the effects differs across the four dimensions. Transparency and Predictability (A), Border Agency Cooperation (C), and Governance and Impartiality (G) are all statistically significant at the 1% level. Specifically, a 1% improvement in border agency cooperation is associated with a 1.236% increase in ASEAN's agricultural exports to China, holding other factors constant. This finding implies that enhanced coordination among border authorities can accelerate customs clearance, reduce inspection frequency, improve administrative efficiency, and ultimately lower trade costs. Similarly, a 1% increase in transparency and predictability leads to a 1.105% increase in agricultural exports [13]. Transparent trade regulations and predictable tariff policies reduce uncertainty and enable exporters to better plan and execute trade activities, thereby facilitating export growth. Governance and impartiality also exhibit a significant positive effect: a 1% improvement in governance quality is associated with a 0.773% increase in agricultural exports. A fair and well-governed institutional environment helps reduce corruption and discriminatory practices, ensuring equal participation in international trade [14]. In contrast, Automation and Simplification of Procedures (D) is only significant at the 10% level. The relatively lower level of statistical significance suggests that the effect may be less stable and warrants further investigation. Given data limitations and potential measurement constraints, this study does not explore this dimension in greater dept.

Overall, the robustness analysis confirms that the key components of trade facilitation—particularly transparency, border cooperation, and governance—play an important role in promoting ASEAN's agricultural exports to China. Improvements in institutional transparency, administrative coordination, and governance quality not only reduce trade costs and uncertainty but also enhance export competitiveness in the Chinese market.

5. Policy Implications

Based on the empirical findings, several policy implications can be drawn to enhance ASEAN's agricultural exports to China and to support evidence-based trade policy design.

(1) Improving Transparency and Predictability

The quantitative results indicate that transparency and predictability in trade policy exert

a significant positive effect on agricultural export performance. When tariff policies and non-tariff measures are transparent and stable, and when traders can easily access information related to import, export, and transportation procedures—including required documentation and forms—agricultural exports from ASEAN countries increase significantly [12]. Accordingly, several measures may be considered. First, tariff information systems should be streamlined and made publicly accessible. Governments may establish centralized and regularly updated digital platforms providing comprehensive information on tariffs and non-tariff barriers. Such platforms can reduce uncertainty and information asymmetry faced by exporters. Second, strengthening legal transparency and regulatory predictability is essential. By enhancing legal frameworks and improving the consistency and clarity of trade-related regulations, ASEAN governments can provide a more stable institutional environment for exporters, thereby safeguarding commercial interests and promoting sustainable regional trade development. Third, administrative efficiency should be further improved. Simplifying approval procedures, digitalizing government services, and reducing bureaucratic delays can lower transaction costs and facilitate smoother export operations. Fourth, deeper engagement in bilateral and multilateral trade agreements may enhance policy credibility. Clearly defined tariff concessions, quota arrangements, and trade commitments can improve policy predictability and strengthen exporters' confidence.

(2) Strengthening Border Agency Cooperation

The empirical results demonstrate that effective cooperation among border management agencies significantly reduces customs clearance time and transaction costs, thereby promoting agricultural exports. In particular, streamlined clearance procedures and faster processing times can substantially lower exporters' operational costs and enhance export performance to China. Several policy directions may therefore be considered. First, expedited customs clearance mechanisms should be established. Governments may cooperate with major trading partners to implement "green channels" or fast-track clearance procedures, particularly for perishable agricultural products. Such mechanisms can reduce delays and mitigate the risk of quality deterioration. Second, enhanced coordination in combating smuggling and illegal trade is essential. Joint enforcement efforts can ensure smoother legal trade flows while protecting the interests of compliant exporters. Third, deeper institutional coordination among border control agencies and transit authorities should be promoted. This may include harmonizing working days and operating hours, aligning procedural requirements, sharing infrastructure facilities, implementing joint inspections, and developing one-stop border posts. Improved administrative integration can significantly reduce duplication and inefficiencies in cross-border procedures. Finally, improvements in customs administration and transport logistics efficiency are crucial. Reducing border delays enhances the predictability and timeliness of goods release, which is particularly important in modern supply chains characterized by just-in-time production and delivery. A more efficient border environment can create a more favorable trade ecosystem for ASEAN exporters, especially small and medium-sized enterprises, thereby strengthening export competitiveness.

(3) Improving Governance and Impartiality

The empirical findings suggest that stronger governance quality and a fair-trade environment significantly enhance export efficiency and competitiveness in agricultural trade. Improvements in governance—such as reducing corruption, minimizing administrative barriers, and strengthening institutional accountability—are positively associated with export performance [13]. Several policy measures may therefore be

considered. For example, they should strengthen anti-corruption efforts and administrative reforms. Governments should enhance anti-corruption measures, simplify administrative procedures, improve government efficiency, and ensure that exporters can fairly obtain the necessary export licenses and documents. They can also strengthen supervision and enforcement to ensure the fair and impartial implementation of trade rules and standards, reducing unfair treatment and unnecessary administrative barriers. Simultaneously, by simplifying trade procedures and reducing the time required for cross-border transportation and customs clearance, the likelihood of fraudulent activities at the border can be reduced.

Overall, enhancing ASEAN's agricultural export competitiveness in the Chinese market requires deeper regional and international cooperation. Strengthening collaboration in trade facilitation initiatives and institutional coordination can contribute to a more efficient and integrated trading environment. In addition, continued investment in infrastructure and technological upgrading are essential. Modernizing border infrastructure, adopting advanced digital systems, and improving customs automation can enhance both efficiency and transparency, thereby supporting the long-term sustainability of trade facilitation reforms [14]. Finally, continuous monitoring and evaluation mechanisms should be established. Systematic data collection and performance assessment can help identify emerging bottlenecks and policy gaps, enabling timely adjustments and evidence-based policymaking. The quantitative analysis presented in this study provides empirical evidence on the role of trade facilitation in promoting ASEAN's agricultural exports to China. These findings offer a reference for designing more effective trade policies and may also provide insights into other economies seeking to enhance agricultural export performance through institutional reforms.

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Digitalization in Megaprojects: Stakeholder Governance, Hope, and Project Resilience

Baris MORKAN[1]
Independent Researcher, New Jersey, USA
ORCiD ID: Baris Morkan https://orcid.org/0000-0002-1135-4934

Abstract. Megaprojects increasingly deploy digital technologies—artificial intelligence (AI), Building Information Modeling (BIM), and collaboration platforms—to manage complexity and uncertainty. Yet empirical evidence shows that similar digital infrastructures often produce sharply divergent resilience outcomes across projects. This conceptual paper develops an integrative theoretical framework proposing how digitalization may influence megaproject resilience through stakeholder governance configurations and the psychological mechanism of hope. We theorize that digital technologies do not directly generate resilience. Instead, their effects are shaped by governance strategies—managing of, for, or with stakeholders—which shape how digital systems are configured and experienced, potentially activating or suppressing stakeholder hope, defined as perceived agency and pathways toward goal attainment. During unexpected events, we argue that hopeful stakeholders are more likely to engage in voluntary collaborative behaviors that enable resilient adaptation, whereas hopeless stakeholders withdraw. By integrating stakeholder governance theory, socio-technical perspectives, and hope theory, this paper contributes a set of theoretically grounded but empirically untested propositions: (1) theorizing digitalization as governance-embedded rather than technologically deterministic, (2) identifying stakeholder hope as a critical psychological mechanism linking digital governance to collaboration, and (3) extending resilience theory by explaining how digital technologies may condition stakeholder citizenship behaviors during crises.

Keywords. Megaprojects; digitalization; stakeholder management; hope; resilience

1. Introduction

Megaprojects are increasingly delivered under profound uncertainty, including climate disruption, regulatory volatility, and technological change [1]. Unexpected events—pandemics, financial crises, and technical failures—have become endemic in megaproject delivery [2]. In response, organizations have invested heavily in digital technologies such as AI analytics, Building Information Modeling (BIM), digital twins, and collaboration platforms, expecting enhanced coordination and resilience [3].

Despite widespread adoption, digitalization has not consistently delivered resilient outcomes [3]. We refer to this phenomenon as the digitalization paradox: the observation that similar digital infrastructures may yield divergent outcomes—facilitating rapid adaptation in some projects while intensifying surveillance or conflict in others [4]. This suggests that technology's impact is not universal but is bounded by specific governance and institutional conditions. Divergent outcomes often emerge under particular project arrangements—for example, adversarial procurement models that structure incentives

[1] Corresponding Author: Baris Morkan, Email: bmorkan1@stevens.edu

and risk allocation, contested data ownership and access rights among stakeholders, or heightened regulatory and contractual oversight that shape how digital infrastructures are configured and used by project participants [5,6].

Indeed, while digital tools can improve collaboration, real-time decision-making, and project performance, their implementation also faces organizational, cultural, and governance barriers that may limit or undermine these benefits [7]. Emerging research reinforces this view. Armanios and Tucci demonstrate that AI performance depends not simply on technological capabilities but on organizational readiness and governance choices navigating tensions between control and autonomy [8]. Liedtka and Locatelli show that project underperformance often stems from failures to engage stakeholder dimensions shaping sensemaking rather than technical deficiencies [9]. Toukola and Ahola demonstrate empirically that digital tools for stakeholder participation generate markedly different outcomes depending on how governance structures shape their implementation [10]. Wijayasekera et al. further show that AI and data analytics in megaprojects require governance structures and organizational alignment to realize their coordination potential [11]. These perspectives collectively suggest that digitalization's contribution depends fundamentally on governance choices shaping how digital infrastructures are configured and enacted within projects.

This paper addresses the following research question: How does digitalization in megaprojects influence resilience through governance configurations and stakeholder psychological mechanisms? We argue that digital technologies do not directly generate resilience. Their effects are shaped by governance strategies, stakeholder hope, and discretionary collaboration. Accordingly, we develop an integrative framework with six propositions explaining governance-embedded digitalization, hope-mediated collaboration, and the digital amplification of resilience mechanisms.

2. Theoretical Background

2.1 Stakeholder Governance and Digital Configuration

Stakeholder governance refers to the structures and practices through which projects engage these actors [8,12]. Building on the existing literature on stakeholder management approaches, we distinguish three stakeholder governance strategies. Management *of* stakeholders emphasizes control, compliance, and risk containment, typically relying on centralized authority and selective stakeholder engagement [13,14]. Managing *for* stakeholders reflects a benevolent representation logic in which project leaders seek to balance stakeholder interests while retaining ultimate decision-making authority [13,14]. Managing *with* stakeholders, in contrast, emphasizes collaboration, shared decision-making, and distributed agency, treating stakeholders as active partners in shaping project processes and outcomes [15,16]. These three strategies are conceived as ideal types—analytical abstractions representing pure forms seldom found in practice, as real megaproject configurations are frequently hybrid and phase-dependent: a project may manage with contractors while managing of community groups, and these configurations may shift following unexpected events as power dynamics and accountability pressures are renegotiated. The framework's propositions are therefore best understood as tendencies associated with dominant governance orientations rather than fixed or universal outcomes.

Each governance mode can be distinguished through a set of observable indicators. Management *of* stakeholders is commonly associated with leadership-controlled data access, AI outputs presented as non-contestable directives, broadcast-oriented communication platforms, and unilateral dispute resolution mechanisms. Managing *for* stakeholders corresponds to filtered data sharing, AI-generated predictions presented as guidance with limited contestability, structured feedback channels, and leadership-mediated dispute resolution. Managing *with* stakeholders, in contrast, aligns with open real-time data access, stakeholder-informed and contestable AI models, multi-directional collaborative platforms, and participatory dispute resolution mechanisms.

In this study, stakeholders primarily refer to internal stakeholders involved in megaproject processes, whose voluntary actions can be critical to project resilience. While the primary focus of the framework is on internal stakeholders, external stakeholders—including community groups, regulators, NGOs, nearby residents, and other actors capable of influencing project processes—are also relevant to project dynamics. In particular, these external actors may initiate, participate in, or amplify the domino effects that shape collective responses to unexpected events [16]. Accordingly, the framework identifies a key boundary condition: stakeholders must possess sufficient structural access to governance processes for hope activation to occur.

This boundary condition reflects the heterogeneous structural positions of megaproject stakeholders, ranging from operational actors (e.g., contractors and engineers) to strategic decision-makers (e.g., project owners, regulators, and public authorities) who differ in authority, resources, and influence over project outcomes. Consistent with Snyder's [17] hope theory, which conceptualizes agency and pathway perceptions as individual-level cognitive states, hope is theorized to originate at the individual stakeholder level and subsequently aggregate—through interaction and collaboration—into collective hope across the stakeholder community. Collective hope, in turn, motivates collaborative citizenship behaviors that support project-level resilience during unexpected events. The activation and aggregation of hope are therefore likely to vary across stakeholder tiers depending on their structural access to governance processes and decision authority. While governance structures shape the conditions under which stakeholders operate, stakeholders remain active agents whose voluntary behaviors ultimately determine whether collaborative responses emerge during unexpected events.

These governance strategies shape how digital technologies are configured. Digital technologies—BIM, AI analytics, digital twins, platforms—offer three core affordances: Visibility (dashboards, BIM models making project status transparent), Anticipation (AI forecasting, scenario simulation), and Interaction (collaboration platforms, communication tools) [18,19]. These affordances are not inherently empowering or constraining. In practice, however, these affordances are rarely distributed uniformly across project participants. Digital infrastructures in megaprojects are typically architected through role-based access controls, technical standards, and expert mediation (e.g., BIM managers or data stewards), which shape how information is accessed, interpreted, and acted upon by different stakeholders [5]. Under control governance, visibility may tend toward surveillance, anticipation toward technocratic control, and interaction toward one-way communication. Under collaborative governance, the same affordances can enable shared sensemaking, participatory problem-solving, and distributed coordination [20].

Control governance tends to produce surveillance-oriented systems with leadership-only dashboards, centralized AI, and restricted platforms. Collaborative governance

tends to produce participation-oriented systems with distributed data access, stakeholder input to AI models, and open platforms. Empirical studies demonstrate that technological capability alone is insufficient, as successful implementation depends on governance mechanisms and organizational alignment [21]. Hussain et al., comparing BIM implementation across the Crossrail (UK) and Nagpur Metro (India) projects, found that despite deploying comparable digital platforms, the two projects achieved markedly different coordination outcomes—a divergence traced to differences in governance architecture, BIM policy alignment, and Common Data Environment configuration rather than the technologies themselves [22]. The study on Hong Kong–Zhuhai–Macao Bridge similarly shows that coordination effectiveness depended not on digital technology per se, but on a governance architecture distributing data access across contractor and authority levels—enabling stakeholders to act on shared situational awareness throughout construction, with reported improvements in cross-organizational coordination attributed to shared data access and integrated information flows rather than to the deployment of digital tools alone [23].

It is important to recognize, however, that each affordance carries potential negative pathways. Visibility affordances can trigger surveillance anxiety and blame cultures when performance metrics are used punitively [19]. Anticipation affordances can produce algorithmic opacity when AI-driven predictions are presented as authoritative directives without stakeholder input, creating fatalism rather than pathway thinking [8]. Interaction affordances can amplify conflict and coordination noise when platforms lack clear governance structures [18]. These negative pathways are not inevitable but are shaped by governance choices—specifically, transparent data rights, contestability mechanisms enabling stakeholders to challenge AI assumptions, and platform moderation rules that channel interaction toward constructive problem-solving rather than conflict escalation.

2.2 Digital Configuration and Stakeholder Hope

Hope is theorized as a cognitive-motivational state constituted by two interdependent components: agency—the belief in one's capacity to initiate and sustain goal-directed action—and pathways—the perceived availability of viable routes through which goals may be achieved [17]. Although hope is frequently conflated with related positive psychological states, it is conceptually and functionally distinct. Unlike optimism, which reflects a generalized positive expectancy regarding outcomes without specifying the means through which they are attained, hope requires both the cognitive appraisal of personal capacity (the will) and the identification of actionable routes (the way) [17]. In this framework, collective hope—shared stakeholder beliefs in group agency and viable collaborative pathways—serves as the focal mediating construct, while individual hope functions as its micro-foundation, providing the psychological substrate from which collective hope emerges through social interaction and governance-embedded digital configurations.

The distinctiveness of hope becomes evident when compared with related constructs often used to explain collaborative behavior in organizational settings. Trust concerns expectations about another party’s reliability and benevolence and is therefore other-directed rather than self-referential, while also requiring time to develop—something the temporary nature of projects may not permit [24]. Psychological safety reflects shared beliefs that interpersonal risk-taking will not result in punishment, indicating the absence of threat rather than the presence of goal-directed motivation [25]. Collective efficacy

captures shared beliefs in a group's capacity to act [26] but lacks hope's pathways dimension—the perceived routes through which collective goals can be pursued. Empowerment and procedural justice describe structural or procedural conditions enabling participation rather than internalized motivational states. Crucially, hope is a multifaceted construct encompassing emotional, cognitive, and action components [27], rendering it richer and more encompassing than constructs such as efficacy or trust that operate through narrower mechanisms. Furthermore, unlike purely social or systemic constructs, hope is tied to existential significance—the sense that one's actions carry deep meaning and purpose [28]—making it particularly suited to megaproject contexts navigating uncertainty, where deep meaning guides practice and commitment to change. This meaning-orientation also implies, however, that hope may be fragile or misplaced when governance structures fail to deliver genuine agency to stakeholders. Hope thus uniquely integrates the will (agency), the way (pathways), and the why (existential meaning), making it the most appropriate construct to explain voluntary stakeholder mobilization during crises when formal coordination is absent. This theoretical grounding is supported empirically: drawing on Hope Theory [17] and Collective Action Theory [29], prior research links hope to engagement across domains, including climate action contexts [27,30] and organizational settings [31].

Digital configurations activate or suppress hope through their affordances. Participation-oriented configurations foster hope by: (1) making collective capability visible through transparent dashboards, (2) providing anticipatory tools enabling stakeholders to identify pathways, and (3) offering interactive platforms facilitating coordination. These affordances strengthen both agency beliefs (stakeholders see their impact matters) and pathway perceptions (stakeholders identify viable routes). The mechanisms through which each affordance operates are distinct. Visibility affordances—shared dashboards and open BIM models—reduce information asymmetry and uncertainty, enabling stakeholders to perceive their contributions as consequential and thereby strengthening agency beliefs [19]. Anticipation affordances—participatory AI analytics and scenario simulation tools—enable stakeholders to jointly explore future states and identify viable courses of action, directly strengthening pathway perceptions by making routes to project goals concrete and negotiable [8]. Interaction affordances—collaborative platforms and communication tools—reduce coordination costs and facilitate cross-boundary problem-solving, reinforcing stakeholders' beliefs that collective action is both possible and effective [32]. Together, these mechanisms explain why participation-oriented digital configurations tend to generate hope: they simultaneously make agency visible, pathways concrete, and coordination feasible. Critically, these configurations do not activate or suppress hope independently of governance strategy—rather, digital configuration moderates the relationship between governance strategy and stakeholder hope, translating governance intent into the affordance structures that determine whether hope is activated or suppressed.

2.3 Hope and Collaborative Citizenship Behaviors

Unexpected events disrupt formal coordination mechanisms and create conditions requiring adaptive stakeholder response [2]. Megaproject resilience during such events depends critically on stakeholder citizenship behaviors: voluntary actions beyond contractual obligations including proactive information sharing, cross-boundary joint problem-solving, voluntary sacrifice, and extraordinary effort [16]. Unlike routine project collaboration—which encompasses contractually mandated coordination,

scheduled reporting, and formally required information exchange—collaborative citizenship behaviors are discretionary and self-initiated, emerging from stakeholders' intrinsic motivation rather than contractual obligation, and are therefore neither predictable through formal governance mechanisms nor enforceable through contractual means [16]. Unexpected events serve as triggers activating the need for these behaviors, elevating voluntary stakeholder action as the primary determinant of adaptive response [16, 33]. Whether stakeholders respond to such triggers with engagement or withdrawal depends critically on their level of hope, which is in turn shaped by governance-embedded digital configurations.

Several mechanisms could explain stakeholder responses to unexpected events, yet hope captures dimensions these alternatives only partially address. Resilience describes the capacity to rebound from adversity but does not explain how stakeholders identify new collaborative pathways when coordination structures collapse [34]. Grit reflects perseverance but is largely dispositional [35], while collective efficacy captures shared beliefs in group capability yet lacks hope's pathways dimension [26]. Hope uniquely integrates the motivational will to act, the cognitive capacity to generate new pathways, and the existential conviction that action carries meaning—addressing all three psychological demands of crisis response simultaneously, and doing so through a mechanism that is state-like and therefore directly activatable through governance choices and digital configurations.

2.4 Collaboration and Megaproject Resilience

Morkan et al. identified three critical transition mechanisms through which individual citizenship behaviors scale into collective megaproject resilience: power in numbers, whereby individual MCBs aggregate to the group level through copying and diffusion; boosting, whereby critical issues reach the right decision-makers through vertical or horizontal routing; and mindset shift, whereby a dominant percentage of a stakeholder group internalizes new collaborative norms, making those behaviors self-sustaining [16]. The framework advanced here builds on and extends this model by theorizing that digital platforms, when configured within collaborative governance structures, are likely to accelerate and sustain each mechanism beyond what face-to-face coordination alone could achieve.

Megaproject resilience encompasses three dimensions: adaptive capacity reflects rapid operational adjustments that maintain project momentum; transformative capacity reflects fundamental redesign when adaptation proves insufficient; and sustained performance reflects the ability to maintain progress despite ongoing volatility [16,36]. Within the framework developed in this study, resilience is conceptualized as an emergent systemic property—a contingent outcome that arises when governance-embedded digital configurations activate stakeholder hope, which in turn motivates collaborative citizenship behaviors enabling adaptive, transformative, and sustained performance when unexpected events occur. Accordingly, resilience is not an inherent property of digital infrastructure but a contingent outcome emerging from governance-contingent socio-technical interactions over time. In practice, digital infrastructures are typically deployed to address operational coordination and information management challenges rather than to build resilience as an explicit design objective [1,11].

Building on Morkan et al. (2023), collaborative citizenship behaviors constitute a key mechanism through which stakeholder collaboration contributes to megaproject resilience. Collaborative citizenship behaviors enable all three dimensions. Proactive

information sharing and cross-boundary problem-solving strengthen adaptive capacity by enabling rapid collective sensemaking. Voluntary sacrifice and extraordinary effort enable transformative capacity by mobilizing resources for fundamental redesign. Sustained collaboration maintains performance despite continuing disruption [16]. While these behaviors can strengthen resilience, their effects are not uniformly positive. Organizational research suggests that discretionary collaboration may also generate unintended consequences, including role overload, informal rule circumvention, or suppressed dissent. In megaproject environments characterized by power asymmetries and institutional constraints, governance structures therefore shape whether such behaviors translate into project-level resilience.

Table 1 summarizes the theoretical relationships developed in Section 2. The table presents ideal-type configurations; real governance arrangements are frequently hybrid and outcomes may vary by context, stakeholder characteristics, and project phase.

Table 1. Linking Stakeholder Governance Strategies to Digitalization, Hope, and Resilience

	Management *OF* Stakeholders	**Managing *FOR* Stakeholders**	**Managing *WITH* Stakeholders**
Governance Logic	Control, compliance, and risk containment; stakeholders as potential risks to be managed	Benevolent representation; leaders balance stakeholder interests but retain ultimate authority	Collaborative partnership; stakeholders as co-creators with distributed decision authority
Digital Visibility (Dashboards, BIM)	Surveillance monitoring: Dashboards, BIM for centralized visibility accessible only to leadership; performance tracking for compliance; information asymmetry maintained	Selective transparency: Filtered information sharing; read-only dashboard access; leaders decide what stakeholders "need to know"	Distributed transparency: Shared real-time data access; open BIM models for joint review; collective sensemaking enabled
Digital Anticipation (AI, Analytics)	Algorithmic control: AI-driven resource allocation (top-down); predictive models optimize efficiency; forecasts direct behavior	Paternalistic forecasting: Leaders interpret analytics "for stakeholder benefit"; predictions shared as guidance; limited ability to challenge assumptions	Participatory foresight: AI insights discussed collaboratively; stakeholders contribute local knowledge; joint scenario planning
Digital Interaction (Platforms)	One-way communication: Broadcast channels for directives; minimal feedback mechanisms; hierarchical workflows enforced	Managed dialogue: Structured feedback channels; surveys and consultations; leaders retain decision authority; input selectively incorporated	Collaborative co-creation: Multi-directional communication; shared digital workspaces; joint problem-solving forums; distributed decision-making
Impact on Stakeholder Hope (Agency & Pathways)	Tends to suppress hope: constrains perceived agency and limits stakeholders' ability to identify or influence viable pathways.	Tends to enable and constrain hope: supports pathway recognition but limits decision authority, constraining agency and making hope conditional.	Tends to activate hope: enhances perceived agency and enables jointly constructed pathways, reinforcing commitment and coordination.
Stakeholder Response during Unexpected Events	Tends toward: Withdrawal, minimal compliance, passive resistance, self-protective behavior	Conditional engagement, waiting for direction, limited initiative, reliance on leadership	Tends toward: Proactive collaboration, voluntary sacrifice, information sharing, joint problem-solving, extraordinary effort

	Management *OF* Stakeholders	Managing *FOR* Stakeholders	Managing *WITH* Stakeholders
Resilience Outcome	Fragility likely; delayed adaptation; potential conflict escalation—though control-oriented governance may yield resilience when stakeholders comply and disruptions are technical rather than relational	Variable resilience; moderate legitimacy; outcomes dependent on leadership judgment and stakeholder willingness to wait for direction	Tends toward resilience across adaptive, transformative, and sustained performance dimensions—contingent on genuine stakeholder access and functioning digital configurations

3. Synthesizing Governance, Digitalization, and Hope for Megaproject Resilience

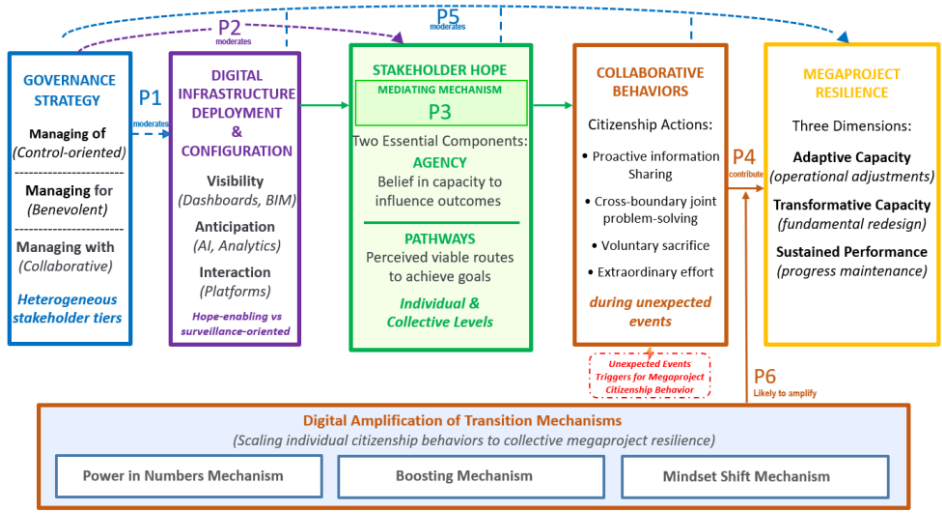


Figure 1. Integrative theoretical framework

Figure 1 illustrates our integrative framework, which brings together the theoretical relationships developed in Section 2. The model begins with governance strategy as the foundational choice shaping the entire pathway. Governance strategy moderates how digital infrastructure is configured, determining whether digital affordances are oriented toward surveillance and control or participation and collaboration. Digital configuration, in turn, tends to shape whether these affordances activate or suppress stakeholder hope—the belief in one's agency to influence outcomes and the perception of viable pathways to achieve goals. Hope—operationalized at the collective level as shared stakeholder beliefs in group agency and viable pathways, grounded in individual hope as its micro-foundation—serves as the critical psychological mediating mechanism determining whether stakeholders engage in collaborative citizenship behaviors or withdraw. Unexpected events are positioned in the framework as triggers—activating conditions that disrupt formal coordination and elevate the role of hope-driven collaborative citizenship behaviors as determinants of megaproject resilience [16,33]. The framework's propositions are therefore most directly applicable under conditions of disruption, when voluntary stakeholder action becomes critical. These citizenship behaviors—proactive information sharing, cross-boundary problem-solving, voluntary

sacrifice, and extraordinary effort—enable megaproject resilience across adaptive, transformative, and sustained performance dimensions. Digital platforms may amplify these effects through power in numbers, boosting, and mindset shift mechanisms, but only when configured within collaborative governance structures that enable stakeholders to coordinate discretionary effort. Resilience capacity does not exist fully formed at project inception but develops cumulatively through iterative disruption–response–learning cycles as stakeholders mobilize collaborative responses to unexpected events [37].

The framework explains the digitalization paradox: identical technologies yield divergent outcomes because governance strategies shape their configuration differently. The model identifies governance strategy as the primary moderator determining whether digitalization contributes to or undermines resilience, while acknowledging that other contextual factors—including contract type, public-private ownership arrangements, institutional trust levels, and cultural assumptions about agency—may independently shape or interact with governance effects on the digitalization-resilience pathway. Based on this integrative framework, we advance six propositions:

Proposition 1: Governance strategy moderates the relationship between digital infrastructure deployment and digital configuration, such that collaborative governance produces participation-oriented configurations while control governance produces surveillance-oriented configurations.

Proposition 2: Digital configuration moderates the relationship between governance strategy and stakeholder hope, such that participation-oriented configurations activate hope while surveillance-oriented configurations suppress hope.

Proposition 3: Stakeholder hope mediates the relationship between digital configuration and collaborative citizenship behaviors, such that participation-oriented configurations increase voluntary collaboration—including proactive information sharing, cross-boundary problem solving, and extraordinary effort—through enhanced agency and pathway beliefs, while surveillance-oriented configurations suppress these behaviors by undermining hope.

Proposition 4: Collaborative citizenship behaviors positively influence megaproject resilience across adaptive, transformative, and sustained performance dimensions.

Proposition 5: Governance strategy moderates the entire pathway from digitalization through hope to resilience, such that collaborative governance amplifies positive effects while control governance suppresses them.

Proposition 6: When digital platforms are configured within collaborative governance structures, they are likely to amplify—that is, accelerate, scale, and sustain beyond what face-to-face coordination alone could achieve—the transformation of individual collaborative citizenship behaviors into collective megaproject resilience through power in numbers, boosting, and mindset shift mechanisms.

4. Discussion

This paper makes three theoretical contributions. First, we theorize digitalization as governance-embedded rather than technologically deterministic. Rather than treating digital technologies as neutral tools, we show how governance strategies shape digital configurations, which enact different outcomes. Second, we identify stakeholder hope as the critical psychological mechanism linking digital governance to collaboration. We show that hope—comprising agency beliefs and pathway perceptions—explains why

stakeholders voluntarily collaborate or withdraw during crises. Third, we extend megaproject resilience theory by explaining how digital technologies condition citizenship behavior activation and scaling. We show that digital platforms amplify power in numbers, boosting, and mindset shift mechanisms—but only under collaborative governance. This contribution specifies the conditions under which digitalization enhances versus undermines resilience.

While this study makes several theoretical contributions as outlined above, it also carries limitations that should be considered alongside its strengths. Limitations include: the conceptual nature requiring testing; hope measurement challenges given its fluctuating nature and individual versus collective levels; governance configurations are theorized as ideal types and their hybrid, phase-dependent nature—including how projects may simultaneously employ different strategies toward different stakeholder groups, and how strategies may shift post-crisis—warrants further theoretical development and empirical investigation; technological heterogeneity as AI, BIM, and platforms may differ; and cultural assumptions about agency that may not generalize universally. More broadly, the framework foregrounds governance strategy as the primary moderating variable, but contract type, public-private ownership arrangements, and institutional trust levels may function as independent or co-moderating influences on the digitalization-hope-resilience pathway—a possibility the current framework does not fully theorize and that future work should address.

A further boundary condition concerns the normative directionality of the framework. The model as presented tends to favor collaborative governance as the pathway to resilience, which risks reading as theoretically biased against control-oriented approaches. It is important to acknowledge that management of stakeholders may yield resilience under specific conditions. In acute safety crises requiring rapid centralized command—such as structural failures, environmental incidents, or regulatory emergencies—distributed decision-making and participatory governance may be too slow or too contested to enable an effective response. Similarly, in highly regulated environments where compliance with legal or contractual obligations is the primary resilience mechanism, centralized control and surveillance-oriented digital configurations may be functionally appropriate and sufficient. The framework's propositions are therefore most directly applicable to megaproject contexts characterized by complex interdependencies, voluntary stakeholder coordination, and disruptions that cannot be resolved through compliance alone. Where disruptions are primarily technical, regulatory, or safety-critical in nature, the governance-hope-resilience pathway theorized here may be less central than formal command structures and pre-established contingency protocols.

The framework's applicability is also bounded by the agency heterogeneity that characterizes real megaproject stakeholder populations. The propositions assume that participation-oriented digital configurations can activate hope across stakeholders, but this assumption may not hold uniformly for low-agency stakeholders—including affected community groups, peripheral residents, and subcontractors with limited contractual standing—whose capacity to act on hope-generated motivation is structurally constrained by their position in the governance hierarchy [12,13]. For such stakeholders, digital platform access without commensurate decision-making authority risks producing what Snyder's (2002) hope theory would characterize as frustrated hope—a state in which pathways are perceived but remain blocked by governance structures—which may suppress rather than activate collaborative citizenship behaviors [17]. The framework's propositions regarding hope activation are therefore most directly

applicable to stakeholders with meaningful governance participation. Extending them to low-agency stakeholders is theoretically plausible but requires the prior condition that governance structures grant real influence, not merely informational access or nominal inclusion in digital participation platforms.

Future research could empirically test the proposed framework using multi-method data capturing governance structures, digital configurations, psychological mechanisms, and behavioral outcomes. Governance strategy can be assessed through project governance documents, contractual arrangements, and data access rules defining stakeholder participation and decision rights. Digital configurations may be operationalized using digital platform logs capturing patterns of data visibility, interaction frequency, and stakeholder participation in collaborative tools. Stakeholder hope can be measured using adapted survey instruments based on Snyder's hope scale capturing agency and pathway perceptions at both individual and collective levels. Collaborative citizenship behaviors may be identified through behavioral indicators such as voluntary information sharing, cross-boundary problem-solving interactions on digital platforms, or peer-reported collaboration measures. Megaproject resilience could then be assessed through event-history analysis of disruptions and recovery trajectories, enabling examination of how hope-driven collaboration shapes adaptive and transformative responses to unexpected events.

5. Conclusion

Megaprojects operate in an era where unexpected events are endemic. Digitalization offers promise but not a panacea. Digital technologies can enhance coordination—but can also intensify surveillance and suppress collaboration upon which resilience depends. This paper advances a governance-embedded, hope-mediated theory of digitalization and resilience.

From a practitioner perspective, megaprojects confronted with uncertainty necessitate governance strategies that harness digitalization to cultivate stakeholder hope and enable collective agency. Managing with stakeholders—enabling participation, making collective capability visible—creates conditions for resilience. Instrumental approaches that configure digital technologies for control rather than collaboration risk suppressing the hope-driven citizenship behaviors upon which resilience depends, particularly when unexpected events disrupt formal coordination mechanisms and voluntary stakeholder action becomes critical. Resilience outcomes are governance-contingent: the same digital infrastructure tends to generate divergent outcomes depending on whether governance structures activate or suppress stakeholder beliefs in agency and viable pathways forward.

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External Influencing Factors and Consumer Behavior in Cross-Border E-Commerce: A Data-Driven Analysis of Chinese Purchase Decisions

Qiang Zhang[a], Yuyi Chen[b,1], Li Zhang[c] and Kaijian Lai[d]
[a] *Business School, Xiamen Institute of Technology, Xiamen, China*
[b] *School of International Business, Xiamen University Tan Kah Kee College, China*
[c] *School of AI and Computer Science, Hubei Normal University, Huangshi, China*
[d] *Business School, Beijing Institute of Technology, Zhuhai, China*

Abstract: This study examines external factors' effects on Chinese consumers' purchase behavior on cross-border e-commerce (CBEC) platforms. Integrating Cue Utilization Theory with the Technology Acceptance Model (TAM), it analyzes platform pricing, logistics timeliness, service level, perceived ease of use and security. A survey of 264 Chinese consumers shows pricing significantly drives purchase behavior. Logistics timeliness influences perceived usefulness and security, while platform service quality affects perceived value and ease of use. A novel moderated-mediation analysis reveals consumer price sensitivity moderates logistics timeliness' effect on purchase behavior via perceived security—this mechanism lacks empirical validation in prior CBEC research. Findings suggest CBEC platforms targeting China should prioritize competitive pricing, efficient logistics, quality service and strong security to enhance trust and repurchase intention. Future research may explore the arbitrating role of customer pride.

Keywords: Cross-Border E-Commerce Shopping Platform, external influencing factors, Consumer Purchase Behavior, Technology Acceptance Model (TAM)

1. Introduction

The cross-border e-commerce (CBEC) sector in China has experienced substantial expansion, reshaping foreign trade and becoming a core pillar of the digital economy. Despite challenges including disrupted logistics, rising costs and variable customs efficiency, the industry has thrived via "Internet + foreign trade". In 2024, China's CBEC trade reached 2.721 trillion yuan, up 14% year-on-year, with 165 comprehensive pilot zones and over 2,300 overseas warehouses. The Chinese government has rolled out supportive policies; the revised *Cross-border E-commerce Retail Import Commodity List* (March 1, 2022) expanded product categories, boosting market vitality, according to Ministry of Finance of the People's Republic of China, et al. (2022) [1].

[1] Corresponding Author: Yuyi Chen, E-mail: 448604958@qq.com
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Consumer purchasing patterns have shifted from offline channels to online daigou and haitao, with the pandemic accelerating this transition. Existing literature has explored technological adoption, trust, satisfaction and perceived risk (Venkatesh et al., 2003; Bhattacherjee, 2001; Kim et al., 2010) [2][3][4]. Ngo et al. (2025) highlighted service quality and return policies in enhancing the degree of trust and buying intention [5]. Wang et al. (2023) identified the chain effects among platform trust, seller trust, logistics trust and repurchase intention [6]. However, prior studies often adopt a fragmented perspective and overlook interdependencies among variables. Most CBEC research focuses on direct or simple mediating effects while ignoring conditional mechanisms and individual differences. Western findings may not apply to China's unique context (Chen et al., 2022) [7], highlighting the need for context-specific research.

To address these gaps, this study integrates Cue Utilization Theory and TAM, taking pricing, logistics timeliness and service quality as external cues. A moderated-mediation model is proposed to examine how price sensitivity moderates the indirect effect of logistics timeliness on purchase behavior via perceived security. Amid rising demand for imported high-quality products, consumers rely heavily on platform external cues to reduce uncertainty. This study investigates how such factors affect consumer perceptions, trust formation, and purchase outcomes of Chinese consumers in the CBEC setting.

2. Literature Review

2.1. Theoretical Framework

Scholars have adopted various theories to examine consumer purchase behavior in the CBEC sector, considering complexities in the CBEC logistics, payments and supervision. This review synthesizes studies on CBEC repurchase intention based on Cue Utilization Theory and the Technology Acceptance Model (TAM). To fill the gap in conditional mechanisms, this study integrates insights from ELM theory, highlighting that individual differences such as price sensitivity moderate the processing of external cues. This theoretical triangulation extends existing CBEC frameworks. This section elaborates the theoretical foundations and related literature on how external factors affect consumer purchasing behavior on CBEC platforms, starting with Cue Utilization Theory and TAM.

2.1.1 Cue Utilization Theory

Scholars have extensively examined cues influencing consumer decision-making in retail and e-commerce contexts. Cox (1962) proposed Cue Utilization Theory, distinguishing between predictive value and confidence value [8]. Olson and Jacoby (1972) classified cues into external and internal types [9]. Richardson et al. (1994) confirmed that these two values jointly determine consumers' quality perception and purchase intention [10].

2.1.2 Technology Acceptance Model (TAM)

The Technology Acceptance Model (TAM), proposed by Davis (1989) based on TRA and TPB, holds that purchase behavior stems from attitude shaped by perceived value in use and ease of use [11]. A simplified TAM focuses on their direct effects on intention, with external factors influencing both constructs [11].

3. Hypothesis Development

H1: Higher perceived price of imported goods leads to perceived usefulness.
H2: Higher perceived price of imported goods enhances perceived ease of use.
H3: Higher perceived price of imported goods strengthens perceived security.
H4: Higher perceived price of imported goods positively drives consumer purchase behavior.
H5: Improved logistics timeliness leads to perceived usefulness.
H6: Improved logistics timeliness enhances perceived ease of use.
H7: Improved logistics timeliness strengthens perceived security.
H8: Improved logistics timeliness positively drives consumer purchase behavior.
H11: Higher platform service quality leads to perceived security.
H12: Higher platform service quality enhances consumer purchase behavior.
H13: Higher perceived security strengthens consumer purchase behavior.
H14: Higher perceived ease of use positively drives consumer purchase behavior.
H15: Higher perceived ease of use leads to perceived usefulness.
H16: Higher perceived usefulness leads to consumer purchase behavior.

4. Data and Methodology

This study adopted quantitative methods with a WenJuanXing (https://www.wjx.cn/) questionnaire based on validated scales and pretested via pilot surveys. The 5-point Likert scale questionnaire surveyed Chinese CBEC consumers on demographics and key perceptions, collecting 350 responses (May–August 2025); 264 valid ones (75.4% rate) were analyzed via Multiple Regression Analysis after invalid exclusion.

5. Data Analysis

5.1. Descriptive Statistics

Table 1. Gender of respondents

gender	frequency	Percentage of
male	130	49.24%
female	134	50.76%
total	264	100.00%

As can be seen from Table 1, males and females accounted for 49.24% and 50.76% of the samples.

Table 2. Age of respondents

age	frequency	Percentage of
Under 20	4	1.52%
20-35	149	56.44%
35-45	71	26.89%
Over 45	40	15.15%
total	264	100.00%

In the points of the age of the respondents according to table 2, only 15.15% were over 45 years old, and 83.33% were between 20 and 45 years old.

5.2. Measurement Scales

The variables were verified using multi-item balances adapted from prior studies. This research adopts on the measurement items and their sources. Each item was rated using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

5.3. Reliability and Validity Analysis

The data were analyzed by SPSS 26. First, illustrative statistics were used to abstract the demographic characteristics of the sample. Second, integrity and strength analyzes were conducted to assess the quality of the mensuration balances. Third, correlation analysis was used to inspect the relationships between the variables. Finally, regression analysis was used to check the hypotheses.

5.3.1 Reliability Analysis

Reliability testing was conducted using Cronbach's alpha coefficients. Table 3 reveals that all Cronbach's alpha coefficients surpassed 0.7, indicating good internal consistency.

Table 3. Reliability Analysis

VARIABLE	CRONBACH'S ALPHA	NUMBER OF ITEMS
Price	0.984	3
Logistics Timeliness	0.981	3
Service Quality	0.983	3
Perceived Security	0.980	3
Perceived Ease of Use	0.983	3
Perceived Usefulness	0.982	3
Purchase Behavior	0.818	3

5.3.2 Validity Analysis

KMO measure and Bartlett's test of sphericity were applied to verify scale validity. As shown in Table 4, the KMO value for all variables was 0.809, and Bartlett's test of sphericity was major, indicating that the data were appropriate for element analysis.

Table 4. Validity Analysis

VARIABLE	KMO VALUE	BARTLETT'S TEST OF SPHERICITY (SIG.)
All Variables	0.809	0.000

5.4 Correlation Analysis

The correlation coefficients for all constructs are summarized in Table 5. Significant positive correlations were observed between all independent variables and the four dependent constructs (perceived security, usefulness, ease of use, and purchase behavior).

Table 5. Correlation Matrix

	1	2	3	4	5	6	7
1. Price	1						
2. Logistics Timeliness	.749**	1					
3. Service Quality	.733**	.762**	1				
4. Perceived Ease of Use	.735**	.768**	.773**	1			
5. Perceived Usefulness	.779**	.757**	.770**	.771**	1		
6. Perceived Security	.764**	.824**	.750**	.757**	.755**	1	
7. Purchase Behavior	.805**	.753**	.749**	.766**	.787**	.783**	1

** Correlation is significant at the 0.01 level (2-tailed).

6. Finding and Discussion

This study explored how CBEC platforms' external factors affect Chinese consumers' purchase behavior via TAM, analyzing with SPSS 26 correlation and regression. Price (β=0.285, $p<0.001$) is the most impactful direct cue (H4 supported); price, logistics timeliness and service quality boost perceived usefulness (H1, H5, H9 supported). Perceived ease of use drives usefulness (β=0.311, $p<0.001$, H15 supported), but price does not affect ease of use (H2 not supported). Service quality (β=0.251, $p<0.001$, H10) and logistics timeliness (β=0.207, $p<0.01$, H6) enhance ease of use; logistics timeliness (β=0.398, $p<0.001$, H7) and price (β=0.172, $p<0.05$, H3) lift perceived security. Usefulness, ease of use and security all drive purchase behavior (H13, H14, H16 supported). CBEC platforms should optimize logistics, service and adopt segmented pricing strategies; high-income, highly educated consumers are key groups. Prioritizing pricing, logistics and service builds trust and repurchase intention, with future research to explore satisfaction and other external factors.

7. Conclusions, Limitations and Future Research

Rooted in TAM and Cue Utilization Theory, this research explores factors shaping Chinese consumers' CBEC purchase behavior, identifying pricing as a key direct driver and logistics timeliness, platform service quality as core indirect factors. Its novel contribution is a moderated-mediation mechanism: price sensitivity moderates logistics timeliness' indirect effect on purchase behavior via perceived security, addressing the lack of conditional mechanism research in CBEC and advancing theoretical understanding. It recommends CBEC platforms optimize pricing, enhance logistics efficiency and service quality to build consumer trust, boost repurchase intention and sales. This study has limitations: a 264-sample size limited to specific consumers, cross-sectional data failing to confirm causality or track preference changes, and a focus on only three external factors (excluding brand reputation, product reviews etc.). Future research can conduct cross-regional/cross-country comparative studies and longitudinal analyses, explore interactions between external factors, integrate qualitative methods (focus groups, in-depth interviews) and examine macro variables' impacts on the model to enrich CBEC consumer behavior research.

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Design and Validation of LoopCart to Encourage Sustainable Circular Economy for E-Commerce in Malaysia

Jun-Wei CHONG[1] and Chien-Sing LEE

Faculty of Engineering and Technology, Sunway University, Malaysia
ORCiD ID: Chien-Sing LEE https://orcid.org/0000-0002-4703-457X

Abstract. The rapid growth of e-commerce, accelerated by the COVID-19 pandemic, has reshaped consumer shopping behaviour while intensifying environmental challenges linked to traditional linear economic models. Conventional e-commerce platforms largely follow a "take–make–dispose" approach, contributing to increase in carbon emissions, packaging waste (unsustainable consumption). This study presents the design and development of *LoopCart*, a mobile e-commerce application that integrates circular economy (CE) principles to promote sustainable consumption. *LoopCart* incorporates features aligned with the 6R framework, e.g. best value comparison, personalized product filtering, repair services, daily quiz, Green Coin reward system, chatbot, and reflective sustainability analytics/report, to encourage responsible consumption. Alpha-beta prototypes are evaluated via the User Experience Questionnaire (UEQ) and the Technology Acceptance Models (TAM) 1-3. The results indicate high user acceptance. Overall, findings have elicited/ validated sample respondents' preferences and confirmed the feasibility of extending design thinking to integrating circular economy principles, e.g. systems thinking, awareness, communication, redesign, attachment and trust, developing the partnership supply chain/new business models, developing impactful rewards, and personalized visual comparisons in terms of sustainability impact, price, and quality.

Keywords: responsible consumption, circular economy, User Experience Questionnaire, Technology Acceptance, engage, systems, market basket analysis

1. Introduction

The linear economy model has evidenced issues with resource efficiency due to low material recovery, amidst depleting resources. For example, in OECD countries, over 21 billion tons of materials are consumed annually but not retained in the consumption cycle (Ellen Arthur Foundation, 2013) [1]. Collini et al. (2022) [2] also highlight several negative impacts on sustainability arising from traditional e-commerce:

a) increased environmental footprint from logistics, excessive packaging, and the disposal of returned products,
b) inefficient use of packaging materials, with no effective strategy to mitigate their environmental impact,
c) low recovery rates of materials and products,
d) fast consumption, without considering repair or reuse,

[1] Corresponding Author: Jun-Wei Chong, 22025530@imail.sunway.edu.my

e) limited awareness and system components for reuse and donation, as most e-commerce platforms lack options for repair, recycling, or donation,
f) lack of integrated mainstream-second-hand e-commerce markets.

According to De Angelis (2020) [3], the circular economy is based on three core principles: conserving and enhancing natural resources, optimizing resource productivity, and eliminating the negative environmental impacts of production and consumption. Hence, the circular economy represents a systematic and transformative approach, offering a unifying framework that addresses the challenge of achieving economic growth and employment while minimizing environmental impact.

To implement circular economy principles, businesses must adapt and innovate their current business model to align with sustainability goals. Japan, the European Union and China, have made significant steps to integrate circular economy (CE) principles into their policy frameworks and industrial practices, especially in the e-commerce sector. In response to these policies, both new and existing businesses in e-commerce have introduced circular products, services, and practices that prioritize reuse, recycling, and extended product life cycles. These solutions create a win-win situation, i.e., consumers gain access to more affordable goods while contributing to sustainable practices, and businesses explore new opportunities within circular economy models.

In Malaysia, the market value of recyclable materials remains relatively low. Based on SWCorp's valuation (Zaki, 2023) [4], recyclable plastics are worth a minimum of RM0.10 per kg, paper RM0.067 per kg, metal RM0.40 per kg, and Tetra Pak (paper, polyethylene and aluminium used in food packaging) RM0.05 per kg. Although these figures point to earnings at the national level, they rarely translate into sufficient income for individual recycling centres. Hence, many recycling centres rely heavily on government support schemes to remain operational.

The Malaysian Investment and Development Authority (MIDA) [5] has thus introduced the Green Technology Financing Scheme (GTFS), to offset the high capital and operational costs of recycling activities. To bridge the gap between low material resale value and rising processing expenses, MIDA (2022) offers:

- a 2% per annum interest/profit rate subsidy for the first seven years,
- a 60% government guarantee of the green component cost to financial institutions,
- targeted tax incentives for companies recycling waste, including (non)toxic waste, chemicals, and reclaimed rubber. Eligible companies can apply for Pioneer Status (70% tax exemption on statutory income for 5 years) and/or Investment Tax Allowance (60% tax exemption on qualifying capital expenditure for 5 years).

1.1 Problem Statement

In Malaysia, recycling centres adopt various models (Rangga et al., 2022) [6]:

1. Informal collection networks: Community-driven or NGO-run drop-off points and neighbourhood collection programmes.
2. Formal municipal partnerships: Centres integrated with local councils or SWCorp facilities for centralised waste sorting.
3. Specialised recyclers: Companies focusing on industrial or specific waste streams (e.g., electronics, rubber, hazardous waste).
4. Integrated Waste-to-Energy (WtE) facilities: Large-scale operations combining recycling with energy recovery, such as the Bukit Tagar Enviro Park plant.

These focus on collection and recycling. The speed by which waste is accumulated is however, much faster than the speed by which waste is processed. There is thus a need

to identify requirements for an integrated main-second hand marketplace ecosystem. The system must be conscious about value, is convenient and affordable, to promote users' willingness to engage in circular economy practices. Our targeted respondents is a Malaysian urban sample population around Subang Jaya.

1.2 Objective

The circular economy (CE) requires not only a mental shift enabled by systems thinking aimed at designing to sustain, and communication to create awareness and to sustain action, but also balancing people, planet and profit (Medkova & Fifield, 2016) [7]. Moreover, CE needs to extend beyond mechanics, e.g. durability, ease of upgrade/ maintenance/repair, standardization and compatibility, to develop attachment and trust (den Hollander, Bakker, & Jan Hultink, 2017) [8]. Hence, design for technology acceptance (Davis, 1989; Venkatesh & Davis, 2000; Venkatesh & Bala, 2008) [9-11]) and Schrepp, Hinderks and Thomaschewski's (2017) user engagement/experience [12] has to correspond with these (Figure 1).

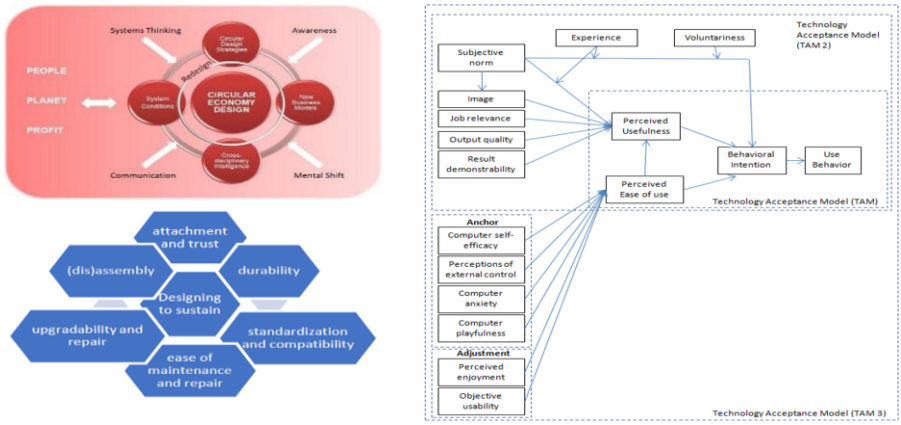


Figure 1. [7]'s systems view (top left), [8]'s system components (bottom left), [9-11]'s TAM 1, 2, 3 (right)

Consequently, the main objective of this project (*LoopCart*) is to design an e-commerce platform that transitions from the traditional linear model to a CE business model by integrating CE principles and supporting the SDGs. This project draws inspiration from the strengths of eBay (second-hand market), Uniqlo (repair, remake, recycle, and donations to NGOs), and Shopee (a leading e-commerce platform in Asia). By combining these strengths, *LoopCart* aims to reshape consumer behaviour from fast consumption to more thoughtful sustainable practices. Table 1 summarizes each of *LoopCart*'s key features, corresponding SDGs, [7-8]'s system characteristics.

1.3 Scope

This study is a software engineering capstone project. Hence, product design as promoted by researchers e.g. van Dam et. al (2020) [13]'s Circular Industrial Product Design is not within the scope of our study.

Table 1. Key features of the proposed application and their alignment with the SDGs

Feature	SDG(s)	[7, 8]'s components	
Second-hand Market: Trade Used Items	SDG 12, 13	Standardization & compatibility	Towards future communication, redesign, new business models
Personalized Filtering (Halal, Allergy)	SDG 3, 10		
Best Value Comparison	SDG 12, SDG 8		
Retain value in circulation: Repair Services	SDG 12	Durability, Disassembly, ease of repair/maintenance/ upgradability	
Retain value in circulation: Recycling Pickup	SDG 11, 12, 13		
Donation for Low-income Families	SDG 1, 2, 17	Durability, Attachment & trust	
Donation to recycling center/old folks' home/orphanage	SDG 3, 17		
Green Coin Reward System	SDG 12		

2. Related work on implementing circular economy in e-commerce

International case studies have informed *LoopCart's* design choices. In the EU, eMAG's solar-powered *Easybox* demonstrate the environmental benefits of sustainable last-mile logistics. In Japan, Uniqlo's RE.UNIQLO STUDIO has proven that repair, reuse, and recycling services can operate alongside profitable retail operations while contributing to social impact through partnerships, e.g. UNHCR donations. *Airism* is unique and desirable. India's *Recykal* digitally links formal and informal recycling sectors while supporting EPR compliance through cloud-based tracking systems. In China, JD.com has promoted reusable packaging and paperless invoicing initiatives, supported by policies under the 14th Five-Year Plan (Yuchuan, 2021). China has also focused on redesign via Alibaba, as reflected in Lazada/Shopee products. Malaysia has launched pilot community recycling centres and achieved a recycling rate of 35.38% in 2023. A comparative summary of these CE strategies is presented in Tables 2 a, b, while the summarized key challenges are presented in Table 3.

Table 2a. Comparative summary of international and Malaysian circular economy case studies

Country	Company	Focus Area(s)	Key Strategies to Circular Economy
Japan [14]	Uniqlo	• Repair, Reuse, Recycling, Remake	• Promote repair/remake of clothes via e-commerce • Clothing donations via UNHCR • Raise social and environmental awareness
Romania [15]	eMAG & Sameday	• Packaging • Green Logistics	• Use recyclable packaging, metal delivery boxes • Solar-powered *Easybox* lockers for last-mile delivery
India [16]	Recykal	• Waste Management, EPR • Digital Platform	• Offers traceable cloud marketplace for waste recycling • Empowers informal sector • Helps brands comply with EPR via apps.
China [17]	JD.com	• Green Logistics • Packaging • Donations	• Adopted electric delivery vans • Paperless invoicing • Reusable cold chain and warehouse packaging • Toy/clothing donation
Malaysia [18, 19]	MBPJ & Nestlé	• Public–Private Partnership	• Set up EPR recycling bins and drop points • Launched pilot EPR collection program • Promoted community recycling

Table 2b. CE attribute for international and Malaysian case studies and relevance to *LoopCart*

CE Attribute	Japan (Uniqlo)	Romania (eMAG)	India (Recykal)	China (JD.com)	Malaysia (MBPJ)	Proposed App Feature
Repair (Extend lifecycle)	✓	×	×	×	×	Repair services
Recycle	✓	✓	✓	✓	✓	Recycling pickup service
Donation	✓	×	×	✓	×	Basket of Hope

Support for green packaging	×	✓	✓	✓	×	Eco-friendly packaging options
Enable user participation in green practices	✓	✓	✓	✓	✓	Green Coin reward system
Sell/Resell/Buy second-hand products	×	×	✓	×	×	Second-hand marketplace
Partnership with NGOs /local gov for CE	✓	✓	✓	✓	✓	Recycling & donation via verified bodies

Table 3. Key challenges and bottlenecks for CE adoption in Malaysian e-commerce

Challenge	Bottlenecks / Barriers
Lack of awareness on responsible consumption (behaviour)	- Inadequate education and outreach programs, lack of convenience and lack of incentives hinder responsible behaviour. Hence, awareness varies by demographic - urban youth are more conscious
Consumer price sensitivity toward sustainable options	- Cost-conscious behaviour deters adoption of circular alternatives by brands
Absence of Extended Producer Responsibility (EPR) schemes	- Many EPR efforts are voluntary, as lack of regulatory mandate limits industry-wide adoption
Limited recycling and material recovery infrastructure	- Recycling facilities are unevenly distributed - Low-quality waste due to lack of segregation at source

These successful CE implementations require policies to promote, digital partnerships, regulatory enforcement, and consumer incentives. *LoopCart* has incorporated these lessons through features e.g. the Green Coin reward system, verified recycling partnerships, and sustainability analytics, while acknowledging that broader impact ultimately depends on supportive policy frameworks.

3. Methodology

Socio-economic considerations determine the degree of transfer to local contexts. Hence, from the literature review, the closest to our context (Table 2b) is Uniqlo. We also draw inspiration from Asia Pacific's 2 most popular online shopping platforms, i.e., Lazada and Shopee, Medkova and Fifield (2016) [7], TU Delft's (2016) [8]'s CE industrial product design qualities, TAM 1, 2, 3 [9-11] (Table 1). To assess TAM's enjoyment construct, Schrepp, Hinderks, and Thomaschewski's (2017) [12]'s UEQ is applied.

3.1 Framework and use case diagram

The Software Development Life Cycle's (SDLC) iterative incremental prototyping methodology is applied. Functions/features are incrementally developed and refined from alpha to beta. Alpha user testing focuses on conceptual validation and preference-based evaluation via a Figma prototype, while beta user testing examines user experience and technology acceptance via a functional coded prototype.

To elicit/validate requirements, the International Requirements Engineering Board's (IREB) Requirements Engineering framework (Figure 2a) is referred to, in line with the SDLC. Due to lack of space, only the use case diagram for the CE subsystem is shown in Figure 2b.

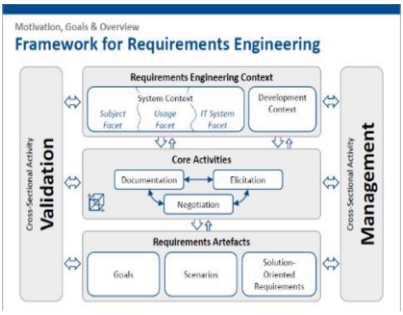


Figure 2a. IREB's RE framework

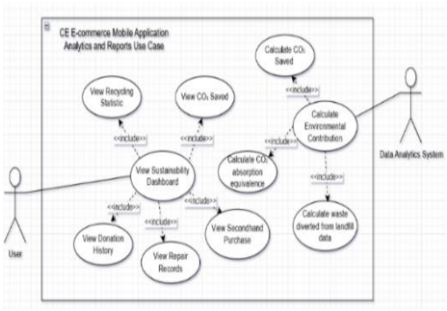


Figure 2b. Use case diagram for CE subsystem

3.2 Development

LoopCart is developed via the cross-platform development framework Flutter and its object-oriented language, Dart, with an MVC architecture (Table 4). *LoopCart* integrates Firebase, a cloud-hosted NoSQL database. Data is stored as an infinite array of JSON objects. The Firebase Database uses a key as the index and value pair as the data store. Data security is enforced via Firebase Authentication, which manages user access, and through Firestore security rules, which restrict access to authenticated users. All client-server communications are protected via HTTPS/TLS encryption.

In terms of scalability, the components are modular, in line with agile methodology. Hence, it would be easy to add/edit/delete any system components/functions, based on user preferences. Moreover, Firebase's auto-scaling infrastructure can accommodate more users and data volumes without manual provisioning or performance degradation.

AI integration includes a chatbot powered by the Google Gemini API (Gemini-2.0-flash), configured with a domain-specific system prompt containing *LoopCart's* features and CE knowledge to provide context-aware user assistance. The waste sorting function applies transfer learning through Google Teachable Machine using a pre-trained MobileNet model, where custom waste categories are trained as the final classification layer via TensorFlow.js for efficient image classification. *LoopCart* works well in both Android and iOS emulators.

Table 4. Mapping functionalities to Model-View-Controller (MVC) Architecture

Functionality	Model	View	Controller
Personalized Product Filtering	User preference storage and filtering logic	Filter options on product listing page	Retrieves filtered product data based on user input
Best Value Comparison	Aggregation of price and rating, comparison algo.	Comparison display (e.g., badges, "Best Value" tag)	Executes comparison logic, routes best value data to view

3.3 User testing

TAM 1, 2, 3 (Figure 1 right) and UEQ are applied to develop the survey questions. Originally proposed by Davis (1989) [9], TAM extends through TAM 2 (Venkatesh & Davis, 2000) [10] and TAM 3 (Venkatesh & Bala, 2008) [11] to examine how users perceive and likely intentions to adopt the technology. Schrepp, Hinderks, and Thomaschewski's (2017) [12]'s User Experience Questionnaire (UEQ) constructs originally consists of 26 semantic differential items. We have used the short version. Both TAM and UEQ constructs applied in this study are in Table 5.

Table 5. TAM and UEQ constructs and respective definitions

TAM 1, 2, 3		UEQ constructs	
Perceived Usefulness (PU)	The extent to which the system enhances task performance/ provides value	Attractiveness	Overall impression and appeal of the product
Perceived Ease of Use (PEOU)	The degree to which the system is easy to learn and use	Perspicuity	Ease of learning, clarity, and understandability
Behavioral Intention to Use (BI)	Users' likely intention to continue using the system	Efficiency	Speed and effort required to complete tasks
Attitude Toward Using	Users' overall evaluation of using the system	Dependability	Predictability, user control, confidence during interaction
Social Influence	The extent to which others influence users' decisions to use the system	Stimulation	Level of engagement, motivation
		Novelty	Perceived creativity and innovativeness of the product

Informed consent is obtained, ethical statements on privacy/anonymity are included prior to data collection.

4. Figma prototype and alpha user testing

Sample Figma prototype screenshots are illustrated in Figures 3a, b, c.

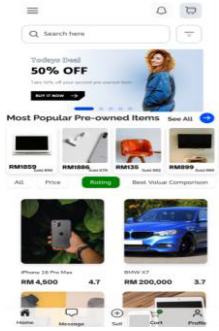


Figure 3a. Main page

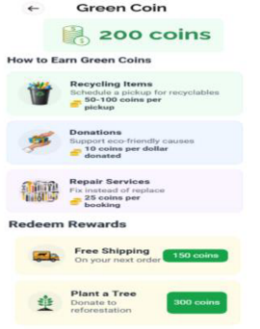


Figure 3b. Green coin page



Figure 3c. Sustainability dashboard

4.1 Alpha user testing

For the alpha user testing, 30 responses are collected. Findings are presented in Tables 6a-c (demographics), 7a-f (e-commerce usage and habits), 8a-d (awareness and everyday CE behavior), 9a-d (Interest in CE). From Table 7b, 6.7% (n = 2) do not shop online. Hence, their responses are not considered for subsequent averages.

4.1.1 Demographics

Table 6a. Gender

Gender	%
Male	63.3
Female	36.7

Table 6b. Age

Age	%
< 21	6.7
21 - 30	93.3
31 - 40	0

Table 6c. Educational level distributions

Education	%	Education	%
Primary/Secondary	3.3	Year 2 university	10.0
Pre-university	16.7	Year 3 university	36.7
Year 1 university	16.7	Postgraduate	16.7

4.1.2 E-Commerce usage and habits

Table 7a. E-commerce (EC) usage

EC Platform	%	EC Platform	%
Shopee	93.3	Facebook MP	0
Lazada	53.3	None	6.7
Amazon	3.3	Taobao	3.3

Table 7b. Online Shopping Frequency

Shopping Frequency	%	Shopping Frequency	%
Daily	0	Once every few months	13.3
Weekly	16.7	Rarely	23.3
Monthly	40.0	I do not shop online	6.7

Note: Respondents could select multiple options

Table 7c. Types of Products Purchased Online

Product Type	%	Product Type	%
Fashion and accessories	30.0	Health & Beauty Products	30.0
Electronics and gadgets	60.0	I do not purchase online	6.7
Home appliances/furniture	40.0	Junk food	3.3
Second-hand/refurbished items	10.0	Small gifts for others/myself	3.3

Table 7d. Devices Used

Device Type	%
Mobile phone	100.0
Laptop	30.0
Tablet	23.3
Desktop computer	13.3

Note: Respondents could select multiple options

Table 7e. EC platform selection influencers

Influencing Factor	%
Price and discounts	60.0
Brand reputation	50.0
Product reviews and ratings	66.7
Personalized product recommendations	13.3
Second-hand marketplace	6.7
Eco-friendly features	16.7
Fast and reliable delivery	30.0
Price comparison feature	36.7

Table 7f. Issues encountered on EC platforms

Issue Type	%
Delivery delays or lost packages	26.7
Poor product quality or damaged items	20.0
Unclear, misleading, missing product info.	43.3
Payment failures or security concerns	10.0
Inaccurate order tracking information	23.3
Unexpected fees or hidden charges	3.3
No, I have not encountered any issues	30.0
Item not matching the product description	3.3

Note: Respondents can select up to 3 options

4.1.3 Awareness and everyday behavior related to circular economy

Table 8a. Awareness about CE

Awareness Level	%
No	50
Heard of it, but not sure what it means	40
No	10

Table 8b. Sources of CE information

Information Source	%	Information Source	%
Social media	16.7	Workplace	6.7
School or university	26.7	E-commerce	3.3
News or online articles	13.3	Never heard of it at all	53.3
Friends or family	6.7		

Note: Respondents could select multiple options

Table 8c. CE behaviors

Behavior	Percentage of frequency				
	Never	Rarely	Sometimes	Often	Always
Donate or give away items you no longer use	13.3	33.3	30.0	16.7	6.7
Recycle packaging or products after online purchases	20.0	40.0	16.7	16.7	6.7
Repair broken items instead of replacing them	16.7	30.0	23.3	20.0	33.3
Buy second-hand items	56.7	13.3	20.0	6.7	3.3
Choose products with minimal/eco-friendly packaging	16.7	40.0	26.7	13.3	3.3
Compare the sustainability impact of products b4 buying	30.0	30.0	33.3	13.3	16.7

Table 8d. Barriers to adopting CE behaviors

Barrier/Difficulty	%
It's inconvenient or time-consuming	66.7
I wasn't aware these options existed online	46.7
I don't trust the quality of second-hand or repaired items	43.3
Lack of attractive incentives or rewards discourages me from practicing these behaviors	83.3
I cannot see any difference whether I do it or not	60.0

Note: Respondents could select multiple options.

4.1.4 *Interest in circular economy e-commerce features*

Interest level in CE e-commerce features (Table 9) reveals the importance of perceived value and thus the preference for easy value comparisons.

Table 9. Interest in CE e-commerce features (in descending order)

***LoopCart*'s features/functions**	**Avg.**	**Sdev**	***LoopCart*'s features/functions**	**Avg.**	**Sdev**
Best Value Comparison	4.03	1.00	Recycling Pickup Services	3.47	1.46
Green Coin Reward System	3.87	1.01	Basket of Hope Donation Feature	3.47	1.20
Repair Services	3.83	1.15	Sustainability Analytics/ Reports	3.45	0.99
Personalized Product Filtering	3.83	1.39	Second-Hand Marketplace	3.03	1.19

Two respondents recommend increasing personalization for a more tailored user experience and keeping the user interface visually neat to ensure better usability.

5. Beta refinement and validation

Based on feedback from alpha testing, three new features are introduced during the beta phase to improve usability, guidance, and user engagement, i.e., AI Chatbot for feature guidance, Daily Quiz with Green Coins, and waste classification assistance.

5.1 Beta prototype and survey design

Sample screenshots of the actual beta prototype are illustrated in Figures 4a-c. The survey is designed based on TAM and circulated via social media. Forty responses are collected. The survey sections are:

- Section 1 - Demographics (4 questions)
- Section 2 - User Experience (6 questions)
- Section 3 - TAM-based acceptance of components/functions (10 questions)
- Section 4 - Open-Ended Feedback and Suggestions (2 questions)

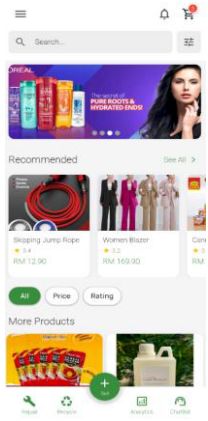


Figure 4a. Main page

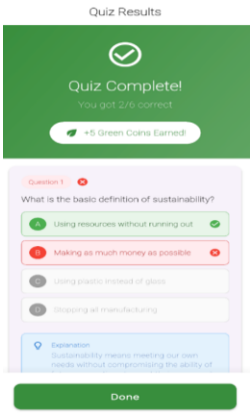


Figure 4b. Daily Quiz

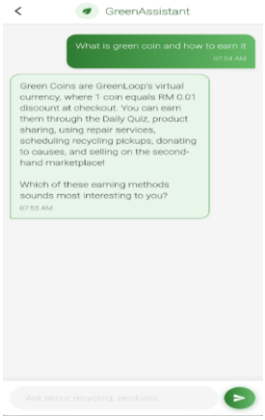


Figure 4c. Chatbot

5.2 Beta user testing

5.2.1 Demographics

Similar to alpha user testing, the sample respondents are from an urban setting around Subang Jaya, Malaysia. Analyses are presented in Tables 10a-d.

Table 10a. Gender **Table 10b.** Age **Table 10c.** Occupation **Table 10d.** Educational level

Gender	%	Age	%	Occupation	%	Education	%
Male	40	< 21	30	Student	90	No formal education	0
Female	60	21 - 30	60	Employed (Full Time)	5	Primary/secondary	0
		31 - 40	5	Employed (Part Time)	0	Pre-university	7.5
		41 - 50	0	Self-employed	0	Year 1 university	15.0
		51 – 60	2.5	Unemployed	0	Year 2 university	12.5
		> 60	2.5	Retired	5	Year 3 university	57.5
						Postgraduate	7.5

5.2.2 User experience

Schrepp's et. al.'s (2017) [12]'s user experience (UX) constructs (Table 11) are applied to evaluate TAM's engagement/enjoyment.

Table 11. *LoopCart's* UEQ rating frequency and averages

Quality aspect	Rating frequency					Avg.	Quality aspect	Rating frequency					Avg.
	1	2	3	4	5			1	2	3	4	5	
Attractiveness	0	2	8	4	26	4.35	Dependability	1	1	11	13	14	3.95
Perspicuity	1	1	7	9	22	4.25	Stimulation	0	2	14	19	5	3.67
Efficiency	0	2	6	12	20	4.25	Novelty	2	1	15	17	5	3.55

5.2.3 TAM-based assessments of technology acceptance

Based on Tables 12a-j, the top 6 categorical averages come from AI-based best value comparison (4.09), followed by Basket of Hope (4.08), Daily Quiz (4.07), personalized product recommendations (4.06), repair services (4.06) and Green Coin reward (4.03). These highlight that value consciousness is primary. Basket of Hope is practical, if the respondent no longer needs/ wants the item and can use the points earned from recycling to buy/repair (repair services is among the top 6). AI chatbot (4.00), Sustainability Analytics and Reports (3.99), second hand marketplace (3.99), recycling pickup services (3.98) require improvement in terms of perceived value. Overall average across all categories is 4.03.

Table 12a. Evaluation of personalized product **Table 12b.** Best value comparison recommendations

Questionnaire Item	Avg.	Sdev	Questionnaire Item	Avg.	Sdev
Personalized recommendations make my product search more efficient.	4.03	1.05	The AI-generated summary helps me better understand price-product quality trade-offs.	4.08	1.02
Personalized recommendations reduce the time finding suitable products.	4.20	1.07	The comparison feature helps me make more informed purchasing.	3.98	1.12
The recommended products accurately reflect my preferences.	3.95	1.08	The AI-generated summary reduces the need to read multiple reviews.	4.20	1.14
			The AI-generated summary is clear, and easy to understand.	4.10	1.01
Categorical average	*4.06*			*4.09*	

Table 12c. Evaluation of AI chatbot

Questionnaire Item	Avg.	Sdev
The AI chatbot helps me understand the platform.	3.93	1.10
The AI chatbot clearly explains the app's features.	3.95	1.13
The AI chatbot helps me understand the Green Coin system.	4.05	1.04
Using the AI chatbot makes the app easier to use.	4.08	1.14
Categorical average	*4.00*	

Table 12d. Evaluation of waste sorting assistance

Questionnaire Item	Avg.	Sdev
The feature helps me identify the correct category for waste items.	3.90	1.03
The recycling tips provided for each category are clear and useful.	4.03	1.12
The feature is easy to use, less confu-sion when sorting recyclable items.	3.98	1.03
The feature motivates me to recycle more regularly	4.15	1.12
Categorical average	*4.02*	

Table 12e. Evaluation of second-hand market

Questionnaire Item	Avg.	Sdev
The feature helps me save money when purchasing products.	4.13	0.99
The feature makes it easier for me to buy or sell used items.	3.83	1.17
The process of buying or selling second-hand items is clear & direct.	3.98	1.03
The Green Coin rewards for the second-hand market are clear.	3.90	1.17
The Green Coin rewards encourage me to buy or sell second-hand items.	4.13	1.04
Categorical average	*3.99*	

Table 12f. Evaluation of repair services

Questionnaire Item	Avg.	Sdev
It is convenient to find repair services for diff. product categories.	4.30	0.97
Repair options are clearly presented and easy to understand.	4.00	1.18
Using repair services reduces my need to purchase new products.	3.88	1.04
The fee structure, Green Coin rewards for repair services are clear.	3.95	1.11
Green Coin rewards encourage me to choose repair services, not buy new items.	4.15	0.98
Categorical average	*4.06*	

Table 12g. Evaluation of recycling pickup services

Questionnaire Item	Avg.	Sdev
The recycling pickup service makes recycling more convenient for me.	4.05	0.96
The pickup scheduling process is easy to use.	3.93	1.10
Green Coin rewards for the recycling pickup service are clear.	4.10	1.08
The Green Coin rewards encourage me to recycle items	3.85	1.19
Categorical average	*3.98*	

Table 12h. Evaluation of Basket of Hope donations

Questionnaire Item	Avg.	Sdev
The donation feature makes it easy to support diff. communities, social causes.	4.15	1.05
The donation process is simple and transparent.	4.05	1.18
Green Coin rewards for donations are clearly explained.	4.00	1.11
The Green Coin rewards encourage me to contribute via donation.	4.13	1.04
Categorical average	*4.08*	

Table 12i. Evaluation of daily quiz

Questionnaire Item	Avg.	Sdev
The Daily Quiz helps improve my knowledge of sustainability topics	4.13	0.97
The quiz questions are clear and easy to understand.	3.98	1.19
Earning Green Coins via quizzes motivates me to participate regularly.	4.10	1.06
Categorical average	*4.07*	

Table 12j. Evaluation of Analytics/Reports

Questionnaire Item	Avg.	Sdev
The analytics feature helps me understand my sustainability impact.	4.10	0.93
The repair & recycling activity reports helps track my participation.	4.03	1.17
Badges encourage me to use sustainability-related features more.	3.93	1.12
The charts, reports are easy to interpret.	3.90	1.13
Categorical average	*3.99*	

Open-ended feedback from beta user testers highlights two main usability challenges related to feature clarity and decision-making. First, users report difficulty in comparing second-hand and new products, particularly in understanding the trade-offs between price, quality, and sustainability impact within a single view. This suggests that while the application provides relevant information, the way it is presented may require users to mentally integrate multiple factors, increasing cognitive effort when purchasing.

Second, users indicate that the number of sustainability features available may be overwhelming for first-time users. Although the wide range of features adds value, the

lack of guided onboarding may hinder initial usability and lead to confusion. This feedback suggests a need for progressive disclosure, for better user experience.

6. Alpha-beta user testing comparisons

LoopCart is developed using an iterative incremental prototyping methodology with two testing phases: alpha and beta. This section compares findings to assess whether user expectations identified via Figma prototype (alpha) (Table 9) are validated after interaction with the actual prototype (beta) (Tables 12a-j).

Comparative alpha-beta findings (Table 13) indicate alpha averages ranging from 3.03 to 4.03, with an overall average of 3.62 (72% acceptance). Beta testing shows consistently high acceptance across all features, with averages between 3.98 and 4.09, with an overall average of 4.03 (81% acceptance). This finding indicates that similar to Lazada/Shopee, on average, perceived value, rewarded by Green Coins, can persuade. Best value can be assessed from personalized filtering key terms and follow through.

Table 13. Comparison between alpha interest and beta acceptance results (in beta descending order and rank)

Feature	Alpha (Avg.)	Beta (Avg.)	Feature	Alpha (Avg.)	Beta (Avg.)
Best Value Comparison	4.03 (1)	4.09 (1)	Waste sorting assistance		4.02 (7)
Basket of Hope donations	3.47 (5/6)	4.08 (2)	AI chatbot		4.00 (8)
Daily quiz		4.07 (3)	Sustainability Analytics/Reports	3.45 (7)	3.99 (9)
Personalized Filtering	3.83 (3/4)	4.06 (4)	Second-Hand Marketplace	3.03 (8)	3.99 (10)
Repair Services	3.83 (3/4)	4.06 (5)	Recycling Pickup Services	3.47 (5/6)	3.98 (11)
Green Coin Reward	3.87 (2)	4.03 (6)			

Note: The Green Coin Reward System beta score (4.03) represents the average of nine Green Coin–related TAM items across multiple features

6.1 Derived Kano model

The Kano model is based on Gaussian distributions (Miyamura & Kano, 2006) [20] and our analyses are based mainly on averages. For this study, we have assigned delighters as those with averages above 80%, and performers, averages between 75-79%. Must-have features are undoubtedly, security, privacy and reliability. These thresholds and their range can be tightened or relaxed depending on market conditions, and in line with design thinking (e.g. by Stanford's d.school, Gemany's Hasso Plattner, Venkatesh et. al).

6.2 Overall implications

The diversity of products, algorithmic strengths and potential partnerships in Lazada/ Shopee are unbeatable and endless. It would be challenging to implement the solar-powered *EasyBox*, as the cost is high. However, *EasyBox's* sustainable last-mile logistics implies that recycling centres can provide Green Coin rewards when users upload a snapshot to the website. Rewards can be based on frequency and/or type of items.

Furthermore, Malaysia is an upper middle-income country. Hence, it may not be easy to transfer from *Recykal* which digitally links formal and informal recycling sectors and provides jobs for the informal sectors. There are few who would be willing to pick up recyclable items from others' homes, unless the returns are promising. Moreover, the greatest difficulty in recycling is manually separating/classifying the items. Some of these problems are mentioned in Lee, Eu, Chai, Chai, Ho, Tan, Morsim, Aye and Siew, (2023) [21] and Lee (2025) [22]. One of the proposed solutions in [22] is to redesign the

garbage trucks' collection area from a general bin to separate bins. This would encourage users to separate their trash at home and get Green Coin rewards by uploading a snapshot to the website. Municipal councils can then send the separated recyclable items to their respective partners, to retrieve the material, redesign, recycle/reuse/repair (e.g. Uniqlo). The supply chain can develop monetization strategies, based on [7, 8]'s CE principles. Lazada/Shopee is ahead in the Asia Pacific. Rewards can be tax rebates/TnGo rewards.

6.3 Limitations of the study

The sample respondents consist of predominantly year 3 university students. Hence, it is skewed. Furthermore, perception studies are self-reported. Hence, there is a degree of subjectivity. However, we do not expect much process differences due to age or non-student populations, even to other regions or demographics. As with Shopee and Lazada, Asia's 2 most popular e-commerce platforms, we conjecture that best value comparisons, personalized recommendations and rewards will still be the Kano delighters. What differentiates are the contents/products and types/quantum of rewards.

7. Conclusion

In conclusion, this project has successfully achieved its intended objectives by designing and developing a mobile e-commerce application that integrates CE principles into the online shopping experience. Aligned with the 6R framework and relevant Sustainable Development Goals (SDGs), *LoopCart* encourages users to shift from traditional fast-consumption behaviour toward more responsible and sustainable practices. It has demonstrated that sustainability-oriented features can be effectively embedded into existing online shopping workflows without compromising usability or UX.

Evaluation results from beta user testing indicates positive user acceptance across most features, particularly in terms of perceived usefulness, usability, and user experience. Several enhancements can be considered for future development. First, is to introduce more advanced personalization by analysing user behaviour and sustainability activities to provide tailored product recommendations, sustainability tips, and Green Coin challenges. Second is enhancing visual comparisons particularly in terms of sustainability impact, price, and quality. Third, is to learn from [7, 8]'s CE principles, develop the partnership supply chain, and impactful rewards (e.g. tax rebates).

Acknowledgement

This was Chong's undergraduate capstone project. Lee added [7, 8, 20-22] to highlight the role of [7, 8]'s CE (especially redesign), Kano model, design thinking, overall implications, limitations of the study, thanks to the reviewers' constructive feedback. We would like to thank the Editor, and respondents who participated. Lee thanks Malaysia's Multimedia Super Corridor, Dr. Kuok-Shoong Daniel Wong for introducing design thinking in 2013, past Malaysian, US, JICA, China grant agencies, and past mentors who promoted mashables. Future studies may include design thinking design and evaluation via Finland's Sustainable Awareness Framework and market basket analyses.

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Building a Resilient Innovation Ecosystem in Oman Through Digital Transformation and Artificial Intelligence

Najiba Said Hamed Al-Zadjali[a,1], Sara Khamis Al Ruzeiqi [a], Divyajyothi M.G. [a] and Omair Asim Al-Zadjali[b]
[a] *University of Technology and Applied Sciences-Muscat, Oman*
[b] *Royal Academy of Management- Muscat, Oman*

Abstract. This paper analyzes Artificial Intelligence (AI) and digital transformation as strategic facilitators for enhancing national innovation ecosystems, with a specific emphasis on Oman's role in its Vision 2040 initiative. Although previous research has examined various factors affecting digital innovation, there is a lack of studies that provide comprehensive insights into how AI influences the developmental processes of innovation capabilities within national contexts. To address this gap, the study employs systematic literature review and a conceptual framework construction methodology, synthesizing existing scholarship on digital transformation, innovation ecosystems, and AI governance. The resulting Digital-AI Innovation Ecosystem Framework (DAIEF) is built upon five core components: digital infrastructure, AI capabilities, policy and governance, human capital, and collaboration. The framework proposes that AI capabilities act as enablers that enhance human potential by supporting data-driven decision-making, improving collaboration, and making innovative systems more resilient. This paper contributes to the literature by offering a context-specific, multi-level framework aligned with Oman Vision 2040, thereby bridging the gap between technology adoption and innovation capacity development. The research also presents policy implications for cultivating sustainable and inclusive digital innovation ecosystems in emerging economies.

Keywords. Digital Transformation, Artificial Intelligence, Innovation Ecosystem, Oman Vision 2040, Smart Governance, Knowledge Economy, Emerging Technologies, Public–Private Partnership, Data-Driven Innovation, and Sustainable Development.

1. Introduction

Countries all over the world are reconsidering how to create, grow, and keep innovation going in the face of rapid technological change, economic uncertainty, and rising public expectations for smart services. The digital revolution and artificial intelligence are the core drivers of this change in re-evaluating the way governments work, the way businesses compete, and how knowledge is created and shared [1], [2], [3]. A combination of these influences the national systems of innovation that encompass policy design, entrepreneurship and its activities, research capacities, public awareness,

[1] Corresponding Author: Najiba Said Hamed Al-Zadjali, Email: Najiba.Alzadjali@utas.edu.om;
Second Author, Sara Khamis Al Ruzeiqi, Email: sara.alruzeiqi@utas.edu.om

etc. Technical advances do not happen to be enclosed within national borders. The transition toward a diversified, knowledge-based economy is one of the strategic priorities of the Oman Vision 2040 Plan [4]. This approach recognizes innovation and digitization alongside the application of technology and human capital as the most critical drivers of long-term economic growth. Consequently, building a robust innovation ecosystem requires a coordinated transformation across governance, education, industry, and community engagement, rather than relying on isolated technology projects. Through AI and digital technologies, these stakeholders can collaborate, exchange data, and co-create value within a dynamic and flexible environment.

Within a healthy innovation ecosystem, resilience means the ability to survive changes, adapt, and continue working on new ideas, services, and businesses [5]. Digital systems and infrastructures have provided institutions with the flexibility to respond according to new opportunities and establish room to implement innovative responses to evidence-based policymaking, whether they are cloud platforms, data analytics tools, or AI-assisted decision systems. Also, they offer academics and entrepreneurs the means and virtual solutions to hastily create studies. These are particularly relevant to Oman at a time when it seeks to enhance the R&D potential and foreign partnerships, encourage the culture of start-ups, and transform the governmental services. Nevertheless, there are roadblocks on the path to a digitally empowered innovation (such as the Internet of Things, or IoT) ecosystem. To ensure that technology developments lead to inclusive and sustainable development, such problems as cybersecurity, responsible use of AI, the digital skills gap, ensuring that regulations are not outpaced by technical developments, and appropriate stewardship of data should be tackled [6], [3]. Unless planned and structured, digital transformation may lead to an array of systems, rather than one integrated innovative environment. Therefore, this paper explores the strategic use of DT and AI to foster a robust innovation ecosystem in Oman. The goal of the study is to provide an integrated framework that could seal the gap in establishing innovation capacity in the long term by using the integrated evaluation of technology, policy, education, industry, and society.

1.1 Theoretical positioning and contribution

The Digital-AI Innovation Ecosystem Framework (DAIEF) is not merely a mixture of models. It addresses some of the unanswered questions of how we presently comprehend the digital transformation and innovation systems. The majority of traditional innovative ecosystem models pay a lot of attention to the structure or stakeholders, infrastructure, and policy [7], [5]. What they fail to understand, though, is how exactly digital technologies, particularly Artificial Intelligence (AI), influence and construct the capacity to innovate. Conversely, a lot of the digital transformation models would focus on adopting new technologies and optimization, yet they do not go all the way and examine how humans and AI can collaborate, co-create solutions, and lead to innovation by engaging in constant learning.

Recent research indicates that AI is altering the role of actors in such ecosystems in a significant manner [2], [7], [8]. People and organizations are not passive consumers of technology, yet they are becoming active contributors, co-designers, and co-creators of innovation. AI technologies improve the work of the human brain, help to make better decisions, and contribute to continuous learning [2], [8], which increases innovation skills. In this regard, AI is a strong capability enhancer, and it contributes to the creation

of knowledge and more responsive and adaptive innovation. The next problem with the current models is that they have a one-size-fits-all form of approach to digital transformation. As a matter of fact, the results vary greatly according to the national situation [9], [10], [4]. Such aspects as institutional structure, digital readiness, labor competence, and economic priorities are contributory. This clarifies the fact that frameworks must be specific to countries, matching the changing technology with that country's national development strategies.

It is also worth noting that innovation does not occur in a vacuum. It arises because of the interaction at numerous levels between firms, institutions, and the ecosystem in general. Infrastructure is important, but the key force in innovation is a combination of policies, skills, networks of collaboration, and systems of knowledge-sharing. Existing models do not always fully describe the dynamics between these relationships.

1.2 Research Problems and Questions

Even though digital technologies are widely used, the precise role of AI in enhancing innovation within national ecosystems particularly in emerging economies such as Oman has yet to be fully analyzed. Prior research has largely focused on either technology adoption or the structural characteristics of innovation ecosystems, rarely integrating both dimensions

To address this research gap, this study investigates how AI-enabled digital transformation supports the existence of innovation ecosystems within the Oman Vision 2040 framework. This research will be guided by the following research questions:

- **RQ1:** aims to determine how digital transformation impacts the development of innovation ecosystems at a national level.
- **RQ2:** What is the rationale for AI being a source of innovation capabilities and ecosystem resilience?
- **RQ3:** What is the beneficial impact of a context-specific framework on the development of the innovation ecosystem in Oman?

1.3 Related work

Table 1 summarizes key academic literature, policy documents, and frameworks that address the role of AI and digital transformation in advancing innovation ecosystems and smart governance [11]– [13].

The literature review reveals three significant key gaps. First, most of the studies focus on either digital transformation or innovation ecosystems without integrating AI as one of the key capabilities [7], [5], [13] that drive them. Second, existing frameworks are largely developed in and for established economies, lacking contextualization for emerging economies [12], [9], [10], [6], [3]. Third, interactions among technological, institutional, and human dimensions are often underestimated. These gaps emphasize the need for a contextualized, integrated framework, prompting the development of DAIEF.

Table 1. Comparative Literature Review on Digitalization, AI and Innovation Ecosystems

Ref.	Authors & Year	Focus Area	Methodology / Approach	Key Contributions	Limitations / Research Gaps
[11]	Ismail, Malone & Van Geest (2014)	Digital transformation and exponential organizations	Conceptual framework based on case studies of tech-driven firms	Explained how digital platforms and data-driven models accelerate innovation capacity	Focuses on private sector; limited discussion on national ecosystems
[1]	Schwab (2016)	Fourth Industrial Revolution	Analytical discussion of emerging technologies	Highlighted AI, IoT, and big data as drivers of economic and social change	Lacks practical roadmap for developing countries
[12]	OECD (2019)	Digital government and innovation	Policy analysis across member countries	Demonstrated how digital governance enhances public innovation and service delivery	Mostly based on developed nations' experiences
[9]	World Bank (2021)	Digital economy for development	Empirical analysis of digital adoption in economies	Showed link between digital infrastructure and economic diversification	Generalized framework without regional specificity
[2]	Brynjolfsson & McAfee (2017)	AI and economic transformation	Economic impact analysis of AI technologies	Established AI as a key productivity and innovation enabler	Limited focus on policy and ecosystem integration
[7]	Nambisan, Wright & Feldman (2019)	Digital innovation ecosystems	Theoretical model of digital platforms and ecosystems	Explained collaboration between stakeholders through digital platforms	Lacks application to government-led ecosystems
[5]	Autio & Thomas (2020)	Innovation ecosystem resilience	Conceptual and empirical synthesis	Introduced resilience as a factor in ecosystem sustainability	Not linked explicitly to AI-driven environments
[10]	UNDP (2020)	Digital transformation for sustainable development	Case study analysis across countries	Connected digital technologies to SDGs and governance reform	Limited technological depth in AI implementation
[13]	Khin & Ho (2019)	Digital technology and organizational performance	Survey-based empirical study	Identified digital readiness as a determinant of innovation success	Focused at firm level rather than national level
[14]	Hanna (2018)	Digital economy policy frameworks	Comparative policy study	Proposed integrated digital strategies for governments	Does not deeply address AI ethics and governance
[15]	Li et al. (2020)	AI adoption in public sector	Case-based analysis	Showed how AI enhances decision-making and service automation	Limited to selected case regions

[6]	European Commission (2020)	AI strategy and innovation	Policy framework documentation	Provided structured AI governance and innovation roadmap	Designed primarily for EU context
[8]	Deloitte (2021)	Smart government and AI	Industry report and case examples	Demonstrated AI use in smart governance and citizen services	Lacks academic validation
[16]	Al-Busaidi & Olfman (2017)	Knowledge sharing and digital collaboration	Empirical research in knowledge management	Emphasized digital collaboration platforms for innovation	Does not integrate AI capabilities
[4]	Oman Vision 2040 Implementation Reports (2022)	National digital and innovation strategy	Policy and strategic documentation	Outlined Oman's focus on digital economy and innovation-driven growth	Requires academic synthesis and technological mapping
[3]	WEF (2021)	Future of digital ecosystems	Global foresight and trend analysis	Identified importance of digital trust, data governance, and AI	Broad outlook without regional application

1.4 Research Methodology

This study employs a systematic literature review methodology alongside the development of a conceptual framework [7], [5]. Relevant literature was identified through searches in Scopus, Web of Science, and Google Scholar using keywords including digital transformation, artificial intelligence, innovative ecosystems, and related terms. The search produced 280 records, with an additional 70 from supplementary sources. After removing duplicates, 180 records were screened, of which 120 were excluded based on titles and abstracts. The remaining 60 full-text articles were assessed for eligibility, leading to the exclusion of 44 studies due to limited relevance or scope. In the end, 16 studies met all the requirements and were retained for analysis. The Digital-AI Innovation Ecosystem Framework (DAIEF) was developed to conceptualize the relationships among technological, institutional, and human variables in the Omani context [7], [5], [14], [16].

DAIEF addresses the identified gaps through three primary contributions. First, it presents an AI-based perspective that positions AI as central to innovation capacity development through human-AI collaboration, continuous learning, and informed decision-making. Second, it emphasizes contextualization by grounding the framework in Oman's specific socio-economic context. Third, it integrates multiple-level innovation infrastructure, governance, human capital, and collaboration into a unified model that demonstrates their interconnectedness in generating sustained innovation outcomes. While conceptually robust, the framework requires empirical validation, suggesting avenues for future case studies and qualitative research.

1.5 Objectives

This study aims to achieve the following objectives:

To investigate how digital transformation influences the development of innovative ecosystems at the national level

To examine the role of AI in building innovation capacity and ensuring ecosystem resilience

To synthesize the literature to identify key dimensions of AI-enabled innovation ecosystems

To develop a conceptual framework contextualized for Oman

To apply the framework to generate policy-relevant insights

Policy Recommendation Objective: To propose policy-relevant insights and a phased implementation roadmap in alignment with Oman Vision 2040, grounded in the Digital-AI Innovation Ecosystem Framework (DAIEF) and an assessment of Oman's current digital and innovation landscape.

1.6 Rationale: Why Oman Needs a Resilient Innovation Ecosystem

Guided by Vision 2040, Oman seeks to transition from an oil-dependent to a knowledge-based economy [4]. This shift requires a resilient, innovative ecosystem capable of generating new ideas, technologies, and industries amid global uncertainty. Oil price volatility highlights the vulnerability of resource-dependent economies; digital transformation and AI can help diversify key sectors, such as manufacturing, logistics, tourism, healthcare, and education [9], [2], [10], [4], while creating opportunities for a growing youth population. Moreover, without an integrated digital infrastructure, organizations remain siloed, limiting collaboration. Digital platforms and AI-enabled systems can connect government, academia, industry, and startups, enabling more responsive policymaking [7], [16]. For Oman to become a regional hub for research and technology, cultivating such an ecosystem is both a strategic imperative and a foundation for long-term development.

2. Background: Oman's Digital and Innovation Landscape

Oman presents a distinctive context characterized by its transition from a resource-based to a knowledge-based economy, its centralized governance structure, and its strategic commitment to digital transformation under Vision 2040. These factors create a compelling rationale for developing a localized innovation ecosystem model rather than adopting a universal one. Innovation and digital transformation are explicitly articulated within Oman Vision 2040 as national development goals [4]. Institutional excellence, knowledge-based growth, economic diversification, and human capital expansion are positioned as foundational pillars of sustainable development.

2.1. Oman Vision 2040

Oman Vision 2040 outlines the transformation of the country's oil-oriented economy toward an innovative and diversified model. The vision emphasizes smart governance, education reform, digital infrastructure development, and increased private sector participation in technology-driven growth [4]. It promotes the adoption of advanced

technologies to foster entrepreneurship, enhance public service efficiency, and strengthen Oman's international competitiveness. The vision also prioritizes human capital development, aiming to equip citizens with the skills necessary to participate in cross-sector innovation networks and contribute to the digital economy. Furthermore, it emphasizes collaboration among government entities, academic institutions, and business organizations to establish a robust research and development ecosystem capable of converting knowledge into economic value through start-ups, technology parks, and innovation centers.

2.2 Current Digital Initiatives in Oman

Oman has launched several digital initiatives to improve government services through smart systems and strengthen its technological infrastructure [4], [17], as shown in Figure 1. E-government platforms have been adopted to increase transparency, reduce administrative burdens, and make public services easier to access [12], [4]. Service availability and operational efficiency have been improved through digital portals for healthcare appointments, education, licensing, and taxation. The creation of institutions such as the Oman Information and Communications Technology Group (OICT) and the Ministry of Transport, Communications, and Information Technology (MTCIT) demonstrate the country's commitment to digital progress. Significant investments have also been made in national digital infrastructure, including data centers, cloud computing, broadband connectivity, and cybersecurity standards [17], [18].

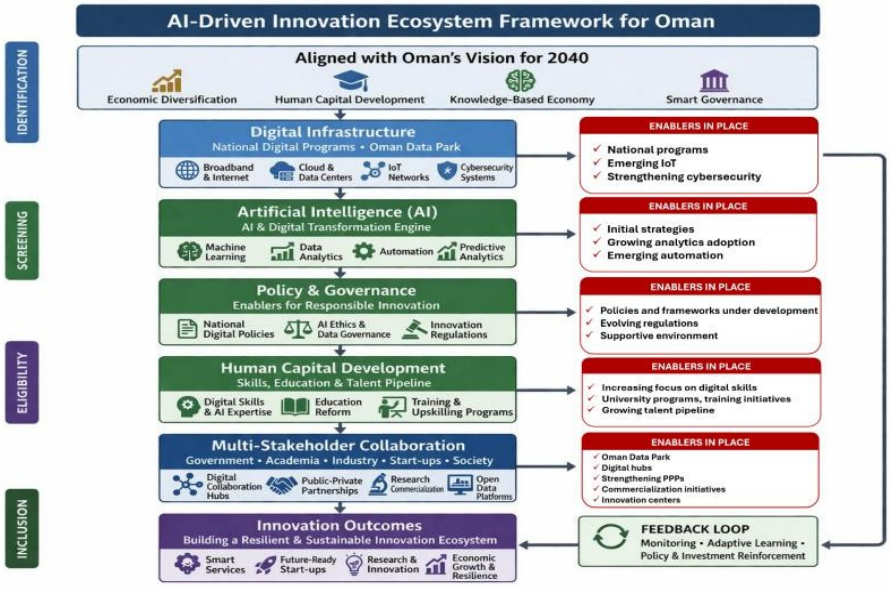


Figure 1. Oman's Digital and Innovation Status

Oman further supports innovation through technology parks, business incubators, and entrepreneurship development programs such as Knowledge Oasis Muscat (KOM) and various start-up support initiatives [4], [19]. Universities and research centers are being strongly encouraged to collaborate with industry partners to facilitate applied research and technology commercialization. Collectively, these efforts indicate that

Oman has developed a robust institutional and digital foundation. While this foundation is necessary for building resilience, flexibility, and future national development, an additional imperative exists to integrate these initiatives into a cohesive, AI-enabled innovation environment.

2.3. Digital and AI-Driven Resilient Innovation Ecosystem

Table 2 establishes the key dimensions of a resilient innovation ecosystem driven by digital and artificial intelligence, detailing the role each dimension plays in generating innovation [12], [2], [7], [5], [8], [16], [3].

Table 2. Key Dimensions of a Digital and AI-Driven Resilient Innovation Ecosystem

Aspect	Description	Role of Digital Technologies	Role of Artificial Intelligence
Innovation Ecosystem	A collaborative network of government, academia, industry, start-ups, and society working together to create and apply knowledge	Digital platforms enable communication, knowledge sharing, and coordination among stakeholders	AI supports intelligent collaboration through data analysis and decision support
Resilience	Ability of the ecosystem to adapt, recover, and sustain innovation during disruptions	Cloud systems, secure networks, and real-time data access ensure continuity of operations	Predictive analytics and automation help respond quickly to crises and changes
Knowledge Flow	Continuous exchange of research, data, skills, and expertise	Shared databases, e- platforms, and digital repositories store and distribute knowledge	AI processes large datasets to generate insights and innovation opportunities
Collaboration	Partnership between institutions for research, development, and entrepreneurship	Online collaboration tools, virtual labs, and digital communication channels	AI-driven tools enhance coordination and optimize collaborative outcomes
Governance and Policy Support	Regulatory and institutional support for innovation activities	E-governance systems improve transparency and service efficiency	AI aids evidence-based policymaking through data modeling and forecasting
Infrastructure	Technological and institutional foundation required for innovation	Broadband, cloud computing, IoT, cybersecurity frameworks	AI utilizes this infrastructure to deliver intelligent services and automation
Sustainability	Long-term ability to generate innovation and economic value	Digital transformation reduces operational barriers and enhances scalability	AI accelerates research, product development, and service optimization
Adaptability	Capability to respond to technological, economic, and social changes	Digital systems allow rapid updates and integration of new technologies	AI enables learning systems that evolve with new data and scenarios

3. Proposed Framework: Digital and AI-Driven Resilient Innovation Ecosystem for Oman

This section presents a strategic framework explaining how Oman can develop a comprehensive innovation ecosystem through the application of digital infrastructure, artificial intelligence (AI), policy support, human capital development, and multi-

stakeholder collaboration. Table 3 outlines the core components, which represent interconnected layers that collectively foster continuous innovation, adaptive capacity, and sustain economic growth.

Table 3. Core Components o the Proposed Digital and AI-Driven Resilient Innovation Ecosystem Framework

Component	Description	Role in the Framework	Expected Impact on Innovation Ecosystem
Digital Infrastructure	Broadband connectivity, cloud computing, data centers, IoT networks, cybersecurity systems	Provides the technological foundation for data exchange, connectivity, and digital services	Enables seamless communication, secure data flow, and scalable digital platforms
Artificial Intelligence (AI)	Machine learning, data analytics, automation, predictive systems	Acts as the intelligence layer for decision-making, optimization, and service automation	Enhances research capability, smart governance, and intelligent entrepreneurship
Policy and Governance	National digital policies, AI ethics, data governance laws, innovation regulations	Creates a supportive regulatory environment for digital and AI adoption	Ensures responsible innovation, transparency, and long-term sustainability
Human Capital	Digital skills, AI expertise, education reform, training programs	Supplies skilled professionals and researchers to operate and innovate within the ecosystem	Drives knowledge creation, start-up culture, and technology adoption
Collaboration	Partnerships among government, academia, industry, start-ups, and society	Encourages knowledge sharing, joint research, and co-creation of solutions	Strengthens R&D, commercialization, and ecosystem resilience

These components interact through a causal positive feedback mechanism. Data generation and connectivity from digital infrastructure feed into AI systems, which generate insights. These insights inform governance and policymaking, which in turn influence investment in human capital and innovation activities. Collaboration mechanisms facilitate bidirectional information flow, creating a feedback loop that enhances ecosystem performance over time. This virtuous cycle illustrates how the combined forces of AI and digital transformation can enable sustainable innovation capacity and adaptive responsiveness.

3.1. Working Principle of the Framework

The integrated, scalable, and secure platforms of digital infrastructure provide all stakeholders with the opportunity to link with each other. Shared data AI-based systems are used to process shared data and generate valuable information, automatize services, and enable informed decision- making. Policy frameworks promote the use of digital and AI technologies in a manner that is not only ethical and secure but also creative. The human capital uses these technologies to produce research findings, develop start-ups, and to offer smart services. Cooperation ensures continued coordination, knowledge, and cross-sector innovation.

These elements work together to form a self-reinforcing loop in which people, technology, and policy are closely interconnected, creating an innovation ecosystem that is resilient, flexible, and aligned with Oman's national development goals, as illustrated in figure 2.

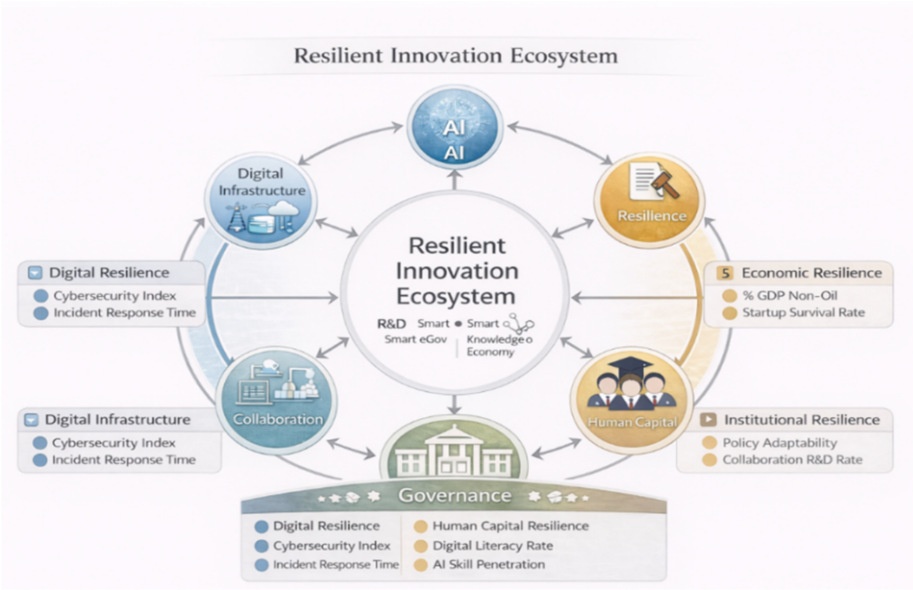


Figure 2. Proposed Framework for a Digital and AI-Driven Resilient Innovation Ecosystem in Oman

4. Implementation Roadmap for Building a Digital and AI-Driven Resilient Innovation Ecosystem

Table 4 exhibits a phased implementation process to assist Oman in developing a resilient innovation environment driven by digital and AI technologies. The strategy is broken down into short-term, mid-term, and long-term tasks to support the long-term use of technology, effective policy adoption, and gradual capacity building.

Table 4. Phased Implementation Roadmap for Developing a Digital and AI-Driven Resilient Innovation Ecosystem in Oman

Phase	Time Horizon	Key Actions	Responsible Stakeholders	Expected Outcomes
Short-Term	1–2 Years	• Strengthen broadband, cloud, and cybersecurity infrastructure • Launch national AI awareness and training programs • Digitize priority government services	MTCIT, Government agencies, Universities, ICT firms	Improved digital readiness, basic AI literacy, and enhanced e-government efficiency
Mid-Term	3–5 Years	• Set up AI research centers and innovation labs • Promote start-ups through incubators and funding schemes, education, and public services • Foster industry–academia R&D collaboration	Government, Universities, Knowledge Oasis Muscat, Private sector	Growth of AI applications, increased start-ups, stronger R&D output, and job creation
Long-Term	6–10 Years	• Develop a fully integrated AI-driven smart governance model •Expand international innovation partnerships •Position Oman as a regional AI and innovation hub	National innovation bodies, international partners, and industry leaders	Sustainable knowledge economy, global competitiveness, resilient innovation ecosystem

4.1. Market Context: Digital and AI Economy in Oman

Outlining the market potential for digital technologies and AI in Oman and the broader Gulf region enhances the research's practical relevance. Table 5 provides an overview of the digital economy, AI sector, and innovation start-up ecosystem [18], [19], [20].

Table 5. Market Outlook for Oman's Digital Economy, AI Sector, and Innovation Start-Up Ecosystem

Market Segment	Current Size (2024)	Projected Growth (by 2030)	Key Drivers	Sources
Digital Economy / ICT Market	Approx. **$5.5–5.6 billion**	Projected to reach **~$9.75–10.41 billion** by 2030–2031	Growth of broadband, cloud services, cybersecurity, AI integration	(Oxford Business Group, 2025)
AI Market (Oman)	Estimated **~$237–240 million**	Expected to rise to **~$647 million** by 2030	Adoption in smart services, automation, government & industry	(Ken Research, 2025)
Innovation & Start-Ups Ecosystem	$127+ million in tech startup funding (registered)	Continued growth with increased investments and supportive programs by 2030	Incubators, accelerators, funding schemes, policy support	(Oman Observer, 2026)

The marketing for digital technologies and artificial intelligence in Oman provides practical grounding for the five core components of the Digital-AI Innovation Ecosystem Framework (DAIEF). Oman's information and communication technology (ICT) market is projected to grow from approximately USD 5.5 billion in 2024 to nearly USD 9.75 billion by 2031, driven by sustained investments in digital infrastructure, cloud computing services, and cybersecurity solutions [18]. This growth directly supports DAIEF's digital infrastructure component by providing the technological base for broadband connectivity, cloud platforms, data centers, and secure networks required for seamless data exchange and scalable digital services, positioning the ICT sector as a critical driver of long-term economic growth (Figure 3) [18]. These market trends are reinforced by national digitalization efforts aligned with Oman Vision 2040, which emphasizes economic diversification and the transition toward a knowledge-based economy, thereby strengthening the policy and governance dimension of DAIEF by ensuring that regulatory frameworks and innovation-friendly policies create a supportive environment for responsible digital and AI adoption. The digital transformation market in Oman has experienced rapid expansion, with forecasts indicating continued momentum; as shown in Figure 4, the market recorded a compound annual growth rate of 19.71 percent between 2020 and 2025, underscoring the accelerating pace of digital modernization across both public and private sectors and reflecting growing organizational readiness to adopt intelligent technologies [20]. This directly contributes to the AI capability dimension of DAIEF, positioning AI as the intelligence layer for decision-making and service automation.

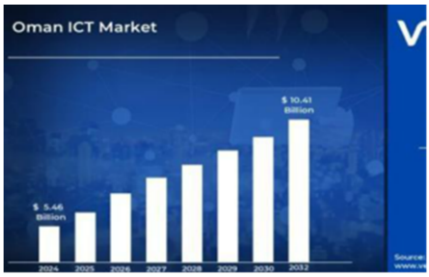


Figure 3 Projected Growth of Oman's ICT Market (2024–2032) with CAGR of 8.9%

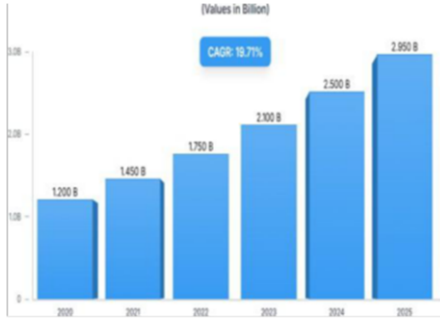


Figure 4. Oman Digital Transformation Market Size Forecast with 19.71% CAGR (2020–2025)



Figure 5. Oman ICT Market Growth Projection from USD 6.42 Billion (2026) to USD 9.75 Billion (2031) at a CAGR of 8.73%

Oman's ICT market is projected to continue its upward trajectory, with estimates indicating growth from USD 6.42 billion in 2026 to USD 9.75 billion by 2031, representing a CAGR of 8.73 percent (Figure 5) [18], further reinforcing the foundational infrastructure required for AI-enabled innovation. In parallel, Oman's AI market is forecast to grow substantially, from approximately USD 237 million to nearly USD 647 million by 2030, driven by increasing adoption of AI-powered solutions across government services, healthcare, logistics, and industrial sectors. This expansion demonstrates growing demand for machine learning, data analytics, automation, and predictive systems while simultaneously creating corresponding demand for digital skills and AI expertise, reinforcing the human capital dimension of DAIEF through the need for education reform, training programs, and talent pipeline development.

4.2. Challenges and Recommendations

Developing a resilient, AI-enabled innovation ecosystem in Oman presents critical challenges that demand coordinated responses. Cybersecurity threats stemming from rapid digitalization require strengthened national infrastructure, secure cloud investments, regular audits, and dedicated incident response teams. Talent gaps in AI and data science call for integrating AI into educational curricula alongside

professional training programs and academic partnerships. Regulatory and policy gaps necessitate updated digital policies, innovation- friendly regulations, and streamlined public-private collaboration mechanisms. Addressing these interconnected challenges through well-coordinated solutions will enable policymakers and stakeholders to advance toward a secure, sustainable innovation system that supports responsible digital economy development and AI adoption in Oman.

5.Conclusion

This study contributes to the literature by proposing a context-dependent framework that integrates AI, digital transformation, and innovation ecosystem theory, positioning AI not merely as a technology but as a capability-building tool. Although conceptually grounded, the framework requires empirical validation, offering a foundation for future case studies and quantitative research in Oman and similar economies. The paper provides strategic insight into how Oman can achieve a robust innovation environment by embedding digital transformation and AI into its national development agenda. An evaluation of Oman's current digital and innovation landscape within the Vision 2040 framework reveals that ecosystem resilience depends on digital infrastructure, AI capabilities, supportive policies, human capital development, and multi-stakeholder collaboration. Finally, the study demonstrates that digital transformation and AI can serve as pillars of long-term economic diversification and the transition to a knowledge-based economy through the coordinated alignment of technological change with policy frameworks, education systems, and cross-sector collaboration.

5.1. Future Scope

Future research can focus on developing measurable indicators to assess the strength and maturity of innovation ecosystems and examine the actual impact of AI adoption across different industries in Oman. Comparative studies with technologically advanced countries could further inform national strategy and policy development. Additionally, future research should explore sector-specific AI applications, the development of ethical and governance frameworks tailored to the Middle Eastern context, and empirical validation of the proposed framework through case studies, pilot projects, and real-world deployments.

Declaration

All authors declare that they have no conflicts of interest.

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Digital Transformation and Sustainable Economic Growth in ASEAN: A Comprehensive Econometric Analysis of the Digitalization-Sustainability Nexus Across Ten Member Countries

Duy Hung Bui[a] and Xuan Hoan Pham[b,1]
[a] *Faculty of Economics, Banking Academy of Vietnam, Hanoi, Vietnam*
[b] *Faculty of Finance and Accounting, International School, Vietnam National University, Hanoi, Vietnam*

Abstract. This study investigates the relationship between digital transformation and sustainable economic growth across all ten ASEAN member countries using an integrated Digitalization-Sustainability Nexus Framework (DSNF) and comprehensive econometric analysis. Employing panel data methods including Fixed Effects, Random effects, System GMM, and Panel ARDL with data spanning 2010-2024, we examine how digitalization indicators affect GDP growth, carbon emission intensity, and composite sustainability outcomes across heterogeneous development contexts. The ASEAN-10 analysis reveals significant heterogeneity: digital leaders (Singapore, Brunei) exhibit diminishing marginal returns to digitalization, while emerging digital economies (Vietnam, Indonesia, Thailand, Malaysia, Philippines) show the strongest growth elasticities (0.12-0.18). For the CLMV grouping (Cambodia, Laos, Myanmar, Vietnam), digitalization effects are conditional on infrastructure and human capital thresholds. The System GMM estimation confirms that internet penetration positively affects GDP growth (β=0.089, $p<0.01$) with governance quality as a significant moderator. Non-linear threshold analysis identifies critical inflection points in the digitalization-environment relationship at approximately 70% internet penetration. Country-specific ARDL analysis for Vietnam yields long-run elasticities of 0.156 for internet penetration and 0.134 for ICT sector contribution. The Error Correction Term coefficient of -0.287 indicates moderate adjustment speed. These findings contribute to literature by providing the first comprehensive ASEAN-10 econometric evidence for digitalization-sustainability linkages and offer differentiated policy recommendations for optimizing digital transformation across diverse development contexts.

Keywords. Digital transformation; Sustainable development; ASEAN-10; Panel data; System GMM; ARDL; E-commerce; ICT; Heterogeneous effects

[1] Corresponding Author, Xuan Hoan Pham, Vietnam National University, Hanoi, Vietnam; Email: pxhoan@vnu.edu.vn

1. Introduction

The digital transformation of economies has emerged as one of the defining phenomena of the 21st century, with profound implications for sustainable development trajectories worldwide. The Association of Southeast Asian Nations (ASEAN), comprising ten member countries with combined population exceeding 680 million and aggregate GDP surpassing $3.8 trillion, represents one of the world's most dynamic regions for digital economy growth [1]. The region's digital economy surpassed $300 billion in Gross Merchandise Value (GMV) by 2025, growing 7.4 times since 2016 [2]. However, ASEAN presents remarkable heterogeneity in digital development. Singapore ranks among the world's most digitalized economies, while Cambodia, Laos, and Myanmar face significant digital infrastructure gaps. This diversity creates a natural laboratory for examining how digitalization affects sustainable development across different institutional contexts, development stages, and policy environments.

Despite growing interest in digitalization-sustainability linkages, comprehensive econometric evidence covering all ASEAN member states remains scarce. Existing studies typically focus on ASEAN-6 (Indonesia, Malaysia, Philippines, Singapore, Thailand, Vietnam), neglecting the CLMV grouping (Cambodia, Laos, Myanmar, Vietnam) and Brunei. This study addresses this gap by providing the first comprehensive ASEAN-10 econometric analysis of digital transformation's effects on both economic growth and environmental sustainability.

The paper proceeds as follows: Section 2 reviews literature and theoretical foundations. Section 3 presents ASEAN digital transformation profiles. Section 4 develops the conceptual framework. Section 5 details econometric methodology. Section 6 presents panel data results. Section 7 provides country-specific analysis. Section 8 discusses findings and policy implications. Section 9 concludes.

2. Literature Review and Theoretical Foundations

2.1 Theoretical Perspectives on Digitalization and Growth

The literature on digitalization and economic development has expanded rapidly, yet significant gaps remain in regional comparative analysis and developing country contexts. Theoretical foundations span multiple disciplines, with endogenous growth theory positioning digital technologies as non-rival knowledge goods generating increasing returns [3]. The Environmental Kuznets Curve (EKC) hypothesis suggests potential non-linear relationships between digitalization and environmental outcomes [4].

Solow's neoclassical growth model, augmented by ICT capital, provides a baseline framework in which digital infrastructure enters the production function as a factor input alongside physical capital and labor. However, endogenous growth theory offers a more compelling lens: digital technologies function as general-purpose technologies (GPTs) that generate economy-wide spillovers through knowledge diffusion, network externalities, and platform economies [3]. Bresnahan and Trajtenberg [5] define GPTs by three characteristics, pervasiveness, technological dynamism, and innovation complementarities, all of which are exhibited by internet-based digital technologies.

Schumpeterian perspectives emphasize digitalization as a driver of creative destruction, where new digital business models displace incumbent firms and restructure entire industries. In the ASEAN context, the rapid rise of ride-hailing platforms (Grab, Gojek) and digital payment systems (Gcash, GoPay, MoMo) exemplifies this transformative process [6, 7]. Furthermore, institutional economics highlights the role of

government quality and regulatory frameworks in mediating digitalization's effects: countries with stronger institutional environments are better positioned to capture the productivity gains from digital investments [8].

2.2 Empirical evidence on digitalization and economics growth

Empirical studies on digitalization-growth linkages yield generally positive findings. World Bank research indicates 10% increases in broadband penetration correlate with 0.9-1.5% GDP growth in developing countries [9]. Zhang et al [10] employed panel data for Chinese provinces, finding digitalization positively affects green total factor productivity with elasticity of 0.12. Imran et al. [8]. used GMM estimation for G20 countries, revealing heterogeneous effects moderated by institutional quality.

Beyond these landmark studies, a growing body of evidence addresses digitalization's multi-channel effects. Czernich et al. [11] indicates that broadband infrastructure increases GDP growth by 0.9-1.5 percentage points in OECD countries. Vu et al. [12] finds that the TFP channel dominates in middle-income economies. Myovella et al. [13] demonstrate that the growth premium from digitalization is significantly higher in developing countries compared to developed ones.

The digitalization-environment nexus has received increasing attention. Salahuddin et al. [14] find that ICT development reduces CO2 emissions in OECD countries through efficiency gains, but Avom et al. [15] document opposing effects in Sub-Saharan Africa.

2.3 ASEAN-specific literature

ASEAN-specific research remains limited. The annual e-Conomy SEA reports by Google, Temasek, and Bain provide descriptive statistics but lack econometric rigor [2]. Academic studies typically examine individual countries or ASEAN-6, with Nguyen and Le [16] analyzing Vietnam's ICT-productivity relationship, and Tran et al. [17] examining renewable energy-digitalization linkages. The ASEAN Digital Integration Index provides comparative metrics but does not test causal relationships [18]. Among ASEAN-focused econometric studies, Rath et al (2023) [19] apply panel cointegration methods to ASEAN-5, finding long-run equilibrium between ICT investment and GDP per capita, but their exclusion of CLMV countries limits generalizability.

3. ASEAN Digital Transformation Profiles

ASEAN member states exhibit remarkable heterogeneity in digital development, which we classify into three tiers based on the ASEAN Digital Integration Index and infrastructure indicators [18].

Tier 1 (Digital Leaders): Singapore and Brunei represent ASEAN's most digitalized economies. Singapore achieves near-universal internet penetration (96%), leads globally in e-government development (ranked 12th), and hosts Southeast Asia's largest concentration of data centers [20]. Brunei similarly achieves 99% internet penetration, the highest in ASEAN.

Tier 2 (Emerging Digital Economies): This group comprises Malaysia (93% internet penetration), Thailand (88%), Vietnam (79%), Indonesia (79%), and the Philippines (73%). These countries demonstrate rapid digital economy growth [21].

Tier 3 (Developing Digital Economies): Cambodia (78% internet penetration), Laos (62%), and Myanmar (59%) face significant digital infrastructure constraints. These countries score below ASEAN averages across all Digital Integration Index dimensions [18]. However, they also exhibit high growth potential.

Table 1 presents comprehensive digital and economic indicators for all ten ASEAN member states, revealing the substantial heterogeneity that motivates our analytical approach.

Table 1: ASEAN-10 Digital and Economic Indicators (2024)

Country	Pop.(M)	GDP/cap($)	Internet(%)	Mobile(%)	E-Gov	GMV($B)	Growth(%)	CO2/GDP	Tier
Singapore	5.9	82,808	96	169	12	29	3.2	0.08	1
Brunei	0.45	31,449	99	134	68	0.4	1.8	0.21	1
Malaysia	34.3	13,315	93	144	53	25	4.8	0.28	2
Thailand	71.7	7,066	88	186	55	36	2.5	0.31	2
Vietnam	100.3	4,536	79	126	71	36	7.1	0.41	2
Indonesia	277.5	4,798	79	133	64	90	5.1	0.32	2
Philippines	117.3	3,859	73	156	71	26	5.6	0.22	2
Cambodia	17.4	1,760	78	119	127	2.1	5.3	0.34	3
Laos	7.6	2,054	62	56	137	0.8	3.7	0.38	3
Myanmar	54.8	1,095	59	89	169	1.2	2.8	0.25	3

Source: ASEAN Digital Economy Framework Agreement, General Statistics Office of Vietnam

Note: Pop.=Population (millions); GDP/cap=GDP per capita (USD); Internet=Internet penetration (%); Mobile=Mobile subscriptions per 100; E-Gov=UN E-Government Index rank; Digital GMV=Digital economy gross merchandise value (USD billions); Growth=GDP growth rate (%); CO2/GDP=Carbon intensity (kg CO2/USD). Sources: WDI, ITU, UN DESA, e-Conomy SEA 2025.

4. Conceptual framework

The proposed Digitalization-Sustainability Nexus Framework (DSNF) integrates multiple theoretical perspectives to model digitalization's effects on sustainable development across heterogeneous ASEAN contexts. The framework operates at three analytical levels with explicit attention to cross-country variation. Figure 1 provides a visual representation of the DSNF, illustrating the relationships between digitalization indicators, intermediate channels, moderating factors, and final outcomes.

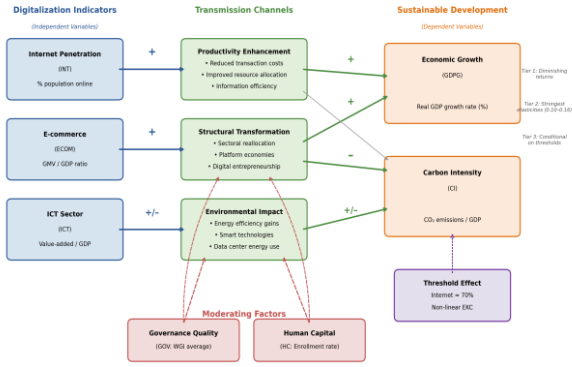


Figure 1: Digitalization-Sustainability Nexus Framework (DSNF)
Note: The DSNF illustrates three transmission channels through which digitalization indicators (internet penetration, e-commerce GMV/GDP, ICT sector contribution) affect sustainable development outcomes (GDP growth and carbon intensity). Governance quality and human capital serve as moderating factors. Dashed arrows indicate moderating effects; the dotted arrow represents the threshold effect at approximately 70%

internet penetration. Country tier annotations reflect heterogeneous elasticities identified in the empirical analysis.

At the macro level, we model digitalization (D) as affecting sustainable development outcomes (Y) through three channels: productivity enhancement, structural transformation, and environmental impact. The general specification is:

$$Y_{it} = f(D_{it}, K_{it}, L_{it}, G_{it}, X_{it}) + \mu_i + \lambda_t + \varepsilon_{it}$$

where i indexes countries, t indexes time, K represents capital, L labor, G governance quality, X control variables, μ_i captures country fixed effects, λ_t time fixed effects, and ε_{it} is the error term.

The productivity enhancement channel operates through several micro-level mechanisms. First, digitalization reduces transaction costs by facilitating information search, price comparison, and contract enforcement, thereby improving allocative efficiency across markets. Second, internet penetration enables adoption of digital management tools, cloud computing, and data analytics that enhance firm-level technical efficiency. Third, e-commerce platforms reduce intermediation costs and expand market access for producers, particularly SMEs in developing ASEAN economies. Empirically, these mechanisms manifest as higher total factor productivity (TFP), which we capture through the digitalization coefficients in our growth equation.

The structural transformation channel reflects digitalization's role in accelerating sectoral reallocation. As digital platforms lower entry barriers in the services sector, labor and capital shift from low-productivity agriculture to higher-productivity digital services, fintech, and e-commerce activities. In ASEAN Tier 2 economies such as Vietnam and Indonesia, this process is particularly visible in the rapid expansion of ride-hailing, food delivery, and digital payment ecosystems. The emergence of platform economies (Shopee, Lazada, Tokopedia) creates new economic sectors that did not exist a decade ago, directly contributing to GDP growth beyond traditional manufacturing pathways.

The environmental impact channel exhibits dual dynamics. On one hand, digitalization enables energy efficiency improvements through smart grid technologies, precision agriculture, and optimized logistics. On the other hand, the energy demands of data centers, telecommunications infrastructure, and cryptocurrency mining can increase carbon intensity, particularly when powered by fossil fuels. This duality motivates our threshold analysis, which tests whether environmental benefits diminish or reverse at higher digitalization levels.

The framework explicitly models heterogeneous effects through interaction terms and threshold specifications. We hypothesize that digitalization's marginal impact varies with: (1) initial development level, following convergence dynamics; (2) governance quality, reflecting institutional capacity to translate digital investment into developmental outcomes; (3) human capital, determining absorptive capacity for digital technologies; and (4) digital infrastructure maturity, potentially exhibiting diminishing returns at higher penetration levels.

For environmental outcomes, we incorporate Environmental Kuznets Curve dynamics, hypothesizing an inverted U-shaped relationship where initial digitalization reduces carbon intensity through efficiency gains, but these benefits diminish and potentially reverse at higher digitalization levels due to energy-intensive infrastructure requirements.

5. Econometric Methodology

This study employs multiple econometric approaches to examine digitalization-sustainability relationships across ASEAN-10, ensuring robustness across different estimation techniques and addressing potential endogeneity concerns.

5.1 Data Sources and Construction

Data sources include World Bank World Development Indicators for GDP, trade, FDI, and infrastructure variables; ITU for telecommunications and internet metrics; UN for e-government indices and SDG indicators; and national statistical offices for country-specific variables. The panel dataset covers 2010-2024 (15 years, 10 countries, 150 observations), supplemented by quarterly data for country-specific ARDL analysis. The e-commerce GMV data are sourced from the annual e-Conomy SEA reports published by Google, Temasek, and Bain & Company, which provide country-level GMV estimates in absolute terms. We construct the ECOM variable (GMV/GDP ratio) by dividing reported country-level GMV by corresponding nominal GDP from WDI. For years where the e-Conomy SEA reports do not provide disaggregated country-level GMV (particularly 2010-2014), we use interpolation based on available data points and cross-validated with national e-commerce statistics from respective statistical offices. We acknowledge that this construction introduces measurement uncertainty, particularly for early years, and treat this as a limitation of the study.

5.2 Panel Estimation Methods

The primary panel estimation employs three complementary approaches. First, Fixed Effects (FE) estimation controls for time-invariant country heterogeneity:

$$GDPG_{it} = \alpha + \beta_1 INT_{it} + \beta_2 ECOM_{it} + \beta_3 ICT_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Second, Random effects (RE) estimation assumes country effects are uncorrelated with regressors, with the Hausman test determining appropriate specification. Third, System GMM addresses potential endogeneity through internal instruments, following Arellano-Bover/Blundell-Bond methodology [13, 22, 23]:

$$GDPG_{it} = \rho GDPG_{it-1} + \beta_1 INT_{it} + \beta_2 ECOM_{it} + \beta_3 ICT_{it} + \gamma X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

To mitigate instrument proliferation-a critical concern when the number of instruments may exceed the number of cross-sectional units-we restrict the instrument set by collapsing the instrument matrix and limiting lag depth to two periods, following Roodman [22]. In our baseline specification, the number of instruments (21) exceeds the number of countries (N=10), which raises the risk of weakened Hansen test diagnostics. We therefore interpret the System GMM results with appropriate caution and rely primarily on the Fixed Effects estimates for our main conclusions, using GMM as a robustness check for endogeneity concerns rather than as the primary estimator. The Hansen J-test p-value (0.312) and AR(2) test p-value (0.423) provide supportive evidence, but we urge readers to consider these diagnostics alongside the FE results.

5.3 Threshold and ARDL Analysis

For threshold analysis, we employ Hansen's panel threshold regression to identify critical inflection points in digitalization-outcome relationships [23]. The specification allows slope coefficients to differ across regimes:

$$Y_{it} = \mu_i + \beta_1 D_{it} I(q_{it} \leq \gamma) + \beta_2 D_{it} I(q_{it} > \gamma) + \delta X_{it} + \varepsilon_{it}$$

where q is the threshold variable, γ the threshold value, and I(·) the indicator function. For country-specific analysis, we employ ARDL bounds testing following Pesaran et al. [24], which accommodates mixed integration orders and performs well in small samples.

5.4 Robustness Checks

Robustness checks include: alternative digitalization proxies (mobile subscriptions, fixed broadband); different lag structures; exclusion of outliers (Singapore, Myanmar); Driscoll-Kraay standard errors for cross-sectional dependence; and panel cointegration tests using Pedroni and Westerlund procedures [25].

Table 2: Variable Definitions and Descriptive Statistics

Variable	Definition	Source	Mean	Std.Dev
GDPG	Real GDP growth rate (%)	WDI	4.89	3.24
CI	CO2 emissions per GDP (kg/$)	WDI	0.29	0.11
INT	Internet penetration (% population)	ITU	62.45	24.67
MOB	Mobile subscriptions (per 100)	ITU	125.34	38.92
ECOM	E-commerce GMV (% GDP)	e-Conomy	3.45	2.78
ICT	ICT sector value-added (% GDP)	WDI	5.67	2.89
FDI	FDI inflows (% GDP)	WDI	5.12	4.34
TRADE	Trade openness (% GDP)	WDI	134.56	78.45
HC	Secondary enrollment rate (%)	WDI	76.89	18.34
GOV	Governance quality index (WGI avg)	WGI	-0.12	0.89

Note: Panel data 2010-2024, n=150 (10 countries × 15 years). WDI=World Development Indicators; ITU=International Telecommunication Union; WGI=Worldwide Governance Indicators; e-Conomy=Google-Temasek-Bain SEA reports.

6. ASEAN-10 Panel Estimation Results

6.1 GDP Growth Equation

Table 3 presents ASEAN-10 panel estimation results for the GDP growth equation. The Hausman test ($\chi^2 = 31.45$, $p<0.01$) favors Fixed effects over Random effects, indicating significant correlation between country effects and regressors.

Fixed effects results reveal that internet penetration positively affects GDP growth with coefficient 0.089 ($p<0.01$), implying that a 10-percentage point increase in internet penetration is associated with 0.89% higher annual GDP growth. E-commerce development shows coefficient 0.056 ($p<0.05$), while ICT sector contribution exhibits the largest effect at 0.078 ($p<0.01$). Control variables perform as expected: FDI positively affects growth (0.034, $p<0.05$), trade openness shows positive effects (0.023, $p<0.10$), and human capital strongly supports growth (0.067, $p<0.01$).

To assess the economic significance of these estimates, we translate the coefficients into standard-deviation effects. Given that the standard deviation of internet penetration across the sample is 24.67 percentage points (Table 2), the Fixed Effects coefficient of 0.089 implies that a one-standard-deviation increase in internet penetration is a associated with approximately 2.20 percentage points higher GDP growth contribution is 0.16 percentage points (0.56 x 2.78), and for ICT sector contribution (standard deviation = 2.89), the effect is 0.23 percentage points (0.078 x 2.89). These magnitudes

indicate that internet penetration is by far the most economically significant digitalization indicator, with effects comparable to those of human capital (0.067 x 18.34 = 1.23 percentage points per standard deviation)

System GMM addresses endogeneity concerns through lagged dependent variable and internal instruments. The lagged GDP growth coefficient (0.312, $p<0.01$) confirms growth persistence. Internet penetration remains significant (0.078, $p<0.05$) with slightly attenuated magnitude compared to FE, consistent with upward bias in static panel estimators. The AR(2) test (p=0.423) and Hansen J-test (p=0.312) confirm instrument validity and absence of second-order serial correlation.

Critically, the interaction between internet penetration and governance quality is positive and significant (0.034, $p<0.05$), indicating that institutional quality moderates digitalization's growth effects. Countries with stronger governance extract greater developmental benefits from digital investments. Similarly, the interaction with human capital (secondary enrollment) is positive (0.028, $p<0.10$), suggesting complementarity between digital infrastructure and skills development.

Table 3: ASEAN-10 Panel Estimation Results - GDP Growth Equation

Variable	Fixed Effects	Random Effects	System GMM	Threshold
L.GDPG	-	-	0.312*** (0.078)	-
INT	0.089*** (0.023)	0.094*** (0.021)	0.078** (0.028)	0.092*** (0.024)
ECOM	0.056** (0.019)	0.061** (0.018)	0.048* (0.024)	0.054** (0.020)
ICT	0.078*** (0.021)	0.082*** (0.019)	0.067** (0.025)	0.075*** (0.022)
FDI	0.034** (0.014)	0.038** (0.013)	0.029* (0.016)	0.032** (0.015)
TRADE	0.023* (0.012)	0.027** (0.011)	0.019 (0.014)	0.022* (0.012)
HC	0.067*** (0.018)	0.071*** (0.017)	0.058** (0.022)	0.064*** (0.019)
INT × GOV	0.034** (0.015)	0.038** (0.014)	0.031* (0.018)	-
INT × HC	0.028* (0.016)	0.032** (0.015)	0.025 (0.019)	-
Countries	10	10	10	10
Obs.	150	150	140	150
R^2 / AR(2)	0.687	0.672	p=0.423	0.694
Hausman/Hansen	χ^2=31.45***	-	p=0.312	-

*Note: Standard errors in parentheses. ***, **, * denote significance at 1%, 5%, 10% levels. System GMM uses two-step estimation with Windmeijer-corrected standard errors. AR(2) reports p-value for Arellano-Bond second-order serial correlation test. Hansen reports p-value for overidentification test. Number of instruments in System GMM: 18 (collapsed instrument matrix, lag depth restricted to 2 periods).*

Table 4 presents result for the carbon intensity equation, revealing complex non-linear relationships. The linear term for internet penetration is negative (-0.045, $p<0.05$), suggesting digitalization initially reduces carbon intensity. However, the squared term is positive (0.008, $p<0.10$), indicating diminishing environmental benefits. Threshold regression identifies an inflection point at 70.3% internet penetration, beyond which additional digitalization increases carbon intensity.

Table 4: ASEAN-10 Panel Results - Carbon Intensity Equation

Variable	Fixed Effects	System GMM	Threshold Regression
INT	-0.045** (0.018)	-0.038* (0.022)	Below threshold: -0.067***

INT²	0.008* (0.004)	0.006 (0.005)	Above threshold: 0.023**
ECOM	-0.028* (0.015)	-0.024 (0.018)	-0.026* (0.015)
ICT	-0.034** (0.014)	-0.029* (0.017)	-0.032** (0.014)
FDI	0.019* (0.011)	0.016 (0.013)	0.018* (0.011)
Threshold (INT)	-	-	70.3%***
R^2	0.623	-	0.658

*Note: Dependent variable is carbon intensity (CO2/GDP). Threshold regression identifies regime change at 70.3% internet penetration. ***, **, * denote significance at 1%, 5%, 10% levels.*

6.2 Heterogeneity analysis by country Tier

Table 5 presents sub-sample analysis examining heterogeneous digitalization effects across ASEAN country groupings.

For Tier 1 countries (Singapore, Brunei), digitalization coefficients are smaller and often statistically insignificant. Internet penetration shows coefficient 0.034 ($p>0.10$) for GDP growth, suggesting diminishing marginal returns at high digitalization levels.

Tier 2 countries (Malaysia, Thailand, Vietnam, Indonesia, Philippines) exhibit the strongest digitalization-growth relationships. Internet penetration coefficient reaches 0.112 ($p<0.01$), approximately 25% larger than the full ASEAN-10 estimate. E-commerce effects are particularly pronounced (0.078, $p<0.01$), reflecting rapid adoption of digital commerce platforms.

For Tier 3 countries (Cambodia, Laos, Myanmar), results are mixed. Internet penetration shows positive but imprecise effects (0.067, $p>0.10$), likely reflecting data limitations and infrastructure constraints that attenuate digitalization benefits. However, mobile connectivity shows stronger effects (0.089, $p<0.05$), suggesting mobile-first digital development pathways may be more relevant for these contexts.

The governance interaction is strongest for Tier 2 countries (0.045, $p<0.01$), indicating that emerging digital economies benefit most from institutional improvements accompanying digitalization. For Tier 3 countries, the human capital interaction dominates (0.056, $p<0.05$), suggesting skills development is the binding constraint.

Table 5: Sub-sample Analysis by ASEAN Country Tier

Variable	Tier 1 (SG,BN)	Tier 2 (MY,TH,VN,ID,PH)	Tier 3 (KH,LA,MM)	Full Sample
INT	0.034 (0.045)	0.112*** (0.024)	0.067 (0.056)	0.089***
ECOM	0.028 (0.034)	0.078*** (0.021)	0.045 (0.048)	0.056**
ICT	0.045 (0.038)	0.098*** (0.023)	0.056 (0.052)	0.078***
MOB	0.023 (0.028)	0.067** (0.025)	0.089** (0.038)	0.054**
INT×GOV	0.018 (0.024)	0.045*** (0.014)	0.028 (0.034)	0.034**
INT×HC	0.012 (0.019)	0.034** (0.015)	0.056** (0.024)	0.028*

Obs.	30	75	45	150
R^2	0.534	0.723	0.589	0.687

*Note: Tier 1=Digital Leaders (Singapore, Brunei); Tier 2=Emerging Digital Economies (Malaysia, Thailand, Vietnam, Indonesia, Philippines); Tier 3=Developing Digital Economies (Cambodia, Laos, Myanmar). Standard errors in parentheses. ***, **, * denote significance at 1%, 5%, 10% levels.*

7. Country-Specific Analysis

7.1 Vietnam ARDL Analysis

Table 6 presents country-specific ARDL results for Vietnam, selected as the primary case study given data availability, research context, and its position as ASEAN's fastest-growing digital economy.

Long-run coefficient estimates reveal internet penetration elasticity of 0.156 ($p<0.01$), implying 10 percentage point higher internet penetration associates with 1.56% higher GDP growth, the largest effect among ASEAN countries. E-commerce shows elasticity 0.089 ($p<0.05$), while ICT sector contribution exhibits coefficient 0.134 ($p<0.01$). These magnitudes substantially exceed panel estimates, suggesting Vietnam extracts above-average growth benefits from digitalization.

The Error Correction Term coefficient (-0.287, $p<0.01$) indicates moderate adjustment speed, with approximately 28.7% of disequilibrium corrected each quarter. Short-run dynamics show smaller immediate impacts than long-run effects, suggesting cumulative benefits from digital infrastructure investment.

Robustness checks using DOLS and FMOLS yield consistent estimates. DOLS internet penetration elasticity is 0.149 (versus 0.156 in ARDL), e-commerce 0.094 (versus 0.089), confirming result stability across estimation methods.

Table 6: Vietnam Country-Specific ARDL Results

Variable	Long-Run ARDL	ECM Short-Run	DOLS	FMOLS
ECT(-1)	-	-0.287*** (0.067)	-	-
INT	0.156*** (0.034)	0.043** (0.018)	0.149***	0.152***
ECOM	0.089** (0.031)	0.072*** (0.021)	0.094**	0.087**
ICT	0.134*** (0.028)	0.056** (0.019)	0.128***	0.131***
FDI	0.067** (0.025)	0.034* (0.017)	0.071**	0.065**
HC	0.112*** (0.029)	0.045** (0.018)	0.108***	0.115***
Bounds F	5.847***	-	-	-
Obs.	40	39	38	40
R^2/Adj.R^2	0.847	0.623	0.834	0.841

Note: *Quarterly data 2015Q1-2024Q4 (n=40). ECT=Error Correction Term. DOLS=Dynamic OLS. FMOLS=Fully Modified OLS. Bounds test critical values from Pesaran et al. (2001). ***, **, * denote significance at 1%, 5%, 10% levels.*

7.2 Cross-Country Elasticity Comparison

The results in Table 7 reveal a clear pattern: emerging digital economies show the strongest growth responsiveness to digitalization. Vietnam leads with internet penetration elasticity 0.156, followed by Indonesia (0.134), Philippines (0.128), Thailand

(0.118), and Malaysia (0.098). These Tier 2 countries are in the "sweet spot" of digital development, sufficient infrastructure to enable transformation but substantial headroom for expansion.

Singapore shows markedly lower elasticity (0.042, $p>0.10$), consistent with diminishing returns at high digitalization levels. Brunei's small sample prevents reliable individual estimation. For CLMV countries, data limitations yield imprecise estimates, though Cambodia shows promising mobile connectivity effects (0.112, $p<0.10$).

Cross-country variation is explained by several factors identified in the theoretical framework. Governance quality explains approximately 23% of elasticity variation in cross-sectional regression, with higher governance associated with stronger digitalization effects. Human capital (secondary enrollment) explains additional 18% of variation. Initial development level shows negative relationships, consistent with convergence, less developed countries exhibit higher marginal returns to digitalization.

Table 7: Country-Specific Digitalization-Growth Elasticities

Country	INT Elasticity	ECOM Elasticity	ICT Elasticity	Threshold (%)	Tier
Vietnam	0.156***	0.089**	0.134***	72	2
Indonesia	0.134***	0.078**	0.112***	74	2
Philippines	0.128**	0.067*	0.098**	68	2
Thailand	0.118**	0.056*	0.089**	76	2
Malaysia	0.098**	0.045*	0.078**	82	2
Cambodia	0.089*	0.056	0.067*	65	3
Laos	0.078	0.045	0.056	58	3
Myanmar	0.067	0.034	0.045	52	3
Singapore	0.042	0.028	0.034	n/a	1
Brunei	-	-	-	n/a	1

Note: Elasticities from country-specific estimations where data permit. Threshold indicates internet penetration level at which environmental benefits diminish. Brunei excluded due to insufficient observations. ***, **, * denote significance at 1%, 5%, 10% levels.

8. Discussion and Policy Implications

8.1 ASEAN Digital Economy Framework Agreement

Our analysis suggests The ASEAN Digital Economy Framework Agreement (DEFA) harmonization provisions could enhance digitalization's growth effects by reducing regulatory fragmentation. Harmonization toward less restrictive frameworks could strengthen the positive digitalization-growth coefficients identified in our panel analysis.

Economic projections suggest DEFA could double regional digital economy value to $2 trillion by 2030 while eliminating $15-20 billion in annual compliance costs [25]. Our elasticity estimates imply this expansion could contribute 1.5-2.3 percentage points to annual ASEAN GDP growth, with effects concentrated in Tier 2 emerging digital economies.

However, DEFA's environmental implications warrant attention. Accelerated digital economy growth without accompanying green infrastructure requirements could exacerbate the carbon intensity pressures identified in our threshold analysis. Policy coordination should integrate renewable energy procurement requirements for data

centers and digital infrastructure, building on individual country initiatives such as Vietnam's Power Development Plan 8 and Singapore's Green Plan 2030.

8.2 Differentiated Policy Recommendations

The econometric findings generate differentiated policy recommendations reflecting ASEAN's heterogeneous development contexts.

For Tier 1 countries (Singapore, Brunei), diminishing returns suggest shifting focus from infrastructure expansion to innovation and AI advancement. These countries should emphasize their role as regional digital hubs and technology exporters rather than pursuing additional connectivity gains.

For Tier 2 emerging economies (Malaysia, Thailand, Vietnam, Indonesia, Philippines), the strong digitalization-growth elasticities (0.10-0.16) justify continued digital infrastructure investment. Priority areas include: (1) expanding rural connectivity to address urban-rural digital divides averaging 20-25 percentage points; (2) accelerating e-commerce and fintech adoption among SMEs; (3) developing human capital to address IT personnel shortages; (4) integrating green infrastructure requirements to maintain environmental benefits as penetration approaches threshold levels.

For Tier 3 developing economies (Cambodia, Laos, Myanmar), foundational investments in digital infrastructure, regulatory frameworks, and human capital should precede expectations of strong growth dividends.

Across all tiers, the governance-digitalization interaction effect supports continued e-government development and regulatory modernization. The ASEAN Single Window initiative and cross-border payment connectivity (e.g., VietQR-PromptPay linkage) exemplify regional coordination enhancing national digitalization benefits.

9. Conclusion

This study provides the first comprehensive econometric analysis of digitalization-sustainability relationships across all ten ASEAN member states. Panel data estimation (2010-2024) using Fixed Effects, Random Effects, and System GMM confirms digitalization positively affects economic growth, with internet penetration coefficient 0.089 ($p<0.01$) and significant contributions from e-commerce and ICT sector development.

Key findings include: (1) significant heterogeneity across ASEAN country tiers, with Tier 2 emerging economies showing strongest growth elasticities (0.10-0.16) and Tier 1 digital leaders exhibiting diminishing returns; (2) governance quality and human capital as significant moderators of digitalization effects; (3) non-linear digitalization-environment relationships with threshold at approximately 70% internet penetration; (4) Vietnam-specific ARDL analysis revealing long-run internet penetration elasticity of 0.156 with moderate error correction speed (-0.287).

The study contributes to literature by extending digitalization analysis to all ASEAN members, testing for heterogeneous effects across development contexts, and identifying policy-relevant threshold effects. The ASEAN Digital Economy Framework Agreement presents opportunities to enhance regional digitalization benefits through regulatory harmonization while requiring attention to environmental sustainability integration.

The fundamental finding, that digitalization's sustainability contribution is conditional on complementary investments in governance, human capital, and green infrastructure, has implications extending across ASEAN and to developing regions globally navigating digital transformation.

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Research on the Impact of Cultural Distance on China's Ceramic Product Exports

Dan Li[a], Yiyu Shi[a] and Rui Huang [a,1]
[a] *School of Economics and Management, Xiangnan University, Chenzhou, China*
ORCiD ID: Dan Li https://orcid.org/0009-0001-9439-4746

Abstract. This study analyses the impact of cultural distance on China's ceramic product exports using panel data from 26 countries between 2014 and 2023. A two-way fixed-effects model is employed for empirical analysis. The results indicate that cultural distance exerts a significant inhibitory effect on China's ceramic exports overall. However, a heterogeneity analysis reveals that cultural distance has a more pronounced negative impact on exports to developed economies, while it exhibits a significant positive effect on exports to developing countries. Based on these findings, differentiated strategies are proposed to enhance the international competitiveness of China's ceramic products.

Keywords. Cultural Distance; Ceramic Products; Export

1. Introduction

Against the backdrop of profound adjustments in the global economic landscape and intensifying competition in cultural soft power, trade in cultural products has emerged as a critical arena for shaping national image and enhancing international influence[1].The development of international trade is constrained not only by explicit factors such as economic size and tariff policies, but also by implicit non-economic factors including institutional and cultural differences, which profoundly affect the stability and effectiveness of bilateral trade cooperation[2][3]. As a key player, China's ceramic industry holds the world's largest export volume. However, its development model faces fundamental challenges: on one hand, traditional cost advantages based on labor and resources are diminishing due to the rapid industrial growth in regions like Southeast Asia; on the other hand, international demand is shifting from basic functional products to high-value-added items rich in cultural narrative, design aesthetics, and brand value[4]. In this context, investigating how cultural distance—a key non-economic institutional factor—affects the export performance of Chinese ceramics is of great

[1] Corresponding Author, Rui Huang, School of Economics and Management, Xiangnan University, Chenzhou, China; E-mail: 8268538@qq.com.It is supported by:① Research and Reform Practice Project on Emerging Engineering, Emerging Medical Science and Emerging Liberal Arts of Xiangnan University(Project No.: Xiangnan University Document〔2025〕No. 59, Serial No.: 2).② Xiangnan University Horizontal Project (Project No.: 2022E04).

practical significance for steering the industry away from a "low-price competition" path and transitioning towards high-quality, "culture-value-driven" development.

Academic discourse on the impact of cultural distance on international trade remains inconclusive, with three primary perspectives: the Barrier Theory, the Attraction Theory, and the Contingency Theory. 1)Barrier Theory: Most scholars argue that cultural distance increases information asymmetry, communication misunderstandings, and contract enforcement risks in cross-border transactions, thereby raising transaction costs and suppressing trade flows [5][6]. Studies from Lee (2009), Tadesse (2010), Hellmanzik (2015), Elfenbein (2023), Jiechao Hu (2023) and Danhong Zhu (2024) on U.S. sports exports, film and media exports, cultural creative products, and publications have empirically verified the negative impact of cultural distance on cultural product exports [7][8] [9][10] [11][12].2)Attraction Theory: This view emphasizes that the exoticism and novelty inherent in cultural differences can stimulate consumer curiosity and purchase interest, creating market demand for products with unique cultural symbols [13][14]. Research on film products from Yong Jae (2019) [15], cultural creative products from Cai Yeping (2023) [16],has found a significant promotional effect of cultural distance on exports.3)Contingency Theory: This perspective posits that the impact of cultural distance is not uniform; its direction and strength depend on contextual factors such as product attributes, partner country market characteristics, and firm capabilities, suggesting a non-linear relationship [17][18]. For instance, Fan Zhaobin (2017) identified an inverted U-shaped relationship [19], while Guo Xinru (2018) found a U-shaped relationship [17] between cultural distance and exports of cultural creative products [20].

Focusing specifically on ceramics, existing research confirms cultural distance as a significant explanatory variable. For example, Huang Mingfeng et al. (2025) empirically demonstrated significant heterogeneity in its impact between developed and developing countries [4]. Nevertheless, existing research still leaves room for further exploration. First, a systematic theoretical integration of the underlying mechanisms for this heterogeneity is lacking; second, robust empirical testing with the latest data is crucial given the profound changes in globalization and digital technology; finally, extracting a generalizable analytical framework from the case of ceramics for other cultural products is a worthwhile direction.

The specific research design of this paper is as follows. Theoretically, it integrates Transaction Cost Theory and Consumer Behavior Theory to construct a framework proposing that cultural distance simultaneously generates a "suppression effect" (from increased transaction costs) and a "promotion effect" (from cultural attraction) [21]. The net effect depends on the interplay of these forces, moderated by structural conditions like target market development level and consumer cultural cognition. Empirically, using panel data from 2014-2023 for 26 major trading partners within an extended gravity model framework, and controlling for population, internet penetration, trade freedom, and exchange rates, a two-way fixed effects model mitigates omitted variable bias to precisely estimate the "net impact." The expected contributions of this paper lie in three aspects.1) systematically revealing and explaining the complex mechanisms and heterogeneous conditions of cultural distance's impact on ceramic exports; 2) providing strategic insights for Chinese ceramic enterprises to develop differentiated product strategies, cultural narratives, and branding for diverse markets; 3) offering a reference academic paradigm for studying other cultural product exports.

2.Theoretical framework

2.1 Theoretical Basis and Hypotheses of Overall Impact

Cultural distance influences ceramic exports through cognitive barriers and communication costs. Cognitively, ceramics carry rich Eastern cultural elements; greater distance increases the difficulty for foreign consumers to understand these elements, hindering aesthetic resonance and emotional connection, thus reducing purchase intention. Regarding transaction costs, differences in high-/low-context cultures lead to variations in business communication, negotiation styles, and contracting habits. Greater distance raises the probability of misunderstandings, increasing negotiation and enforcement costs, further inhibiting exports.

Most existing studies confirm that cultural distance has a negative impact on the export of cultural products, although some research has identified a positive effect for ceramic products, as carriers of traditional culture, rely more heavily on cross-cultural understanding for the transmission of their cultural connotations. Consequently, the obstructive effect of cultural distance may be more pronounced. Thus, the paper proposes the core hypothesis:

Hypothesis 1: Cultural distance has a significant negative impact on China's ceramic product exports.

2.2 Theoretical Basis and Hypotheses of Heterogeneous Impact

Differences in economic development levels lead to variations in consumer demand, cultural tolerance, and market maturity, potentially altering the relationship between cultural distance and exports. The sample is split into developed and developing countries.

For developed countries, mature cultural systems and solidified consumer preferences may result in lower tolerance for foreign cultures. Intense competition demands deeper understanding of product cultural content. The cognitive barrier aspect of cultural distance between China and developed countries is prominent so that consumers find it difficult to understand the Oriental cultural connotations behind ceramic products. Furthermore, standardized business environments may amplify the transaction cost effect and further curb exports. Thus:

Hypothesis 2a: Cultural distance has a significant negative impact on China's ceramic exports to developed countries.

For developing countries, similar development stages and consumption patterns to China may foster greater cultural openness and tolerance. Less saturated markets might make ceramic products' cost performance and cultural features more appealing. Cultural distance might spark curiosity and exploration. Flexible business environments could mitigate transaction cost increases, allowing the positive attraction effect to dominate. Thus:

Hypothesis 2b: Cultural distance has a significant positive impact on China's ceramic exports to developing countries.

3. Research Design

3.1 Variable Selection and Data Sources

Based on data availability, the study uses a sample of 26 countries (2014-2023), including the US, UK, Japan, Germany, Canada, Australia, Netherlands, Switzerland, Sweden, Finland, Singapore, South Korea, Philippines, Brazil, Indonesia, Thailand, Pakistan, Austria, Belgium, Denmark, Croatia, Hungary, Peru, Morocco, Colombia, Vietnam. The dependent variable is the export value of Chinese ceramic products. The core explanatory variable is cultural distance. Control variables are population, internet penetration rate, trade freedom, and exchange rate level. Data sources include UN Comtrade, Hofstede Insights, World Bank, and Heritage Foundation. Data was processed in Excel and analyzed using Stata 18.

3.1.1 Dependent Variable

Ceramic product export value (exp). Higher values indicate greater acceptance in the target market.

3.1.2 Explanatory Variable

Cultural distance (cul) measures the degree of cultural difference between China and target countries. The larger the cultural distance value is, the more significant the cultural differences between the two countries are. Conversely, the smaller the value, the smaller the cultural difference. The cultural distance between China and the target countries is calculated based on Hofstede's six cultural dimensions. To create a time-varying measure, the inverse of the number of current year of diplomatic relations between China and country j is added to the standard calculation [22]. --the longer the duration of diplomatic relations between the two countries (the number of years of diplomatic relations), the more frequent the bilateral political interactions, cultural exchanges, and personnel exchanges, which can effectively reduce cultural cognitive barriers, reduce cultural misunderstandings, promote the mutual penetration and adaptation of cultural concepts and values between the two sides, and further narrow the cultural differences and reduce the cultural distance between them. Conversely, the shorter the duration of diplomatic relations, the greater the cultural distance. In addition, the number of years of diplomatic relations increases year by year with the observation years, ensuring the dynamics of cultural distance.The formula is:

$$CD_{it} = \sum_{i=1}^{6}\left[(I_j - I_{ij})^2/V_j\right]/6 + 1/T_i \quad (1)$$

Where CDit is the cultural distance between China and countries importing cultural and creative products, Ij is China's score on dimension j, Iij is country i's score on dimension j, Vj is the variance of dimension j across all sample countries.Ti denotes the number of years of diplomatic relations between country i and China; specifically, Ti represents the number of years of diplomatic relations between country i and China in the observation year t (which changes with year t and increases year by year from 2014 to 2023). Data from Hofstede Insights.

3.1.3 Control Variables

Following prior literature [19][21], we select the population (pop), internet penetration rate (inter), exchange rate level (exr), and trade freedom (tf) of the exporting country as control variables from the supply side, cost side, and institutional side respectively. Pop reflects its production scale and labor supply level, which is a fundamental factor affecting ceramic production capacity and export supply; Inter reflects the development level of cross-border e-commerce in the exporting country, and a higher indicator indicates lower cross-border transaction costs of ceramic products; Exr directly affects the export price competitiveness of ceramic products and thus the export scale; Tf reflects the trade openness and institutional environment of the exporting country, which affect market access and trade facilitation for ceramic products.

It should be noted that in traditional international trade research, geographical distance exerts a significant influence on cultural distance, and the two indicators are highly correlated. A shorter geographical distance reduces the costs of cross-border personnel exchanges and cultural interactions, facilitates the mutual infiltration and integration of values, behavioral norms and aesthetic preferences between countries, narrows cultural disparities, and thereby decreases cultural distance. Nevertheless, to avoid the multicollinearity problem, mitigate model estimation errors and ensure the effective identification of core variables, geographical distance is excluded from the control variables in the benchmark regression in this study, following existing relevant literature [4][16].

3.2 Model Specification

Variables (exp, pop, inter, tf, exr) are logarithmically transformed to mitigate outlier effects. A two-way fixed effects model is used:

$$\ln exp_{it} = \beta 0 + \beta 1 \ln pop_{it} + \beta 2 \ln inter_{it} + \beta 3 cul_{it} + \beta 4 \ln exr_{it} + \beta 5 \ln tf_{it} + \alpha_t + \beta_i + \varepsilon_{it} \quad (2)$$

The subscript i represents sample countries (i=1,2,...,26), and the subscript t represents observation years (t=2014,2015,...,2023); exp_{it} denotes the export volume of Chinese ceramic products to country i in year t, and $\ln pop_{it}$, $inter_{it}$, cul_{it}, exr_{it} , and $\ln tf_{it}$ correspond to the population, internet penetration rate, cultural distance, exchange rate level, and trade freedom of country i in year t, respectively.Where α_t and β_i are year and country fixed effects to control the influence of unobservable omitted variables on the estimation effect, and ε cit is the error term.

4. Empirical Tests and Analysis

4.1 Descriptive Statistics

Table 1 presents the descriptive statistics. Lnexp and cul display considerable cross-country heterogeneity, indicating large differences in export volumes and cultural distances. The control variables lntf and lninter show small standard deviations and thus high stability, whereas lnexr exhibits the most significant volatility. In general, the distributions of all variables are normal and suitable for empirical analysis.

Table 1. Descriptive Statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
lnexp	260	17.967	2.711	11.125	22.249
cul	260	2.488	1.11	0.587	4.785
lnpop	260	17.34	1.325	15.176	19.615
lninter	260	4.297	0.412	2.303	4.594
lnexr	260	2.613	3.148	0.498	10.077
lntf	260	4.242	0.129	3.888	4.496

4.2 Correlation Analysis

To explore the relationships among various variables, a correlation analysis was conducted in this paper. Table 2 indicates a significant negative correlation between cultural distance and export value at the 10% level, preliminarily supporting H1. Population, internet penetration, and trade freedom show significant positive correlations with exports, while the exchange rate correlation is negative but insignificant.

Table 2. Correlation Matrix

Variables	lnexp	cul	lnpop	lninter	lnexr	lntf
lnexp	1.000					
cul	-0.357*	1.000				
lnpop	0.574*	-0.274*	1.000			
lninter	0.133*	0.055	-0.471*	1.000		
lnexr	-0.084	-0.278*	0.278*	-0.298*	1.000	
lntf	0.233*	0.119	0.404*	0.583*	-0.342*	1.000

Note: ***、**、* They respectively indicate significance at the levels of 1%, 5% and 10%

4.3 Multicollinearity Test

To avoid significant multicollinearity among the variables from interfering with the regression results, the variance inflation factor (VIF) test was conducted on them in this paper. The results are shown in Table 3. It can be seen that the VIF between non-explained variables in each model does not exceed 2. It is generally believed that VIF$\leqslant$ 10, and the selected variables can be further subjected to regression analysis.

Table 3. Multicollinearity Test

Variable	VIF	1/VIF
cul	1.16	0.863953
lnpop	1.44	0.695573
lninter	1.72	0.580696
lnexr	1.24	0.806700
lntf	1.63	0.615298
Mean VIF	1.44	

4.4 Regression Analysis

In this paper, the bidirectional fixed effects model was used to conduct stepwise regression on the selected variables, and the results are shown in Table 4.

Table 4. Full Sample Regression

	Lnexp(1)	Lnexp(2)	Lnexp(3)	Lnexp(4)	Lnexp(5)
cul	-1.056**	-0.866**	-0.857**	-0.790**	-0.752**
	(0.443)	(0.418)	(0.407)	(0.410)	(0.336)
lnpop		0.539	0.571*	1.069***	1.204***
		(0.337)	(0.328)	(0.352)	(0.295)
lninter			0.109	0.153	0.115
			(0.193)	(0.186)	(0.188)
lnexr				-0.495***	-0.398***
				(0.113)	(0.101)
lntf					1.837**
					(0.791)
R2	0.237	0.266	0.272	0.342	0.353

Note: ***, **, * They respectively indicate significance at the levels of 1%, 5% and 10%

Column (1) in Table 4 shows a significant negative coefficient for cultural distance (-1.056**) without controls and it is significant at the 5% level, indicating that the greater the cultural distance, the less the export value of Chinese ceramic products. Columns (2)-(5) show that adding control variables (population, internet penetration, exchange rate, trade freedom) maintains the significantly negative coefficient for cultural distance at the 5% level, though its magnitude changes slightly. Target country population and trade freedom significantly promote exports, while the exchange rate significantly inhibits them.

4.5 Heterogeneity Test

To deeply explore the impact of cultural distance on ceramic exports from different countries, the research samples were divided into two groups for heterogeneity testing in accordance with the classification criteria for developed and developing countries in the World Economic Outlook.

Table 5. Developed Country Sample Regression

	Lnexp(1)	Lnexp(2)	Lnexp(3)	Lnexp(4)	Lnexp(5)
cul	-1.288***	-1.097**	-1.103***	-1.165**	-1.159***
	(0.488)	(0.438)	(0.423)	(0.458)	(0.416)
lnpop		0.760**	0.807**	0.740*	0.766**
		(0.386)	(0.376)	(0.411)	(0.377)
lninter			-0.624	-0.637	-0.623
			(0.561)	(0.562)	(0.570)
lnexr				0.075	0.063
				(0.171)	(0.159)
lntf					-0.359
					(1.015)
R2	0.228	0.276	0.391	0.421	0.435

Note: 1. ***, **, * They respectively indicate significance at the levels of 1%, 5% and 10%
2. Developed countries include the United States, Japan, Singapore, South Korea, Germany, Austria, Belgium, Denmark, Finland, the United Kingdom, Sweden, the Netherlands, Switzerland, Canada and Australia

Table 6. Developing Country Sample Regression

	Lnexp(1)	Lnexp(2)	Lnexp(3)	Lnexp(4)	Lnexp(5)
cul	48.300**	75.630**	96.765**	86.192*	102.884**
	(49.141)	(43.240)	(48.682)	(45.838)	(46.004)
lnpop		-9.959***	-9.156***	-6.935***	-6.986***
		(1.863)	(2.047)	(2.023)	(1.994)
lninter			-0.367	-0.300	-0.375
			(0.388)	(0.365)	(0.362)
lnexr				-0.719***	-0.642***
				(0.203)	(0.204)
lntf					2.014*
					(1.060)
R2	0.240	0.427	0.433	0.505	0.525

Note: 1. ***, **, * They respectively indicate significance at the levels of 1%, 5% and 10%
2. Developed countries include the United States, Japan, Singapore, South Korea, Germany, Austria, Belgium, Denmark, Finland, the United Kingdom, Sweden, the Netherlands, Switzerland, Canada and Australia

As can be seen from Table 5, for developed countries, cultural distance has a significant negative correlation with export volume at the 1% level, and the cultural distance coefficient decreases with the addition of control variables. It can be seen from Table 6 that for developing countries, cultural distance has a significant positive correlation with export volume at the 5% level, and the cultural distance coefficient increases with the addition of control variables. Cultural distance leads to prominent heterogeneity in the types of target countries for China's ceramic product exports.

5.Discussion

5.1 The Overall Negative Impact of Cultural Distance on China's Ceramic Product Exports

The empirical results show that cultural distance generally exerts a significant inhibitory effect on China's ceramic product exports. From the perspective of practical implications, it is necessary for the government and industry organizations to construct a systematic cross-cultural adaptation system. Meanwhile, the application of digital trade platforms, virtual display technologies and social media marketing can effectively reduce the costs of cross-border information communication and market verification, thereby fundamentally lowering the cognitive threshold and acceptance resistance of consumers in the international market.

5.2 The Negative Impact of Cultural Distance on China's Ceramic Product Exports to Developed Countries

The results of the heterogeneity test indicate that the inhibitory effect of cultural distance on China's ceramic product exports to developed countries is particularly prominent. This implies that the export of Chinese ceramic products needs to shift from cost competition to value competition. Enterprises can promote the "Cultural Value +" high-end brand strategy, shift the marketing focus from product functions to the dissemination of process

concepts, philosophical connotations and sustainable development values, transform cultural differences into unique brand assets and scarcity, further obtain cultural premium, and avoid low-end homogeneous competition.

5.3 The Positive Impact of Cultural Distance on China's Ceramic Product Exports to Developing Countries

Cultural distance has a significant positive effect on China's ceramic product exports to developing countries. To consolidate and expand this effect, at the product level, on the premise of maintaining the core of Chinese culture, it is feasible to appropriately integrate the regional color preferences, totem symbols or practical functions of the target market to enhance the cultural affinity and emotional connection of the products. At the market expansion level, strategically deploying new media platforms such as short videos and live e-commerce to transform Chinese style into a visible, tangible and participatory consumption trend is conducive to improving market share and brand awareness.

6. Conclusion

Based on panel data of China's ceramic product exports to 26 trading partners from 2014 to 2023, this paper empirically investigates the impact of cultural distance on these exports, and through heterogeneity analysis, reveals differential patterns across countries with varying levels of economic development. The findings indicate that cultural distance exerts a significant overall inhibitory effect on China's ceramic exports. After controlling for variables such as population, internet penetration rate, trade freedom, and exchange rates, this effect remains robust, suggesting that cultural differences reduce export scale by raising cognitive barriers and transaction costs. Heterogeneity tests show that for developed countries, the inhibitory effect of cultural distance is stronger and statistically significant, attributable to their mature cultural systems and entrenched aesthetic preferences, which amplify cross-cultural cognitive barriers. In contrast, for developing countries, cultural distance exhibits a significant positive promotional effect, as exotic cultural features stimulate consumer curiosity, and flexible business environments mitigate transaction cost pressures. Integrating transaction cost theory and consumer behavior theory, this study constructs a "dual-effect game" analytical framework for cultural distance, elucidates the moderating mechanism of economic development levels, and enriches research on heterogeneity in cultural product trade. It also offers recommendations for the differentiated positioning of China's ceramic exports: for developed countries, deep cultivation of cultural value transformation is needed, while for developing countries, enhanced output of cultural characteristics is advisable. Although this study has achieved certain progress, it still has limitations. For instance, the sample covers only 26 countries, and the measurement of cultural distance does not incorporate factors of cultural dynamic change. Future research could expand the sample scope and, combined with firm-level microdata, explore the moderating role of cultural adaptation strategies, thereby providing more precise support for the ceramic industry to overcome cultural barriers and enhance international competitiveness.

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The Role of Information and Communication Technologies (ICT) in Facilitating Green Economic Performance: Evidence from Developing Nations

Do Nhat Anh Phan, Thi Huong Giang Vu, Tam Thanh Duong, Thi Xuan Mai Do, Xuan-Hoa Nghiem[1]

International School, Vietnam National University, Hanoi, Vietnam

Abstract. This study investigates whether information and communication technologies can drive green growth in an unbalance panel of 28 developing Asian countries from 1990 to 2024. Empirical findings from fixed effects and random effects model show that both research and development (R&D) and information and communication technology (ICT) have a positive and statistically significant impact on green growth, highlighting the role of innovation in improving energy efficiency. Financial development exerts significantly positive impact; trade openness exerts significantly negative impact on green growth while the effects of remaining variables are negligible. This study contributes by distinguishing between different dimensions of technological progress. The findings provide important policy implications for promoting sustainable development in developing countries.

Keywords. Green growth; Technological progress; Research and development (R&D); Information and communication technology (ICT); Developing countries

1. Introduction

Environmental issues, particularly climate change, are becoming a global challenge as the fossil fuel-based growth model depletes resources and increases greenhouse gas emissions. Recent reports from the IPCC and WMO show that average global temperatures have risen sharply, with 2024 recorded as the hottest year in observational history, reflecting a worrying warming trend driven by high emissions from fossil fuel production and consumption. Developing countries, despite having lower per capita emissions compared to developed countries, suffer more severe losses from the impacts of climate change due to limitations in adaptation capacity, infrastructure, and financial resources[2].

The concept of green growth emerged as a development orientation that helps countries achieve economic growth while protecting the environment and using resources efficiently. According to the OECD, green growth is about promoting growth

[1] Corresponding Author. Xuan-Hoa Nghiem, Email: hoanx@vnu.edu.vn

[2] For a detailed review of consequences of climate change and environmental pollution, readers can refer to Bakry et al. [5] [6] [7]; Nghiem et al. [8]; Guo et al. [9], Nasreen et al. [10], Wang et al. [11], Nghiem et al. [12].

while maintaining "natural assets" that provide resources and environmental services for people. According to the World Bank, technological progress – measured by total factor productivity (TFP) growth, not just by increases in capital or labor – is a core driver in shifting the growth model from one based on accumulation to one based on innovation. However, technological advancements not only increase output but also have the potential to restructure growth models towards a more environmentally friendly direction. Theoretically, technology promotes green growth through three main channels: improving energy efficiency and reducing energy intensity per unit of GDP [1], expanding the use of renewable energy such as solar and wind power [2], and reducing the cost of clean production and pollution control technologies. However, in the early stages of industrialization, technological innovation can increase the scale of production, leading to higher energy consumption and emissions [3] [4], while many developing countries are still constrained by institutional, infrastructure, and financial limitations, preventing the widespread adoption of green technologies as expected.

Because both of the driving mechanisms and potential risks coexist, the relationship between technological progress and green growth is complex and requires empirical study. Particularly in the context of developing countries, where maintaining high economic growth rates is crucial while simultaneously addressing environmental issues, clearly demonstrating the true role of technological progress is vital for policies promoting green growth. This issue is particularly important in developing Asian economies where high economic growth is needed to maintain people's well-being but environmental degradation has become increasingly serious. To the authors' best knowledge, while there exist several studies on the determinants of green growth, a study specifically dealing with Asian developing economies is missing, making it difficult for these governments to craft and implement appropriate measures. The current study is aimed at filling these voids in the literature. This study aims to analyze the impact of technological progress on green growth in developing countries over the past 35 years, thereby providing empirical evidence for sustainable development policy planning. The remainder of the paper is structured as follows: Section 2 provides a review of the literature, Section 3 describes model specification, data; Section 4 discusses results while Section 5 concludes the study with policy implications and recommendations.

2. Literature review

Green growth is the dominant development trend of the 21st century, serving as both a goal and a driving force for long-term development. Technological advancements, particularly in renewable energy, environmental research, and engineering innovation, play a key role in promoting a green economy [13] [14]. Following the previous literature, this study employs the adjusted net savings, including particulate emission damage (measured in current USD) from World Bank's World Development Indicators to proxy for green economic performance (gef). Amid several indicators for green economic performance/green growth, this series is selected thanks to its ease of access and popularity [15].

According to Kwilinski [16], the role of technology innovations, including the promotion and improvement of green technology development and exportation (R&D), contributes significantly to fostering the growth of green economic activities and creating a self-replicating cycle of sustainability. However, the commercialization of patented technology is crucial to achieving green growth as patents only signify technological

advancements rather than having much effect on promoting green growth without effective commercialization [16]. Durrani [17] suggests that investing in education positively contributes to the development of green economies; however, this investment is only effective after the capacity for research and environmental consciousness exceed certain levels. Fang [18] notes that in developing countries, increased research and development (R&D) play an important role in reducing emissions, particularly from industrial and investment activities, and facilitate the transfer of technology and the diversification of economies. Therefore, R&D (randd) will also be included in the model.

Another variable closely related to R&D is the information and communication technologies (ICT) which has been widely confirmed to exert significant impact on various aspects of life, ranging from economic growth, energy consumption [6], to carbon emissions [8]. Consequently, ICT is expected to affect economic growth (in general) and green growth (in particular). Yet, the impact of ICT on green growth remains scant, especially in Asian developing economies which in turn, prompted the authors to conduct this study. Therefore, we reason that ICT also exerts positive impact on green growth. [3]Another variable that is also controversial is financial development. While the impact of financial development on economic growth and environmental sustainability is voluminous (and controversial), the influence of this variable on green growth remains unclear and under-explored. Therefore, we expect that the sign of the impact of financial development on green growth remains unclear. In addition to ICT and financial development, foreign direct investment (FDI) may also exert strong influence on green growth either positively or negatively (the pollution-halo and pollution-haven hypotheses). Similarly, trade openness and urbanization have been confirmed to affect economic growth and environmental sustainability. Yet, their impact on green growth especially in the context of developing Asian nations remain limited. This study aims to fill these voids in the literature.

3. Estimation techniques

The econometric model is established as follows:

$$gef_{it} = \beta_0 + \beta_1 rd_{it} + \beta_2 ict_{it} + \beta_3 urb_{it} + \beta_4 fd_{it} + \beta_5 trade_{it} + \beta_6 gov_{it} + \beta_7 fdi_{it} + \varepsilon_{it} \quad (1)$$

where gef stands for green economic performance, RD: research and development expenditure (% of GDP); ICT: information and communication technology adoption; URB: percentage of urban population (% of total population); fd: financial development (proxied by domestic credit provided to the private sector by banks-% of GDP); TRADE: trade openness; GOV: government effectiveness; FDI: foreign direct investment inflows (% of GDP); i: Country; t: Time; ε: error term. Detailed information about these variables are presented in Table A2 in the online appendix found at: https://docs.google.com/document/d/1nOl7FAF1Clk2vf8iPwIrfzMcYojiGl4S/edit?usp=drive_link&ouid=113336956295405889282&rtpof=true&sd=true

[3] Although the ICT sector has witnessed juggernaut development with the invention and adoption of mobile phones and the Internet, fixed telephone subscriptions/infrastructure still play a significant role as it can reduce digital divides [19]. Further, fixed telephone lines serve as the historical and structural foundation for fixed broadband networks which in turn, significantly drive long-term economic growth [20] and attract long-term FDI [21].

4. Estimation results

4.1. Correlation

Table 1: Correlation analysis

	ggl	randd	ictl	urban	fdl	to	gov
ggl	1.0000						
randd	0.3103*	1.0000					
	0.0000						
ictl	0.7819*	0.2766*	1.0000				
	0.0000	0.0000					
urban	-0.0063	-0.0021	-0.0392	1.0000			
	0.8652	0.9672	0.2580				
fdl	0.4209*	0.1610*	0.4722*	0.2564*	1.0000		
	0.0000	0.0020	0.0000	0.0000			
to	-0.2102*	-0.0836	-0.2067*	0.3426*	0.3106*	1.0000	
	0.0000	0.1162	0.0000	0.0000	0.0000		
gov	0.1944*	0.0751	0.1531*	0.3303*	0.5388*	0.3191*	1.0000
	0.0000	0.1711	0.0001	0.0000	0.0000	0.0000	
fdi	-0.0636	-0.0208	-0.0462	0.0962*	-0.0046	0.3035*	-0.0314
	0.0860	0.6899	0.1899	0.0030	0.8912	0.0000	0.4078

Results from Table 1 show that the pairwise correlation between each pair of variables is less than 0.5 in all cases, implying that there is no problem of multicollinearity among these variables. Therefore, we can proceed with the estimation.

4.2. Estimation results

Table 2: Estimation results

gef	VIF	RE	FE
randd	1.09	330915**	229107.2**
		(0.018)	(0.014)
ict1	2.57	2761.514***	-1218.667***
		(0.000)	(0.008)
urban	1.32	-4.49e+08	5.86e+10***
		(0.643)	(0.000)
fd	3.83	5.13e+09***	-7.94e+08
		(0.000)	(0.388)
to	1.60	-3.16e+09 ***	3.97e+09***
		(0.000)	(0.000)
gov	2.20	-3.27e+10	-2.55e+10
		(0.464)	(0.630)
fdi	1.17	3.09e+09	-3.45e+09*
		(0.161)	(0.057)
constant		1.04e+11	-3.40e+12***
		(0.119)	(0.000)
Hausman test		-257.50	

Note: p-value in parenthesis; ***, **, * denote significance at 1%, 5% and 10% levels, respectively. Source: Authors' own works.

It should be noted that the variance inflation factor (VIF) statistics for all variables are less than 4, we can confirm that there exists no problem of multicollinearity among variables in this study[4]. Further, it is worth-mentioning that results of the Chi-square statistics of the Hausman test is negative and significant, indicating that we can not reject the null and therefore, RE model should be chosen instead of the FE model[5].

[4] The threshold values of 4 for VIF statistics is commonly used in the literature. For example, see O'brien [23].
[5] The preference of RE model over FE model is recorded in the literature. Readers may refer to Hausman and Taylor [24] as well as Baltagi [25].

Table 2 provides the results of the estimation using random effects (RE) and fixed effects (FE) models. In the RE model (which is preferred by Hausman test result), the two main variables used to represent technological progress are the level of development of fixed telecommunications (ict1) and R&D spending (randd). The results show that R&D expenditure has a positive and significant impact on green growth, indicating that R&D efforts of these countries will be paid off. Further, ICT also releases a positive and significant impact on green growth. These results are consistent with the research of Bakry et al. [6] (2023b) as well as Khan et al. [22] (2025) who demonstrated that ICT and technological innovation can positively impact economic growth. Next, financial development is found to exert significant and positive impact on green growth which implies that, when combined/integrated with ICT (which also has significant and positive impact on green growth), may produce stronger benefits for green growth. However, the effects of trade are significant yet negative, meaning that while trade can benefit conventional growth, it is detrimental to the environment and therefore, green/sustainable growth. The remaining variables, namely government effectiveness and FDI show insignificant results, implying that the impact of these variables is negligible.

5. Conclusions, policy implications, limitations and future research directions

Empirical findings confirm that research and development (R&D) contributes significantly to this model, demonstrating that innovation is the primary driver of sustainable green growth. Similarly, ICT variables exert positive impact on economic growth while urbanization and trade openness have an unexpected adverse impact on green growth, highlighting the risks of excessive and fast urbanization. While government effectiveness and FDI are insignificant, financial development has significantly positive impact while trade openness has significantly negative impact on green growth, confirming the role of financial development while warning of the pros and cons of trade.

Results from this study offer several policy implications and recommendations. In the context, limited financial resources and infrastructure for transformation, governments should strengthen investments into research and development activities as well as facilitate the adoption of ICT. Given the negative impact of trade openness on green growth, these developing Asian economies are strongly recommended to impose stricter environmental regulations and practices on export-import activities. Further, given the benefits of financial development, policymakers should carry out measures to strengthen financial development in these economies.

While the authors tried their best to conduct a study as thoroughly as possible, this manuscript is still subject to certain limitations which in turn, open new directions for future research. First, this study only employs FE and RE models in which variables are used in their level forms, implying that potential endogeneity may exist. Therefore, researchers may want to use other methods such as GMM or IV to tackle this issue. Second, this paper exclusively focuses on developing Asian economies while ignoring others such as developed nations or countries in other continents. This constrains the generalization and applicability of results to other countries. Consequently, scholars may want to expand the sample size to include other economies in other regions. Finally, the missing data/observations may also limit reliability of results and inferences. Future studies may need to extend the sample size to get more reliable results.

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Research and Application of Key Technologies for Digital and Intelligent Monitoring of Moving-Boat ADCP

Wenjing ZHOU[a], Shan DENG[a], and Siwei JIANG[a, 1]
[a] *Bureau of Hydrology, Changjiang Water Resources Commission, China*

Abstract. Moving-vessel Acoustic Doppler Current Profilers (ADCP) are the primary tools for hydrological discharge measurement. However, existing systems face significant challenges. In practical operations, data post-processing heavily depends on closed-source software (e.g., WinRiver II). Specific challenges include tedious manual compilation, inconsistent spatial datums across measurement transects due to vessel drift, and simplistic two-dimensional result presentations. To overcome these challenges, the objective of this paper is to propose a self-developed, full-chain automated processing technique for ADCP data. This method operates independently by directly parsing raw binary PD0 streams. A "vector component interpolation" technique automatically repairs blind zones, while a "fixed section projection method" standardizes GPS track correction for strict spatial alignment. Furthermore, it automatically executes power-law extrapolation and five-point velocity extraction. Validation using Han River field data shows this approach effectively filters out invalid edge data. Track correction eliminates cross-section width closure errors to 0 m. The automated discharge error is merely -2.97%, and processing time is reduced from 30 minutes to under 1 minute. Additionally, generated 3D velocity distribution heatmaps intuitively visualize mainstream cores and boundary layers. Ultimately, this method resolves ADCP post-processing "black box" issues, enhancing automation and visualization for smart hydrology.

Key words: Moving-vessel Acoustic Doppler Current Profiler; Track Correction; Python; Velocity Distribution Visualization; Smart Hydrology

1. Introduction

While Moving-vessel Acoustic Doppler Current Profilers (ADCP) serve as the primary tools for hydrological discharge measurement, grassroots hydrological stations still face significant operational bottlenecks when dealing with high-frequency, large-flow measurement [1, 2] tasks. Currently, the application of ADCP data exhibits three major technical limitations:

(1) Data Black Box and Format Barriers: Mainstream ADCP devices store data in proprietary binary formats. Post-processing heavily depends on closed-source commercial software (e.g., WinRiver II) [3, 4]. This encapsulation of core algorithms prevents users from customizing data cleaning rules and creates "data silos".

[1] Corresponding Author, Siwei Jiang, Bureau of Hydrology, Changjiang Water Resources Commission, China; E-mail: 524107243@qq.com.

(2) Spatial Misalignment: Actual measurement trajectories often exhibit irregular "S"-shaped swings due to water flow resistance and vessel navigation. Traditional processing relies on integration along this actual moving trajectory, leading to inconsistent physical meanings of starting distances across different runs and hindering spatial superposition.

(3) Insufficient 3D Reconstruction: Existing survey outcomes focus primarily on the numerical output of "total discharge," overlooking the massive velocity profile data collected by the equipment. This lack of capability to instantly generate three-dimensional flow field data cubes limits its application in digital twin scenarios.

Extensive research on ADCP data post-processing has been conducted globally. For instance, the United States Geological Survey (USGS) developed QRev, an open-source tool for data quality control and discharge calculation. However, it is primarily research-oriented, possesses weak operational interactivity, and lacks targeted support for specific velocity extraction methods. Furthermore, current mainstream methods for flow field reconstruction (e.g., Kriging interpolation or CFD model assimilation) mostly require offline processing, struggling to meet the real-time demands of digital twin applications.

To overcome these challenges, this paper proposes a fully self-controlled, full-chain automated processing technique for moving-vessel ADCP data. The main research contents include:

(1) Low-level Parsing of Heterogeneous Data: Decoding binary data streams (e.g., PD0) to establish a standardized vertical line data model.

(2) Data Governance Under Physical Constraints: Proposing a vector-independent interpolation cleaning algorithm and an orthographic projection correction algorithm for vessel tracks based on a seven-parameter transformation.

(3) Multi-Run Fusion and Refined Reconstruction: Developing a 3D flow field reconstruction technique based on power-law extrapolation and multi-run vector averaging.

(4) Digital-Intelligent Platform Validation: Validating the algorithm's robustness using measured data from the Han River Baihe Station and designing a monitoring platform architecture oriented towards smart hydrology.

2. Overall Architecture and Digital-Intelligent Technology System

The proposed digital-intelligent monitoring system is designed to transform raw ADCP data into standardized results and 3D flow field cubes through a modular "data factory" approach. By decoupling physical measurements from business logic, the system achieves a full-chain automated flow from raw signals to compiled reports.

As illustrated in Fig. 1, the workflow integrates five core modules.

(1) Parameter Configuration Module: Users define business rules for the physical world here. Core parameters include the coordinates of the baseline points $A(X_a, Y_a)$and $B(X_b, Y_b)$ for the standard cross-section, the effective vertical line range, and the deviation threshold D_{lim} used to reject abnormal vessel tracks. This design completely separates "where the measurement was taken (GPS)" from "where the calculation should be based (standard cross-section)."

(2) Underlying Parsing Module: This module directly reads binary files, extracts fundamental information such as latitude (Lat), longitude (Lon), water depth (D), and velocity at each binV_{bin}, and converts them into unified in-memory objects.

(3) Cleaning and Correction Module: This module is crucial for ensuring data quality. On one hand, it repairs data gaps through vector interpolation. On the other hand, it utilizes an orthographic projection algorithm to forcibly "straighten" the curved actual vessel track onto the user-defined standard cross-section and automatically filters out invalid points with severe deviation based on D_{lim}.

(4) Generalization and Compilation Module: This module performs virtual resampling on the standard cross-section. For the surface and near-bed blind zones inaccessible to ADCP measurements, it employs the power-law formula for scientific extrapolation, followed by the extraction of characteristic velocities at specified points.

(5) Fusion and Reconstruction Module: This module averages data from multiple round-trip measurement runs to generate a smoothed cross-sectional flow velocity distribution cloud map.

Through this full-chain workflow, the system reduces manual processing tasks that originally took hours to mere minutes, while ensuring the traceability and standardization of the processing results.

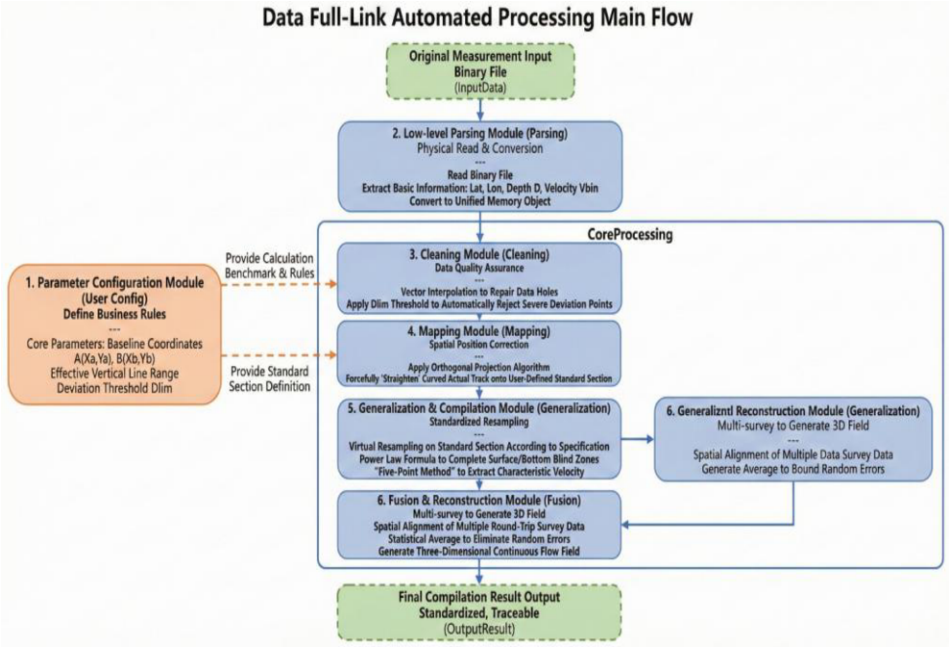


Figure 1. Data full link processing flow chart.

3. Raw Data Cleaning and Track Standardization Processing

The quality of raw ADCP data directly dictates the confidence level of subsequent flow field inversions. Addressing prevalent issues of "signal noise" and "track drift," this paper proposes a data governance algorithm coupling physical mechanisms with geometric constraints.

3.1. Binary Parsing and Vector-Independent Interpolation

To bypass the opacity of commercial software, a universal decoding engine was developed to extract spatial, physical, and quality attributes directly from raw binary streams (e.g., PD0). ADCP measurements frequently suffer from blind spots caused by suspended solids or side-lobe interference (defined by $1-\cos(\theta)$). s.

Traditional holistic interpolation often distorts the directionality of velocity vectors. To address this, we propose a vector-independent interpolation method [5]. For identified invalid cells ($V_{invalid}$), orthogonal components are processed separately:

$$\begin{cases} V_E(Z) = Interp(V_E(Z_{up}), V_E(Z_{down})) \\ V_N(Z) = Interp(V_N(Z_{up}), V_N(Z_{down})) \end{cases}$$

Among these, z_{up} and z_{down} represent the depths of the upper and lower adjacent valid layers, respectively. After restoration, the velocity is reconstructed using the composition formula $V = \sqrt{V_E^2 + V_N^2}$. Experiments show that this method can effectively avoid directional smoothing distortion in strongly sheared flow layers, preserving the physical continuity of the flow field.

3.2. Spatial Alignment via Orthogonal Projection

During actual moving-vessel measurements, because of flow resistance and navigation skills, the vessel's trajectory often exhibits irregular "S-shaped" swings, as shown in Fig. 2. If the cumulative track is directly used to calculate the cross-sectional area, it would lead to a systematic overestimation of the flow discharge. To address this, this study introduces an interactive correction strategy based on "user-defined benchmarks."

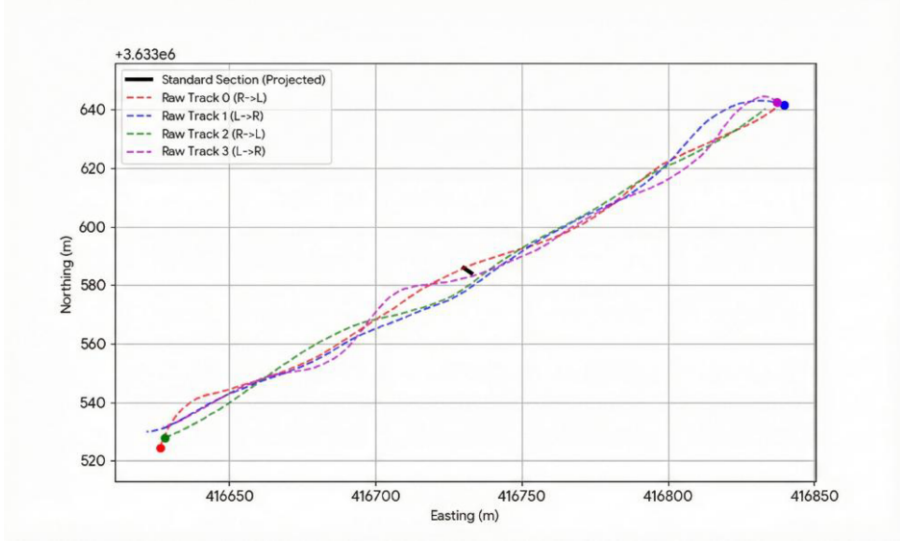


Figure 2. Survey ship trajectory chart.

To standardize cross-sections, GPS coordinates (WGS-84) are first unified into a planar projection system using the Bursa-Wolf seven-parameter transformation model

[6-8]. Subsequently, an orthogonal projection algorithm forces discrete measurement points $P_i(X_i, Y_i)$ onto a user-defined standard cross-section line L_{AB}. The unit direction vector is defined as:

$$\overrightarrow{u_{AB}} = \frac{\overrightarrow{AB}}{|\overrightarrow{AB}|}$$

Projection Calculation: Calculate the projection vector of measurement point P_i relative to the starting point A:

$$\overrightarrow{L_{proj}} = (\overrightarrow{AP_i} \cdot \overrightarrow{u_{AB}}) \cdot \overrightarrow{u_{AB}}$$

Standard Starting Distance Calculation: The corrected starting distance is the magnitude of the projection:

$$L_{standard} = \overrightarrow{AP_i} \cdot \overrightarrow{u_{AB}} = (X_i - X_A)\cos\ \alpha + (Y_i - Y_A)\sin\ \alpha$$

where, α is the azimuth angle of the standard cross-section.

Spatial Quality Control (QC) and Filtering Calculate the vertical offset distance $Offset_i$ of each measurement point from the standard cross-section:

$$Offset_i = |\overrightarrow{AP_i} \times \overrightarrow{u_{AB}}|$$

The system sets a threshold D_{lim} (e.g., 20 m) and automatically filters out abnormal track points where $|Offset_i| > D_{lim}$. This mechanism effectively eliminates interference from non-standard data caused by the survey vessel avoiding obstacles or drifting uncontrollably, ensuring the spatial representativeness of the compiled results.

4. Multi-Run Result Fusion and Cross-Sectional Velocity Distribution Visualization

4.1. Vertical Resampling and Blind Zone Inversion

To unify multi-run data onto a consistent spatial grid, the standard cross-section is discretized into virtual vertical lines at fixed intervals, with user-defined boundaries to exclude stagnant near-bank zones. For unmeasurable surface and near-bed blind zones, the classical hydraulic power-law model is utilized for extrapolation:

$$u(z) = u_{ref} \cdot \left(\frac{z}{z_{ref}}\right)^{1/m}$$

Where, z_{ref} is the height above the riverbed of the measurement layer closest to the blind zone, and u_{ref} is its measured velocity. The exponent m defaults to 6 (i.e., the 1/6th power law). However, for digital twin applications, users are supported to dynamically adjust the m value based on riverbed roughness (e.g., cobbles, silt) to obtain a boundary layer velocity distribution that better aligns with actual physical laws.

Standardized Extraction Based on the completed full vertical velocity profile, the system automatically extracts velocity vectors and flow directions at relative water depths (e.g., 0.0, 0.2, 0.6, 0.8, 1.0), generating results tables that comply with national standards.

4.2. Vertical Resampling and Blind Zone Inversion

Relative motion during actual surveys causes non-synchronized sampling times for the same spatial locations across different runs. Using the standard starting distance as an absolute spatial axis, data from all measurement runs (K) are mapped into a unified coordinate system to construct a spatiotemporal index [9, 10]. To eliminate random turbulent noise, vector averaging is applied to all data falling within each virtual vertical window:

$$\bar{\vec{V}}_{ij} = \frac{1}{K}\sum_{k=1}^{K} \vec{V}_{ij}^{(k)}$$

Where, K is the number of runs, and i, j are grid indices. Validation shows that after vector averaging over 4 runs, the root mean square error of the flow field is significantly reduced, and the main flow path structure becomes clearer and more stable, providing a high-confidence initial field for numerical simulation.

5. Results and Application

5.1. Experimental Data and Environment

To verify the proposed workflow, field data was collected at the Baihe Station on the Han River on December 1, 2021. The survey utilized a RiverRay 600 kHz phased-array ADCP in a channel approximately 310 m wide with a maximum depth of 12 m. Four complete measurement runs (two left-to-right and two right-to-left) were recorded in raw binary PD0 format.

5.2. Validation of Automated Workflow

The orthogonal projection algorithm successfully corrected the original GPS tracks, which initially exhibited a maximum deviation of 15.6 m from the baseline. As illustrated in the corrected GPS track map (Fig. 3), after correction, the closure error of the cross-section width converged to 0.00 m, effectively eliminating geometric biases. The corresponding cross-sectional underwater terrain profile is shown in Fig. 4.

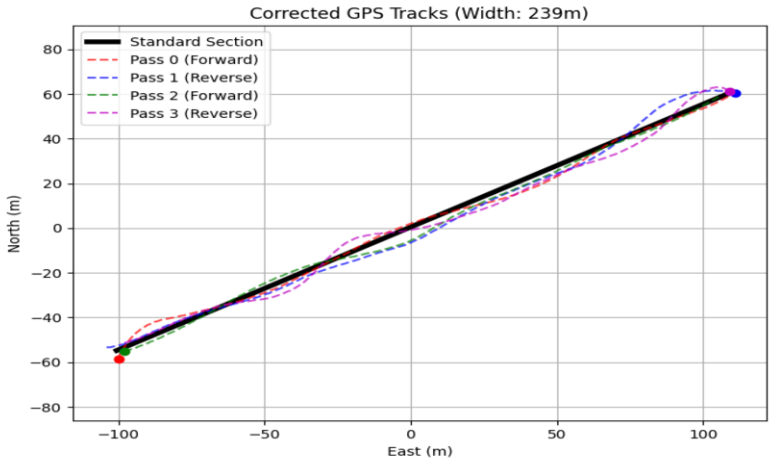


Figure 3. Corrected GPS track map.

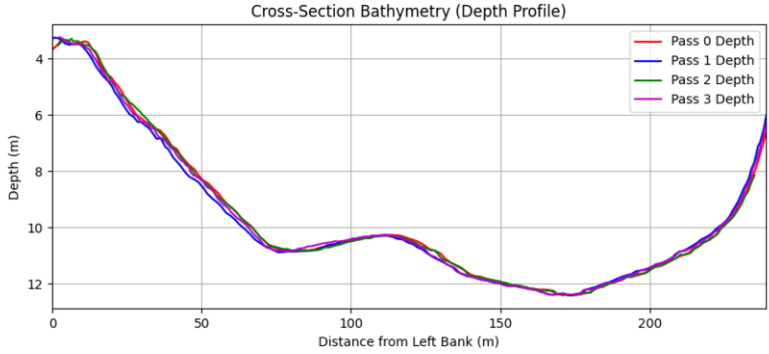


Figure 4. Cross-sectional underwater terrain profile.

The spatiotemporal fusion algorithm significantly reduced turbulent noise. As detailed in the error statistics in Table 1, the average velocity Root Mean Square Error (RMSE) across all layers dropped to 0.049 m/s.

Table 1. Multi-measurement return flow velocity fusion error statistics table.

Run ID	Direction	Surface Layer (0.2H) RMSE (m/s)	Main Flow Layer (0.6H) RMSE (m/s)	Average RMSE (m/s)
Station_000	L -> R	0.042	0.075	0.064
Station_001	R -> L	0.075	0.049	0.064
Station_002	L -> R	0.05	0.041	0.049
Station_003	R -> L	0.07	0.072	0.072

Furthermore, the automated discharge calculation yielded 567.71 m^3/s, representing a relative error of only -2.97% compared to the official validated reference value (585.12 m^3/s). These results demonstrate high consistency and robustness for practical hydrological operations.

5.3. 3D Visualization and Digital Twin Integration

The fused high-precision data allowed for the generation of a detailed cross-sectional velocity heatmap, as depicted in Fig. 5. The visualization clearly revealed a maximum vertical average velocity of 0.334 m/s and identified a "thalweg and main flow misalignment". This phenomenon, characterized by the high-velocity core being spatially offset from the maximum depth, is a critical hydrodynamic feature influenced by upstream structures that traditional 2D reports fail to capture:

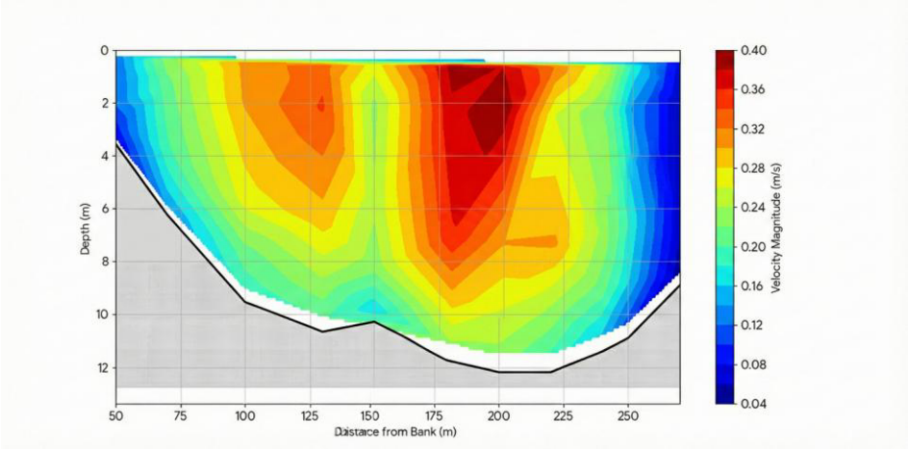


Figure 5. Cross-sectional flow velocity distribution heat map.

Performance comparisons, summarized in Table 2, confirm that the proposed model significantly outperforms traditional closed-source tools in both spatial alignment and fully automated 3D reconstruction capabilities.

Table 2. Comparison between past models and the proposed model.

Feature / Aspect	Traditional Commercial Software (e.g., WinRiver II)	Mainstream Open-Source Tool (e.g., QRev)	The Proposed Model (This Paper)
Data Parsing	Closed-source binary parsing	Open-source MATLAB/Python parsing	Fully independent underlying binary decoding
Spatial Alignment	Integration along the actual trajectory	Integration along the actual trajectory	Forced Orthogonal Projection to standard section
Multi-Run Fusion	Unaligned, simple numerical averaging	Limited spatial alignment	Strict temporal-spatial alignment & Vector averaging
Output Outcome	Total discharge & 2D planar tracking	Enhanced discharge & error analysis	Standardized 5-point results & 3D flow field heatmap
System Interactivity	Desktop-bound, manual intervention required	Script/Desktop-based, low interactivity	Cloud-based microservice components, high interactivity

By encapsulating these algorithms into microservices, the system is seamlessly integrated into a WebGL-based digital twin platform [11, 12]. This platform functions as a "virtual intelligent laboratory," allowing researchers to remotely analyze 3D flow fields and intelligently identify channel shifting patterns and erosion trends without repeated on-site surveys [13, 14].

6. Conclusion

This study established a fully autonomous, full-chain automated processing workflow for moving-vessel ADCP data. By developing underlying decoding algorithms independent of commercial software, the research achieves a standardized transition from raw binary signals to compiled results.

The primary innovation lies in the reconstruction of the spatial reference system through a forced orthogonal projection method, which ensures strict spatial alignment for multi-run data. Coupled with vector-independent interpolation and blind-zone power-law inversion, the proposed system reduces flow field RMSE to 0.049 m/s and maintains discharge error within 3%. Furthermore, the microservice-based architecture enables the instant reconstruction of 3D flow fields within digital twin environments, advancing hydrological monitoring from offline analysis to real-time online service.

Future work will focus on integrating multi-beam bathymetry and side-scan radar data for holistic "topography-flow field" fusion. Additionally, porting the algorithms to edge-computing terminals on unmanned vessels will be investigated to achieve real-time "measurement while computing" capabilities.

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Asymmetric Effects of Digital Infrastructure Development on China's Urban–Rural Income Gap: Evidence from Provincial Panel Data, 2019–2024

Yanying GUO, Yiqi LIU, Liangliang WANG[1]
School of Marxism, Xi'an Shiyou University, Xi'an, China
ORCiD ID: Liangliang WANG https://orcid.org/0009-0005-9623-2766

Abstract. Using provincial panel data (2019–2024) and a two-way fixed effects model, this study investigates digital infrastructure's impact on China's urban–rural **income** gap. Baseline estimates reveal that 1% increase in internet penetration reduces the gap by 0.01382 units—a finding robust to alternative measures and lagged specifications. Crucially, a pronounced North–South asymmetry emerges: digital infrastructure drives income convergence in the South but temporarily widens the gap in the North. These findings highlight that equitable digital dividends depend on local endowments, necessitating regionally differentiated policies.

Keywords. Digital Infrastructure, Urban-rural Income Gap, Digital Divide

1. Introduction

The urban–rural income gap remains a key concern in China's macroeconomic research. Since the launch of 5G commercialization in 2019, digital infrastructure has expanded rapidly, with fifth-generation mobile networks and big data systems driving significant technological upgrading. By 2024, China's Internet penetration rate had reached 78.6%, and rural digitalization has accelerated markedly [1]. Notably, the expansion of digital infrastructure has closely coincided with a gradual narrowing of the urban–rural income gap, suggesting a potential structural link between digital development and income convergence [2]. However, this parallel trend has also sparked ongoing academic debate over whether digitalization primarily generates a 'digital dividend' that promotes inclusive growth or intensifies a 'digital divide' that reinforces inequality across regions and social groups.

Existing scholarship offers three main perspectives. First, convergence theory, emphasizes the 'digital dividend'. Yin and Choi argue that digital infrastructure reduces information frictions and enhances rural market participation [3]. Ma et al. further contend that the magnitude of such benefits depends on the regional penetration of the digital infrastructure [4]. Zhang and Zhao also confirm its positive role in promoting urban–rural integration [5]. Second, polarization theory, highlights the risks of a 'digital divide' [6]. Drawing on Acemoglu and Restrepo's 'race between man and machine'

[1] Corresponding Author: Liangliang WANG, wangliangliang@xsyu.edu.cn

framework [7], scholars such as Peng and Dan suggest that disparities in regional endowments may cause digital infrastructure to exacerbate inequality [8]. Third, difference theory, focuses on threshold effects and spatial heterogeneity. Wang et al. identify significant regional variation [9]. Akerman underscores skill complementarities between broadband access and high-skilled labor [10]. And Wang emphasizes the mediating role of technology market development [11].

Despite these insights, limited attention has been paid to the increasingly salient North–South disparities in China's economic geography. This study therefore adopts a spatial heterogeneity perspective to examine the asymmetric effects of digital infrastructure across diverse regional contexts.

1.1. Digital Dividend and Income Convergence

From the perspective of human capital theory, digital infrastructure acts as an equalizer by expanding access to information and educational resources. Improved connectivity facilitates online learning and digital literacy training, directly enhancing rural human capital and labor market competitiveness [10]. Furthermore, integrated digital networks lower transaction costs and eliminate market friction, allowing rural households to increase their bargaining power and engage in high-value, platform-based employment such as live-streaming e-commerce. Consequently, this factor market integration promotes inclusive regional development and narrows the income gap.

- H1: The development of digital infrastructure helps narrow the urban-rural income gap.

1.2. Digital Divide and Spatial Asymmetry

In terms of regional development and technological transition theories, the distributional consequences of digital infrastructure are heavily constrained by local factor endowments. Grounded in Acemoglu and Restrepo's 'race between man and machine' framework [7], we argue that digital transformation is inherently skill-biased. In northern regions characterized by traditional heavy industries and slower marketization, advanced digital deployment disproportionately benefits urban, high-skilled workers, thereby widening the urban–rural skill premium. Moreover, industrial automation risks displacing low-skilled rural labor, while a lagging rural digital inclusion rate creates a 'dividend bias' that temporarily exacerbates regional inequality.

- H2: The impact of digital infrastructure on the urban-rural income gap possesses significant spatial asymmetry.

2. Method

2.1. Data Sources and Variable Selection

This study constructs a balanced panel dataset covering 31 provincial-level administrative regions in China from 2019 to 2024. The dependent variable is the urban–rural income gap, measured by the ratio of per capita disposable income of urban residents to that of rural residents, which captures relative income disparities across

regions and over time. The core explanatory variable is the level of digital infrastructure development, proxied by provincial Internet penetration rates, reflecting the extent of digital connectivity and accessibility. To mitigate omitted variable bias and improve estimation accuracy, several control variables are included, namely the level of economic development, average years of education, and government expenditure intensity. These controls account for regional heterogeneity in economic capacity, human capital, and public sector involvement.

Table1. Descriptive Statistics of Main Variables

	Definition	N	Min	Max	Mean	Std. Dev.
GAP	Urban-rural income gap	186	1.764	3.357	2.354	0.322
Internet	Digital infrastructure level	186	0.230	0.580	0.399	0.078
Ln GDP	Economic development	186	10.492	12.338	11.241	0.390
Edu	Average years of education	186	5.808	12.782	9.565	1.048
Ln Gov	Government expenditure intensity	186	7.264	9.827	8.727	0.576

As show in the Table 1, descriptive statistics describe an average urban–rural income gap of 2.354, with substantial variation across provinces, indicating pronounced regional imbalance. Meanwhile, both education levels and Internet penetration display significant dispersion, providing adequate variation to identify the spatially heterogeneous effects of digital infrastructure.

2.2. Correlation Analysis

Correlation analysis is conducted to preliminarily examine the strength and direction of relationships between key variables before formal regression estimation. It helps identify whether digital infrastructure, income gap, and control variables are linearly associated, providing an initial validity check of the data structure. In addition, correlation analysis can detect potential multicollinearity among explanatory variables, ensuring that subsequent regression results are not biased by excessive interdependence. Overall, it offers a necessary diagnostic step to improve model specification and enhance the interpretability and reliability of empirical findings.

Table 2. Correlation Analysis Matrix

Variables	GAP	Internet	Ln GDP	Edu	Ln Gov
GAP	1				
Internet	-0.387***	1			
Ln GDP	-0.410***	0.478***	1		
Edu	-0.480***	0.241***	0.683***	1	
Ln Gov	-0.249***	0.069	0.355***	0.284***	1

Notes: *** indicates statistical significance at the 1% level (two-tailed test). All observations = 186.

As show in the Table 2, the correlation analysis describes that the correlation coefficient between $Internet$ and $GAP$is -0.387, which is significant at the 1% level, preliminarily verifying the convergence hypothesis. In addition, $lnGDP$, Edu, and $lnGov$ are also significantly negatively correlated with GAP.

2.3. Empirical Model Specification

To rigorously identify causal links and control for unobservable omitted variables to the maximum extent, this study constructs a baseline regression model incorporating a two-

way fixed effects specification. The standard mathematical presentation of the econometric model is formulated as follows:

$$GAP_{it} = \alpha + \beta_1 Internet_{it} + \beta_2 lnGDP_{it} + \beta_3 Edu_{it} + \beta_4 lnGov_{it} + \mu_i + \lambda_t + \varepsilon_{it} (1)$$

where i and t denote the province and year, respectively. GAP_{it} represents the urban–rural income gap for province i in year t, measured by the ratio of per capita disposable income of urban residents to that of rural residents. $Internet_{it}$ is the core explanatory variable denoting the level of digital infrastructure development, proxied by provincial Internet penetration rates. For regression analysis, the Internet penetration rate is measured as a decimal proportion. The vector of control variables includes $lnGDP_{it}$, Edu_{it}, and $lnGov_{it}$. α is the constant term, and β_1 to β_4 are the parameters to be estimated. Additionally, μ_i represents the province fixed effect utilized to capture time-invariant regional heterogeneity, λ_t signifies the time fixed effect to absorb macroeconomic shocks common to all provinces, and ε_{it} is the idiosyncratic error term. To justify the model selection, the Hausman test yields a statistic of $\chi^2(3) = 4.107 (p = 0.250)$. Although the null hypothesis is not strictly rejected, a two-way fixed effects specification is conceptually optimal here. Following Baltagi [12]and Wooldridge [13], since our sample covers the entire population of 31 Chinese provinces rather than a random draw from a larger conceptual population, the unobserved individual heterogeneities are best treated as fixed parameters.

To account for potential heteroskedasticity and serial correlation within provinces, the regression employs cluster-robust standard errors at the provincial level.

3. Results and discussion

3.1. Baseline Regression

Table 3. Baseline Regression Results

Variable	B	Std. Error	t	VIF
Year	0.004	0.018	0.206	2.501
Internet	-1.382***	0.438	-3.155	3.073
Ln GDP	0.095	0.082	1.158	2.678
Edu	-0.141***	0.026	-5.325	2.019
Ln Gov	-0.085***	0.037	-2.279	1.207

Notes: * p<0.1, ** p<0.05, *** p<0.01.

As show in the Table 3, the baseline regression results demonstrate that after controlling for individual and time effects, the unstandardized coefficient of $Internet$ is -1.382, which is highly significant at the 1% level. This indicates that, at the national level, digital infrastructure generally releases a digital dividend; for every 1 percentage point increase in the internet penetration rate, the urban–rural income ratio significantly decreases by an average of 0.01382 units. That is, a full 1-unit increase (100 percentage points) in internet penetration would result in a 1.382-unit reduction in the gap. Among the control variables, the coefficient of Edu is -0.141, indicating that the improvement of education level is a core driver in narrowing the urban-rural gap. The coefficient of

$lnGov$ is -0.085, confirming the regulatory role of fiscal allocation.

3.2. Robustness Checks

This paper conducts robustness checks to verify the reliability and stability of the baseline regression results. By replacing the core explanatory variable with broadband access rate, it tests whether the estimated impact of digital infrastructure on the urban–rural income gap is sensitive to alternative measurements. Robustness checks help reduce concerns about measurement error, omitted variable bias, and model dependence. Consistent results across specifications strengthen the credibility of the findings and ensure that the observed digital dividend effect is not driven by a specific proxy or estimation method.

Table 4. Robustness checks: Alternative explanatory variable and lagged effect.

Variable	(1) Alternative proxy (Broadband)	(2) Lagged effect (Lag_Internet)
Broadband	-0.901*** (0.206)	-
lag_ Internet	-	-0.912** (0.391)
Ln GDP	0.183** (0.085)	-0.276 (0.173)
Edu	-0.107*** (0.026)	0.042 (0.059)
Ln Gov	-0.152*** (0.041)	0.151 (0.141)
Year	-0.009 (0.014)	-
Controls	Yes	Yes
Province FE	No	Yes
Year FE	No	Yes

Notes: * p<0.1, ** p<0.05, *** p<0.01. Model (1) VIF<3.1, no multicollinearity.

As shown in the Table 4, the robustness check results further validate the stability of the empirical findings. The coefficient of broadband access remains significantly negative at the 1% level, confirming that digital infrastructure consistently reduces the urban–rural income gap. Control variables behave as expected: education level and government expenditure both exhibit significant negative effects, while GDP shows a positive association with the dependent variable. Multicollinearity is not a concern, as all variance inflation factors are below 10. Overall, the results in Table 4 reinforce the reliability of the baseline regression and support the conclusion that digital infrastructure plays a robust role in promoting income convergence. To examine the temporal persistence of the digital dividend and mitigate potential contemporaneous reverse causality, the baseline model is re-estimated using the one-period lagged variable ($Lag_Internet$). As shown in Column (2) of Table 4, the coefficient of $Lag_Internet$ remains significantly negative. This indicates that the convergence effect of digital infrastructure on the urban–rural income gap is highly robust and continuous over time.

3.3. Heterogeneity Analysis

Table 5. North-South Heterogeneity Grouped Regression Results

Group	Variable	B	Std. Error	t	VIF
Northern Region	Year***	-0.165	0.035	-4.699	3.194
	Internet***	3.062	0.846	3.618	3.194
Southern Region	Year***	0.08	0.015	5.393	2.058
	Internet***	-3.752	0.307	-12.219	2.058

Notes: * p<0.1, ** p<0.05, *** p<0.01. F-test for group differences confirms that the North-South asymmetry is statistically significant at the 1% level.

As show in the Table 5, to capture spatial heterogeneity, this study conducts a sub-sample analysis based on the traditional geographical dividing line of the Qinling Mountains and the Huaihe River. Following this standard, the 31 provinces are classified into two regions. The Northern Region includes Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. The Southern Region includes Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, and Tibet. As shown in the Table 5, the results reveal pronounced asymmetry between these two regions. Results in the Table 5 reveal pronounced asymmetry. In the South, digital infrastructure exhibits a clear convergence effect: supported by a vibrant private sector and high marketization, digital technologies penetrate agricultural value chains, enabling farmers to share in value-added gains.

In contrast, in the North, the coefficient shifts markedly. Amid a transition from heavy industry, digital infrastructure tends to widen disparities in the short term. Urban high-skilled groups capture most digital dividends, while low-skilled rural labor faces marginalization. This divergence not only supports Hypothesis 2 but also underscores the urgency of mitigating the digital divide in northern regions.

3.4. Endogeneity and Instrumental Variable Selection

Table 6. Results of Two-Stage Regression Analysis

Variables	Stage 1		Stage 2	
	Coefficient	Std. Error	Coefficient	Std. Error
Constant	-3.41	2.243	3.389	11.417
Lag_ Internet	0.966***	0.025	—	—
Internet	—	—	-1.392***	0.486
Ln GDP	-0.002	0.005	0.038*	0.023
Edu	0	0.002	-0.009	0.009
Ln Gov	-0.005***	0.002	-0.007	0.009
Year	0.002	0.001	-0.002	0.006
Province_ ID	-0.00001	0.00000	0.00006	0.00000
R^2	0.966		0.317	
Adjusted R^2	0.965		0.29	
F-statistic	701.824***		11.473***	

Durbin-Watson	1.62	0.426
Observations	155	155

Notes: * p<0.1, ** p<0.05, *** p<0.01. In Stage 2, "Internet" refers to the instrumented values from the first stage.

As show in the Table 6, to address potential endogeneity from reverse causality, this study employs a Two-Stage Least Squares approach using the one-period lagged internet penetration rate as an instrumental variable. This IV satisfies the relevance condition due to the path-dependent nature of infrastructure development and meets the exogeneity requirement as a predetermined variable unaffected by current income gap fluctuations. The empirical results confirm the validity of the IV. The first-stage F-statistic of 701.824 rules out weak instrument concerns. In the second stage, the coefficient of digital infrastructure remains significantly negative, reinforcing the baseline finding that digital expansion robustly narrows the urban-rural income gap even after controlling for endogeneity.

4. Conclusion

Using panel data from 31 Chinese provinces, this study finds that the impact of digital infrastructure on the urban–rural income gap is significantly heterogeneous and strongly conditioned by regional economic endowments. Although a nationwide "digital dividend" convergence effect is observed, pronounced North–South disparities indicate that the benefits of digitalization are unevenly distributed, necessitating differentiated policy responses across regions.

First, the prevailing policy emphasis on "construction over application" in digital village development should be adjusted. In northern regions, priority should be given to preventing technological polarization through "inclusive digital adaptation." This requires increased fiscal investment in rural basic education and vocational training to enhance digital literacy and operational skills, thereby reducing the risk of labor displacement caused by automation and digital substitution.

Second, in southern regions, policy should shift from expanding consumer-side digital access toward deeper industrial integration. By strengthening data linkages between platform enterprises and local agricultural sectors, more equitable value-sharing mechanisms can be established, enabling rural populations to move beyond low-end labor participation and engage more fully in digital value creation across industrial chains.

Third, at the national level, an inclusive institutional framework should be established. Targeted broadband and network fee subsidies for remote rural areas, combined with dynamic monitoring systems for digital poverty, can ensure that digital transformation contributes to more balanced regional development and supports the long-term goal of common prosperity.

Finally, this study has certain limitations that point toward future research directions. Due to macro-level data availability, the current analysis relies on provincial-level panel data, which may mask more granular intra-provincial disparities between specific counties or villages. Future research could utilize individual- or household-level micro-data to explore the mechanisms of digital inclusion more deeply. Additionally, examining the specific impacts of emerging digital technologies, such as artificial intelligence and agricultural Internet of Things, on rural labor markets remains a promising avenue for subsequent investigation.

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Section 4

Interdisciplinary Field of Modern Management and Big Data

Modern Management based on Big Data VII
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Correlation Power Analysis on SLH-DSA Algorithm

Yang CAO [a], Jun LI[b], Zhibo DU[a] [1], Kang YANG[b] and Huixin LI[b]
[a] *School of Cybersecurity, Chengdu University of Information Technology, Chengdu 610225, China*
[b] *System of Systems and Artificial Intelligence Laboratory, AVIC Chengdu Aircraft Design & Research Institute, Chengdu 610041, China*

Abstract. To address potential side-channel security vulnerabilities in the implementation of stateless hash-based digital signature algorithms, this paper proposes a Correlation Power Analysis attack method targeting SLH-DSA. The method selects the private key parameter SK.prf as the attack target and analyzes the random number generation function within the SLH-DSA signature process. Through data flow analysis of the private key during the function's operation, the execution phase of the permutation function in the underlying SHAKE256 hash is identified as the sensitive information leakage point. Consequently, the parity checksum of the permutation function is chosen as the intermediate variable for the power analysis attack. On this basis, a power leakage model is constructed using the Hamming Weight model. By utilizing the Pearson correlation coefficient to analyze the linear correlation between hypothetical and actual power consumption, the side-channel power analysis of the private key parameter SK.prf is achieved. The proposed attack method is initially validated through simulation experiments. The simulation results indicate that the secret key can potentially be recovered using a small number of power traces, demonstrating the theoretical feasibility of the method. However, further empirical research is required to verify the actual effectiveness of this attack in real-world physical implementations.

Keywords. Post-quantum cryptography, SLH-DSA algorithm, Side-channel analysis, Correlation power analysis

1. Introduction

With the rapid advancement of quantum computing, traditional public-key cryptosyste ms face severe threats from quantum algorithms, notably Shor's [1] algorithm. Consequ ently, the standardization of Post-Quantum Cryptography (PQC) has emerged as a glob al priority. The Stateless Hash-Based Digital Signature Algorithm (SLH-DSA [2]), rece ntly finalized by NIST [3], is renowned for its high quantum robustness. Its security con servatively relies on the well-understood properties of underlying hash functions rather than complex mathematical assumptions.

However, despite their mathematical security, the physical implementations of cryptographic algorithms inevitably leak side-channel information, such as power consumption [4] and electromagnetic radiation. Stateless hash-based schemes warrant specific and urgent side-channel investigation because their signature generation

[1] Corresponding author: duzb@cuit.edu.cn

processes heavily rely on symmetric primitives, particularly the SHAKE256 extendable-output function. During these operations, the private key and sensitive intermediate variables are manipulated directly within the hardware or software execution state, making them highly susceptible to power analysis attacks on embedded devices. Therefore, evaluating the physical implementation security of SLH-DSA is a critical prerequisite for its secure practical deployment.

Despite this risk, a significant gap exists in PQC side-channel evaluations. Current research predominantly focuses on lattice-based schemes (e.g., ML-KEM, ML-DSA) [5-10], exploiting lattice-specific operations such as polynomial multiplication and rejection sampling. Conversely, physical security analyses of stateless hash-based signatures remain scarce, largely confined to fault injection attacks against SPHINCS+ or basic differential power analysis on older stateful schemes like XMSS [11-13]. Although potential leakage in SPHINCS+ has been noted, a systematic Correlation Power Analysis targeting the key derivation and pseudorandom number generation mechanisms of the newly standardized SLH-DSA is notably absent.

To address this gap, we propose a Correlation Power Analysis on SLH-DSA that recovers the private key $SK.prf$ by exploiting the SHAKE256 permutation's parity checksum during pseudorandom number generation. Using a Hamming weight model and Pearson correlation, our simulations validate the attack's theoretical feasibility, highlighting the urgent need for robust side-channel countermeasures in physical deployments.

2. Preliminaries

2.1. SLH-DSA Algorithm Description

Derived from the SPHINCS+ scheme, SLH-DSA utilizes a multi-layer tree structure—integrating the Forest of Random Subsets, WOTS+, and a hypertree—to balance signature size and computational efficiency. During signing, the pseudorandom number R is generated via the PRF_{msg} function (Equation (1)). This function invokes SHAKE256 to hash the concatenated private key $SK.prf$, public key $PK.seed$, and message M, producing an $8n$-bit output, where n is a parameter-specific length.

$$\begin{aligned} R &= PRF_{msg}(SK.prf, PK.seed, M) \\ &= SHAKE256(SK.prf \,||\, PK.seed \,||\, M, 8n) \end{aligned} \tag{1}$$

2.2. SHAKE256 Algorithm Description

SHAKE256[14] , utilized for pseudorandom number generation in SLH-DSA, employs a sponge construction based on the Keccak-f[1600] permutation. Its 1600-bit internal state S is modeled as a $5 \times 5 \times 64$ matrix $A[x, y, z]$ (Figure 1). Operating at a bitrate of $r = 1088$ bits, it absorbs and squeezes data by applying the permutation to each block. Following the FIPS 202 standard, we define the state's fundamental data units: a Lane (denoted as $Lane(x, y)$) represents a 64-bit word along the z-axis; a Row represents 5 bits along the x-axis; and a Column represents 5 bits along the y-axis.

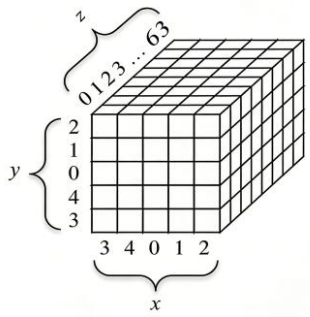


Figure 1. The internal state S of Keccak-f[1600].

2.3. CPA Attack

Correlation Power Analysis [15] was proposed by Brier et al. in 2004. It is a side-channel analysis method based on statistical principles. Its core idea is to utilize the correlation between the power consumption of a device executing a cryptographic algorithm and its internal data. By statistically analyzing the power traces of multiple encryption operations, it recovers sensitive data such as secret keys.

3. CPA Attack on SLH-DSA

3.1. Analysis

SLH-DSA heavily relies on the SHAKE256 hash function for critical operations, including key derivation, message digestion, and pseudorandom number generation. To inject essential randomness into the signature, the PRF_{msg} function (Equation (1)) generates the randomizer R by padding and directly absorbing the private key $SK.prf$, public key $PK.seed$, and message M into the SHAKE256 sponge construction.

Because SHAKE256's bitrate r exceeds the combined length of the keys, the first message block fully absorbs $SK.prf$, $PK.seed$, and the beginning of M. The concatenated input stream maps sequentially into the state matrix $A[x, y]$ along the x-axis. Consequently, the 16-byte $SK.prf$ exactly fills $Lane(0,0)$ and $Lane(1,0)$, the 16-byte $PK.seed$ occupies $Lane(2,0)$, $Lane(3,0)$ and M starts at $Lane(4,0)$.

During the first Keccak-f[1600] round's θ step, the parity checksum $C[0]$ is computed (Equation (2)) by XORing $A[0,0]$ (bytes 0–7 of $SK.prf$), $A[0,1]$ (bytes 8–15 of M), and three padding constants ($A[0,2]$ to $A[0,4]$). Consequently, this intermediate variable $C[0]$ directly captures the cryptographic interaction between the secret $SK.prf$ and the known message M.

$$C[0] = A[0,0] \oplus A[0,1] \oplus A[0,2] \oplus A[0,3] \oplus A[0,4] \quad (2)$$

To accurately model physical leakage, we trace CMOS dynamic power to state transitions in data buses and registers. Although the Hamming Distance model rigorously captures these bit flips, unpredictable or zero-cleared prior hardware states in software implementations practically reduce it to the Hamming Weight model. During the Keccak-f[1600] permutation, load operations frequently transfer the checksum $C[x]$ across the data bus. Because the associated power consumption strongly correlates with

the number of active high bits, utilizing the HW of $C[x]$ provides a robust, physically grounded approximation for our leakage model.

3.2. Attack Method

Based on the analysis, the CPA algorithm is designed as follows:

- Fix the target keys ($SK.prf$, $PK.seed$) and execute N SLH-DSA signatures using randomly varying messages M_i. Concurrently, collect the power traces $T_i(t)$ during the PRF_{msg} execution, where i and t denote the trace index and time sample, respectively.
- Target the index-th byte of $SK.prf$. Initialize $index = 0$, with the range of index being [0, 15].
- Synchronously traverse all possible values sk for each byte dimension of $SK.prf$, where the range of sk is [0, 255]. Fill the traversed $SK.prf$, $PK.seed$, and message M_i into the internal state matrix $A[x, y]$ of Keccak-f[1600], where $x \in \{0, \dots, 4\}$ and $y \in \{0, \dots, 4\}$.
- Select the θ step of the first round of the SHAKE256 permutation function Keccak-f[1600] as the sensitive leakage point. Calculate the parity checksum $C[x]$ during the θ step calculation process. The calculation of $C[x]$ is shown in Equation (3), where $x = index // 8$.

$$C[x] = A[x, 0] \oplus A[x, 1] \oplus A[x, 2] \oplus A[x, 3] \oplus A[x, 4] \tag{3}$$

- If $index < 8$, select the index-th byte of $C[x]$ as the intermediate variable for the attack; if index ≥ 8, select the (index - 8)-th byte of $C[x]$ as the intermediate variable. The Hamming Weight (HW) model is selected as the power model. Calculate the hypothetical power$H_{\mathrm{i,sk}} = HW(C[x])$.
- For each guessed key sk, calculate the correlation [16] coefficient between its hypothetical power vector $\mathrm{H_{i,sk}}$ and the real power trace matrix $\mathrm{T_i(t)}$ according to Equation (4), where $\overline{\mathrm{H}}$ and $\overline{\mathrm{T}}$ represent the sample means of the hypothetical power and real power, respectively.

$$\rho(sk) = \frac{\sum_{i=1}^{N}\left(H_{i,sk} - \bar{H}\right)(T_i - \bar{T})}{\sqrt{\sum_{i=1}^{N}\left(H_{i,sk} - \bar{H}\right)^2}\sqrt{\sum_{i=1}^{N}(T_i - \bar{T})^2}} \tag{4}$$

- The guessed key sk corresponding to the maximum correlation coefficient is identified as the attack result for the index-th byte of $SK.prf$.
- Increment $index$ and jump to Step 2 to continue the attack until all bytes of $SK.prf$ are recovered.

4. CPA Attack Experiment on SLH-DSA

To verify the effectiveness of the attack scheme proposed in this paper, a side-channel simulation experiment was conducted to recover $SK.prf$. A Python-based simulation program was employed to simulate the target device executing the PRF_{msg} function. The target key was set to 0x76277d47aae8c2b7af328cea0c805c41, and Gaussian noise was introduced to simulate measurement noise in a real-world environment.

4.1. Attack Experiment

Applying the proposed CPA algorithm to 50 simulated traces, we first targeted byte 0 of $SK.prf$. Calculating the Pearson correlation across all 256 byte candidates ($sk_{guess} \in \{0, \ldots, 255\}$) revealed a distinct global maximum of $\rho = 0.8964$ for $sk_{guess} = 0x76$ (Figure 2). This prominent peak significantly exceeds the correlations of all incorrect candidates, confirming the successful recovery of the target byte.

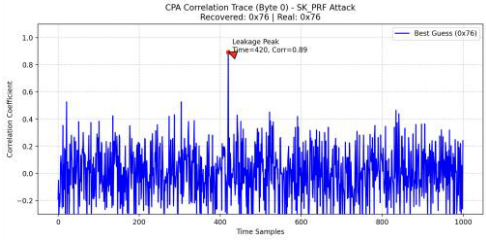


Figure 2. Correlation Power Trace for Byte 0.

4.2. Analysis of Attack Experiment Results

As shown in Table 1, the remaining key bytes were attacked sequentially, and the recovered key matches the original private key $SK.prf$ preset in the experiment. The experimental results demonstrate that the Hamming weight leakage model constructed in this paper can accurately reflect the internal power characteristics of the algorithm, verifying that the proposed attack method is feasible and effective.

Table 1. Correct guess values for each byte and their corresponding correlation coefficients

Byte	Guess value	Correlation coefficient	Rank
0	0x76	0.8964	1
1	0x27	0.8569	1
2	0x7d	0.7981	1
3	0x47	0.8046	1
4	0xaa	0.8976	1
5	0xe8	0.8526	1
6	0xc2	0.9151	1
7	0xb7	0.9111	1
8	0xaf	0.8634	1
9	0x32	0.8773	1
10	0x8c	0.8730	1
11	0xea	0.8880	1
12	0x0c	0.8642	1
13	0x80	0.7858	1
14	0x5c	0.8617	1
15	0x41	0.8471	1

5. Conclusion

This paper proposes a Correlation Power Analysis attack targeting the private key $SK.prf$ during the pseudorandom number generation process of SLH-DSA. By analyzing the data flow, we identify the underlying SHAKE256 permutation phase as the primary leakage source and exploit its parity checksum as the intermediate variable. By utilizing a Hamming Weight leakage model and Pearson correlation, simulation

results demonstrate that $SK.prf$ can be recovered with a small number of power traces, validating the theoretical feasibility of the attack. However, as these findings are simulation-based, the actual effectiveness in real-world physical implementations requires further empirical verification. Ultimately, this study provides a theoretical basis for SLH-DSA side-channel evaluation and highlights the critical need for future hardware-based testing and robust countermeasure development.

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Research on Non-Metallic Gas Pipeline Detection Technology Based on Acoustic Wave Reflection

Yonglong Yang[a,1], Hui Ye[a], Haitao Yan[a], Zhao Le[a], Zhongsheng Yang[a] and Kaifeng Wu[a]
[a]*CCCC Second Highway Consultants Co., Ltd., Wuhan 430056, China*

Abstract: To address the challenge of accurately locating non-metallic gas pipelines, a detection method based on acoustic reflection principles is proposed in this paper. Initially, pulsed acoustic waves are generated near the pipeline valve and are captured by three high-sensitivity sensors deployed on the ground surface. Based on this, a soil-pipeline coupled theoretical model is established, utilizing the same observation system to simulate the acoustic wave propagation process and generate theoretical signals. The pipeline burial depth in the model is iteratively adjusted, and the cross-correlation value between the actual and theoretical signals is computed until it reaches its maximum, thereby determining the pipeline burial depth that most closely approximates the actual depth. Subsequently, based on the optimized theoretical model, forward wavefields are simulated using pulsed signals and reverse wavefields are simulated using actual recorded signals. Normalized cross-correlation is then applied under imaging conditions to ultimately obtain a spatial imaging profile of the pipeline. Tests conducted on an actual pipeline detection project in Jiangxia District, Wuhan, demonstrate that the pipeline burial depth inverted by the proposed method shows good agreement with actual excavation results, with depth deviations falling within an acceptable range. This verifies that the method possesses high detection accuracy and strong engineering applicability.

Keywords: Non-metallic Gas Pipelines, Acoustic Reflection, Cross-correlation

1. Introduction

Polyethylene (PE) pipes were widely adopted as the preferred material for medium- and low-pressure urban gas distribution systems due to their advantages in easy installation, strong corrosion resistance, and excellent environmental performance. However, it was found that most early installed PE pipelines lacked complete as-built documentation, or their surface reference markers were altered over time, making the accurate spatial positioning of underground pipelines difficult to obtain [1]. This situation not only created significant challenges for municipal construction projects and gas utility operations but also posed serious threats to urban public safety [2,3]. As traditional excavation methods were proven to be inefficient and costly, the development of rapid, accurate, and convenient PE pipeline detection technologies was recognized as a critical issue to be addressed. From a technical development

[1] Corresponding author: Yonglong Yang, E-mail: Yoonlong@126.com

perspective, detection methods for underground metal pipelines were well established, with mainstream technologies like electromagnetic induction and ground-penetrating radar being effectively used for metal pipeline localization [4]. However, due to PE material's non-conductive and non-magnetic properties, traditional electromagnetic-based detection equipment was rendered completely ineffective, which became the major technical bottleneck restricting accurate detection of non-metallic gas pipeline networks.

In recent years, with the rapid advancement of urbanization in China, gas pipeline damage accidents caused by third-party construction were observed to show a high incidence trend [5]. These incidents not only caused significant casualties and property losses, but also triggered serious public safety concerns, making precise detection technology for non-metallic gas pipelines become a key research focus in the geophysical exploration field. Through systematic experiments, Xiong Junnan et al. established the optimal parameter range for ground-penetrating radar in detecting PE pipelines, demonstrating that ideal detection results were obtained when the ratio of pipe diameter to burial depth exceeded 0.1[6]. The magnetic gradient method innovatively applied by Bai Xuefeng effectively addressed the positioning challenges of deeply buried pipelines [7]. However, all existing detection technologies were found to have significant engineering applicability limitations [8-10]. The ground-penetrating radar method was constrained by requirements for surface flatness and electromagnetic environment, making it difficult to ensure detection accuracy in complex pipeline network areas [11]. The electromagnetic induction method was only applicable to specific working conditions with pre-buried tracer wires. The magnetic gradient method had anti-interference advantages, it suffered from defects including incomplete theoretical framework and low construction efficiency [12]. Although acoustic vibration methods can detect the planar location of pipelines, their accuracy in depth detection is low [13-15]. These technical bottlenecks were recognized as severely restricting the safety management level of urban underground gas networks, highlighting the urgent need to develop more universal new detection methods.

To address the aforementioned technical challenges, a non-metallic gas pipeline detection method based on acoustic reflection was proposed in this study. The advantages of this method were demonstrated by its ability to achieve non-destructive inspection during pipeline operation. Compared with the traditional ground-penetrating radar method, detection efficiency was significantly improved, and operational costs were substantially reduced by this approach. To validate the practical value of this technology, an engineering verification was conducted by the research team based on a PE gas pipeline detection project in Jiangxia District, Wuhan. Practical application confirmed that the acoustic vibration detection method could accurately identify the spatial position of non-metallic PE gas pipelines. Excavation verification further proved that its positioning accuracy fully met engineering requirements, demonstrating the reliability and applicability of both the method and its supporting equipment in real-world engineering environments.

2. Method

After the acoustic wave was excited by the source, it propagated through the soil and reached the surface of the PE pipeline. It was then reflected by the pipeline surface, propagated again through the soil to reach the ground surface, and was finally captured

by acoustic sensors placed on the surface. To investigate this process, numerical simulation was conducted in this study using the finite-difference method. This method replaces the temporal and spatial partial differential operators in the acoustic wave equation with finite differences, and then iteratively solves the discretized acoustic wave equation to achieve numerical simulation of the wave equation. The first-order velocity-stress acoustic wave equations are as follows:

$$\frac{\partial p}{\partial t} = -\rho v^2 \left(\frac{\partial v_x}{\partial x} + \frac{\partial v_z}{\partial z}\right) \tag{1}$$

$$\frac{\partial v_x}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{2}$$

$$\frac{\partial v_z}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} \tag{3}$$

Where ρ is the density of the medium, v is the compressional wave velocity in the medium, v_x and v_z are the particle vibration velocities in the medium, and p is the stress wave field. After applying Taylor expansion, the finite-difference scheme of the above equations is obtained as follows:

$$\begin{aligned} v_x^{n-\frac{1}{2}}\left(i+\frac{1}{2},j\right) = v_x^{n+\frac{1}{2}}\left(i+\frac{1}{2},j\right) + \\ \frac{1}{\rho}\frac{\Delta t}{\Delta x}\sum_{k=1}^{N} D_k^{(N)}\left[p^n\left(i+k,j\right) - p^n\left(i-k+1,j\right)\right] \end{aligned} \tag{4}$$

$$\begin{aligned} v_z^{n-\frac{1}{2}}\left(i,j+\frac{1}{2}\right) = v_z^{n+\frac{1}{2}}\left(i,j+\frac{1}{2}\right) + \\ \frac{1}{\rho}\frac{\Delta t}{\Delta z}\sum_{k=1}^{N} D_k^{(N)}\left[p^n\left(i,j+k\right) - p^n\left(i,j-k+1\right)\right] \end{aligned} \tag{5}$$

$$\begin{aligned} p_{i,j}^{n-1} = p_{i,j}^{n} + \rho v^2 \frac{\Delta t}{\Delta x}\sum_{k=1}^{N} D_k^{(N)}\left[v_x^{n-\frac{1}{2}}\left(i+\frac{1}{2}+k,j\right) - v_x^{n-\frac{1}{2}}\left(i+\frac{1}{2}-k,j\right)\right] + \\ \rho v^2 \frac{\Delta t}{\Delta z}\sum_{k=1}^{N} D_k^{(N)}\left[v_z^{n-\frac{1}{2}}\left(i,j+\frac{1}{2}+k\right) - v_z^{n-\frac{1}{2}}\left(i,j+\frac{1}{2}-k\right)\right] \end{aligned} \tag{6}$$

Where Δx and Δz are the spatial step sizes in the x- and z-directions, respectively, Δt is the time step size, $2*N$ is the order of the finite difference, n is the discrete time index, and $D_k^{(N)}$ is the finite-difference coefficients. In the forward modeling of seismic waves using the wave equation, excitation can be applied not only on the velocity components but also on the stress components.

A model M_0 is established to simulate the actual formation-pipeline system, with the pipeline depth denoted as h_0, serving as an accurate reference for computation. And In the numerical simulation, the upper boundary of the model was set as a free boundary, while the left, right, and lower boundaries were set as absorbing boundaries. Acoustic signals are excited on the surface of model M_0 and collected at positions x_0, x_1 and x_2, which are recorded as the actual acoustic traces $rec_0(t), rec_1(t), rec_2(t)$. A pipeline-soil computational model M_1 is then constructed. Acoustic signals are excited and collected at fixed distances x_0, x_1 and x_2 on the model surface, recorded as $R_0^1(t)$, $R_1^1(t)$ and $R_2^1(t)$. The acoustic signals received are cross-correlated, denoted as:

$$f^1 = \sum_{i=0}^{2} \int_0^T rec_i(t) R_i^1(t) dt \tag{7}$$

Here, $rec_i(t)$ denotes the received signal at the receiver point x_i on the surface of model M_0, $R_i^1(t)$ represents the received signal at the receiver point x_i on the surface of model M_1, t denotes time, and T denotes the maximum recording time. A model M_2 was obtained by updating the pipeline depth of model M_1 to h_2. With T being the total computation time, the above steps were repeated to acquire the acoustic signals on the surface of model M_2, which were recorded as $R_0^2(t)$, $R_1^2(t)$ and $R_2^2(t)$. The corresponding cross-correlation result was then obtained. Through repeated iterations and modifications to the model depth, the pipeline depth h was traversed within the range [0, H], where H was the actual maximum possible burial depth. For the k-th iteration, the surface recordings $R_0^k(t)$, $R_1^k(t)$ and $R_2^k(t)$ were recorded, along with their cross-correlation result with the actual acoustic recordings as follow:

$$f^k = \sum_{i=0}^{2} \int_0^T \mathrm{rec}_i(t) R_i^k(t) dt \tag{8}$$

Here, $rec_i(t)$ denotes the received signal at the receiver point x_i on the surface of model M_0, $R_i^k(t)$ represents the received signal at the receiver point x_i on the surface of model M_k, t denotes time, and T denotes the maximum recording time. When the cross-correlation result reached its maximum, the corresponding model M_k was recorded.

Then, a numerical simulation was conducted based on model M_k, and its forward wavefield was denoted as $P(x,z,t)$. The surface-acquired acoustic records were then used as sources to reconstruct the wavefield $P'(x,z,t)$ based on model M_k. The imaging profile $I(x,z)$ of the actual pipeline was finally obtained by cross-correlating the forward wavefield $P(x,z,t)$ with the reconstructed wavefield $P'(x,z,t)$ as follow:

$$I(x,z) = \int_0^T \frac{P(x,z,t)P'(x,z,t)}{P^2(x,z,t)}dt \quad (9)$$

3. Numerical Example

To verify the accuracy of the algorithm, a theoretical pipeline-soil model M_0 and a computational pipeline-soil model M_1 were established in this study. Both models were constructed using a regular grid of 50 × 50 with a grid spacing of 0.1 m. In model M_1, the initial burial depth of the pipeline was set to 0.6 m, while in model M_0, the pipeline depth was fixed at 2.5 m to provide a standard reference signal. The specific validation procedure was as follows: First, an identical acoustic signal was excited at the coordinate (1.0 m, 0m) in both models, and three receivers were placed along the horizontal ground surface at (3.0 m, 0m), (4.0 m, 0m), and (5.0 m, 0m) to synchronously record the reflected signals. Second, the time-domain signals collected from M_0 and M_1 at each receiver were cross-correlated to obtain a sequence of cross-correlation functions. These functions were then superimposed according to receiver positions to form an integrated comparison curve. When the superimposed cross-correlation function reached an extremum, it was determined that the pipeline position in the current M_1 model was closest to that in the theoretical model M_0. At this point, the pipeline depth parameter in M_1 was updated, and the next iteration was initiated.

Based on the above procedure, the reflected wavefields were sequentially simulated for three working conditions with pipeline depths of 1.5 m, 2.0 m, and 2.5 m, respectively. As shown in figure 1, the corresponding acoustic imaging profiles for each condition were obtained, clearly reflecting the imaging characteristics of the pipeline-reflected signals under different burial depths. These results verified the effectiveness and reliability of the proposed algorithm in terms of spatial localization and imaging.

Table 1. The soil and PE pipe material physical property parameters

Material	Density (kg/m^3)	p-wave velocities (m/s)
soil	2000	236.36
PE pipe	900	2182.2

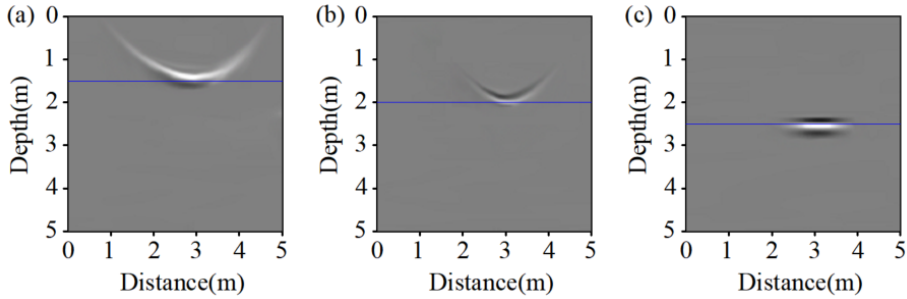


Figure 1. Imaging profiles of the computational model:a) Pipeline depth h = 1.5 m;b) Pipeline depth h = 2.0 m;c) Pipeline depth h = 2.5 m.

As can be observed from figure 1, when the pipeline depth in the computational model was set to 1.5 m, the significant discrepancy compared with the theoretical model depth (2.5 m) resulted in the failure of acoustic waves to focus effectively, and the reflected energy did not converge. This was manifested in the imaging profile as a broad, gentle arc-shaped response diffused along the acoustic propagation path, lacking distinct localization features. As the pipeline depth in the computational model was updated to 2.0 m, the difference from the theoretical model depth was reduced. The reflected energy began to converge toward the pipeline position, leading to a noticeable contraction of the arc-shaped response range in the imaging profile. The energy concentration was improved, and the phase axis became clearer, although some degree of diffusion remained. When the pipeline depth in the computational model was finally iterated to exactly match that of the theoretical model, the reflected energy reached its optimal convergence state. In the imaging profile, the energy was highly focused at the actual pipeline location, forming a clear and continuous phase axis that accurately delineated the geometric shape and spatial distribution of the pipeline. This result not only verified the convergence of the algorithm during parameter optimization but also demonstrated the reliable spatial localization and imaging capability of the proposed method.

4. Field data

To validate the accuracy of the algorithm, this study relied on the company's pipeline detection project for field verification. The project site was located in Jiangxia District, Wuhan City, where all the gas pipelines within the work area were made of PE material, buried at a depth of approximately 1.5–2.0 m, and no tracer lines had been pre-installed. In order to accurately detect the spatial distribution of the gas pipelines in this area, the independently developed CSPD-21 gas pipeline detection instrument (see Figure 2) was utilized. Acoustic signals were generated at the gas valve, and the reflected signals were collected at multiple points using acoustic sensors. After processing with the algorithm proposed in this paper, the imaging profile was ultimately obtained.



Figure 2. CSPD-21 gas pipeline detection instrument

The partial area imaging results from this detection were shown in figure 3, with an imaging range of 10 m × 3 m. As can be seen from the figure, due to the presence of heterogeneous overburden and medium disturbance above the pipeline, numerous diffraction arcs and spurious signals were generated in the imaging profile. These

interferences primarily originated from the uneven compaction of the overlying soil layer, which caused discrepancies between the equivalent wave velocity used in modeling and the actual formation wave velocity, thereby leading to wavefield distortion during the imaging process. Nevertheless, near the actual burial location of the pipeline, the cross-correlation function between the measured data and theoretically calculated data reached its maximum value here, enabling the energy contributed by the pipeline-reflected wave during imaging to significantly exceed the interference background. Consequently, the pipeline target could still be clearly imaged, with its spatial morphology and alignment accurately presented. According to the profile, the pipeline was mainly buried at depths between 1.5 m and 2.0 m, extending in a continuous linear pattern, which was consistent with the actual installation conditions.

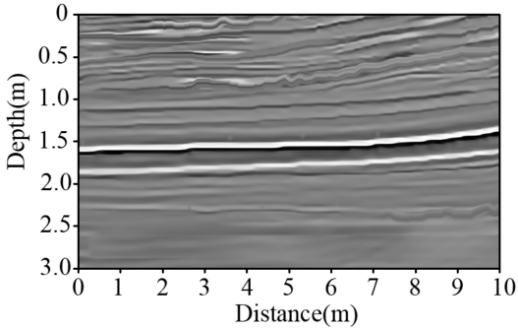


Figure 3. Pipeline Detection Imaging Profile

To validate the accuracy of the detection results, two typical locations at 2.0 m and 6.0 m from the starting point of the survey line were selected for excavation verification within the experimental area. The on-site excavation scenario is illustrated in figure 4. After field measurements using a tape measure, the actual burial depth of the pipeline at the 2.0 m location was determined to be 1.8 m, while the imaging depth corresponding to the algorithm proposed in this paper was approximately 1.7 m. At the 6.0 m location, the actual burial depth of the pipeline was measured as 1.6 m, with the corresponding imaging depth being about 1.5 m. According to the industry standard "Technical specification for urban underground pipeline detection and survey" (CJJ61-2017), the allowable error in the burial depth detection of concealed pipelines was required to be no greater than 7.5%. The results obtained from this detection were evaluated and confirmed to meet this accuracy requirement. The results indicate that the relative errors between the imaging depths and the measured burial depths were all within an acceptable range, with both trends and values showing general consistency. This comparative outcome effectively verifies the detection accuracy and reliability of the proposed algorithm in practical engineering environments, demonstrating its favorable applicability for spatial positioning of non-metallic pipelines.



Figure 4. On-site excavation photos: a) at 2.0 m; b) at 6.0 m.

5. Conclusion

In this paper, a non-metallic gas pipeline detection method based on acoustic reflection is proposed. Acoustic pulse signals are first excited near the pipeline valve, and three highly sensitive acoustic sensors are deployed on the ground to collect the acoustic signals. Subsequently, a coupled soil–pipeline model is established, and the same observation system is employed to simulate the excitation and reception of acoustic waves, from which theoretical acoustic signals are obtained. The cross-correlation between the actually acquired signals and the theoretical signals is calculated, and the pipeline burial depth in the theoretical model is iteratively updated. This procedure is repeated until the cross-correlation reaches its maximum, at which point the pipeline depth in the theoretical model is closest to the actual depth. Based on the final iterated model, wave-field imaging is further performed: the forward propagating wave-field is simulated using the pulse signal as the source, and the backward propagating wave-field is simulated using the actually recorded acoustic signals as the source. The two wave-fields are then subjected to normalized cross-correlation according to the imaging condition, thereby yielding a spatial imaging profile of the pipeline. To verify the effectiveness of the method, field tests were carried out in combination with a pipeline detection project in Jiangxia District, Wuhan. It was demonstrated by the excavation verification results that the errors between the pipeline burial depths calculated by the algorithm presented in this paper and the actual burial depths were all less than 7.5%. This was found to comply with the requirements of the industry standard “Technical specification for urban underground pipeline detection and survey” (CJJ61-2017). It was concluded that the proposed method possesses good engineering applicability and detection accuracy. The CSPD-21 gas detection equipment was demonstrated to be capable of accurately locating the spatial distribution of PE gas pipelines. However, its applicability was found to remain limited under complex working conditions, such as those characterized by greater burial depths (exceeding 10 meters), loose and porous overlying strata, or the absence of auxiliary gas wells. This limitation was primarily attributed to the difficulty in achieving effective penetration of acoustic energy through the overlying layers, which resulted in a significant reduction in detection accuracy. To further enhance the detection capability of the equipment in deep and complex strata, efforts will be focused on increasing the acoustic emission energy and optimizing sensor accuracy, aimed at achieving synchronous improvement in both detection depth and precision.

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A Grounded Theory Study on Cosmetic Adverse Event Surveillance in Chongqing

Yanyin Yang, Yingjie Liu, Qinghua Deng, Guangxiu Cao and Xiaohong Zheng[1]
Chongqing Medical and Pharmaceutical College, Chongqing, China

Abstract. *Objective:* To comprehensively understand the current development status of cosmetic adverse reaction monitoring in Chongqing, analyze potential issues, and propose targeted countermeasures to promote the sustainable and healthy development of the local cosmetic industry. *Methods:* Data were collected through literature review, expert interviews, and questionnaires. Statistical analysis was performed using SPSS 26, while qualitative data processing and theoretical construction were conducted using the classic grounded theory approach, enabling an in-depth grounded study of cosmetic adverse reaction monitoring in Chongqing. *Results and Conclusions:* The monitoring system in Chongqing faces challenges such as "top-suspended and bottom-blinded" "structural deficiencies, regulatory difficulties in emerging formats, and low reporting quantity and quality. To address these issues, we propose a "one-consolidation and three-reinforcements" regulatory framework and a "simplification-for-quality-and-efficiency" strategy to enhance the effectiveness of cosmetic adverse reaction monitoring.

Keywords. Grounded theory; Cosmetic adverse reaction monitoring; Chongqing

1. Introduction

Driven by socioeconomic development, consumption upgrades, and evolving aesthetic norms, the global cosmetics market has experienced exponential growth. Concurrently, cosmetic safety has emerged as a critical public health concern requiring international collaboration. Adverse reaction monitoring constitutes a critical safeguard for cosmetic safety [1]. Globally, the United States collects cosmetic adverse reactions through FDA's Voluntary Cosmetic Reporting Program (VCRP), but the lack of mandatory reporting requirements for enterprises leads to systemic loopholes in risk monitoring, resulting in severe underestimation of adverse reactions [2]. As a pioneer in cosmetic regulation, the European Union has established a monitoring network based on Regulation (EC) No 1223/2009, requiring that every cosmetic product sold in the EU market must have a clearly defined "Responsible Person" (usually manufacturers, importers or distributors

[1] Corresponding Author: Xiaohong Zheng, Chongqing Medical and Pharmaceutical College, China; Email: zxh10760@163.com.
First Author: Yanyin Yang, Chongqing Medical and Pharmaceutical College, China; Email: 383765857@qq.com
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within the EU). The Responsible Person serves as the primary accountable party for cosmetic safety and the core executor of adverse reaction monitoring and reporting. They must continuously monitor all adverse reactions and use this information for regular product safety assessments to proactively prevent risks [3]. Turkey, as a representative of emerging markets, established a cosmetovigilance system in 2012 by referencing EU Regulation (EC) No 1223/2009, requiring participation from medical institutions and manufacturers in adverse reaction reporting, with emphasis on systemic risk assessment. However, Turkish studies show that even with mandatory reporting systems in place, challenges remain such as insufficient attention from medical staff and low self-reporting rates among consumers [4]. China, as the world's second-largest cosmetic consumer market, In 2022, the National Medical Products Administration (NMPA) issued, for the first time, the Measures for the Administration of Cosmetic Adverse Reaction Monitoring (hereinafter referred to as "the Measures") [5], clarifying that cosmetic registrants and filers are the primary responsible parties for adverse reaction monitoring. This concept is highly similar to the EU's "Responsible Person" system, but China's late start means its current development status is similar to Turkey's. Currently, Chongqing has 35 cosmetic production enterprises [6]. Annual reports on cosmetic adverse reaction monitoring in Chongqing from 2020 to 2024 show that the number of reports originating from registrants, filers or production enterprises were: 0, 0, 1 (0.02%), 1 (0.01%), and 2 (0.01%) respectively [7]. In comparison, retrieved 2024 annual reports show that Hubei Province had 119 reports (1.0%) from registrants and filers [8], while Gansu Province had 56 reports (1.4%) [9]. These data not only reflect the relatively backward development level of Chongqing's cosmetic industry but also reveal the serious absence of responsible parties (registrants and filers) in cosmetic adverse reaction monitoring.

In the context of China's nationwide efforts to streamline administration and revitalize industries, post-market monitoring has become indispensable for regulatory oversight. A pressing challenge lies in synchronizing monitoring mechanisms with the dynamic evolution of the cosmetics sector while identifying pivotal risk control points. To address these challenges, this study adopts the classical grounded theory as the scientific qualitative methodology to conduct an in-depth investigation of cosmetic adverse reaction monitoring in Chongqing. By systematically analyzing existing issues and exploring innovative solutions, our research aims to contribute to the sustainable development of the local cosmetics industry.

2. Subjects and Methods

2.1 Survey Participants

This study employed a random sampling method to administer the questionnaire. To enhance the response rate and improve the sample representativeness of the target population, community personnel across various districts of Chongqing were invited through multiple channels, including phone calls and text messages, to disseminate and complete the questionnaire. The questionnaire consisted of both closed-ended and open-ended questions. The closed-ended questions were designed to assess participants' awareness of cosmetic adverse reaction monitoring and evaluate the current status of such monitoring in Chongqing. The open-ended questions were intended to collect participants' suggestions and recommendations for improving the monitoring system.

The questionnaire was primarily administered through the online platform Question Star, with a small portion of responses collected via WeChat or email.

The expert interview questionnaire was derived independently from the open-ended questions in the main survey. Two representatives from each of the following stakeholder groups—regulatory authorities, cosmetic registration/filing applicants, and dermatologists from medical institutions (serving as cosmetic adverse reaction monitoring and assessment bodies)—were invited for individual interviews. Each interview was conducted once and documented as interview transcripts.

2.2 Methodology

2.2.1 Questionnaire Design

The questionnaire was developed through multiple rounds of discussion among research team members and finalized by the principal investigator, containing three main components: basic demographic information of respondents, their awareness of cosmetic adverse reactions and potential issues in the monitoring system, as well as their suggestions for improving adverse reaction monitoring and industry development. All items were phrased neutrally, and an explicit statement of anonymity and data confidentiality was provided at the beginning of the questionnaire. Prior to formal distribution, a pilot test was conducted with a small sample (n=51), and ambiguous items were revised based on the feedback received.

2.2.2 Quality Control

After initial design, the questionnaire was refined through expert consultation to optimize content validity and feasibility, followed by systematic verification of response logic, completeness and accuracy during data collection.

2.3 Data Processing and Statistical Analysis

All collected data (including literature, questionnaires, and interview transcripts) underwent double-entry, dual-person verification and logic checks to exclude outliers. Basic characteristics of the collected information were described using percentages (%). Qualitative analysis of string-type variable data was performed through grounded theory coding. For the two multiple-choice items—”personal reporting channels for cosmetic adverse reactions” and “access pathways to cosmetic safety information”—which play key roles in specific measures, statistical analysis was conducted using SPSS 26, in alignment with the scientific research approach of grounded theory, to derive more fundamental insights.

3. Results and Analysis

3.1 Demographic Characteristics

The survey yielded 145 valid responses, with females representing 85.52% (n=124) of the total respondents. Distribution across age cohorts was as follows: 2.76% (n=4) aged

18 years or below, 62.07% (n=90) belonging to the 19-29 years category, 33.79% (n=49) within the 30-49 years range, and 1.38% (n=2) in the 50-59 years group. Occupation-based distribution analysis showed: 53.1% (n=77) from pharmaceutical/chemical sectors, 14.48% (n=21) from STEM disciplines, and 7.59% (n=11) representing humanities/arts backgrounds, while 24.83% (n=36) were classified under other professions. Educational attainment stratification demonstrated that 3.45% (n=5) completed high school education, 86.21% (n=125) held bachelor's degrees, 8.28% (n=12) had master's degrees, and 2.07% (n=3) possessed doctoral qualifications.

The collected interview transcripts—two from each of the three stakeholder groups (regulatory authorities, cosmetic registrants/filing agents, and dermatologists from medical institutions serving as cosmetic adverse reaction monitoring and assessment bodies), totaling six transcripts—were analyzed together with the qualitative data from the open-ended questions in the survey questionnaire and ten representative publications retrieved from the CNKI database using the search terms “Chongqing” , “cosmetics” and “adverse reactions” in the topic, keyword, and abstract fields. All these materials were subjected to grounded theory coding analysis.

3.2 Cosmetic Usage Patterns

Regarding the returned questionnaires, the frequency of cosmetic use and skin test habits, as well as the purchasing channels and receipt retention habits for cosmetics, are shown in Figure 1a-d, respectively. The data indicated that using cosmetics 0–2 times per week constituted the majority, while only 6.90% of respondents performed a skin test upon first use of a cosmetic product. 89.97% of purchases were made through e-commerce platforms, and 40.00% of respondents discarded receipts directly. Further analysis revealed that the behavior of performing skin tests and retaining outer packaging/receipts was largely independent of age group, gender, and educational level.

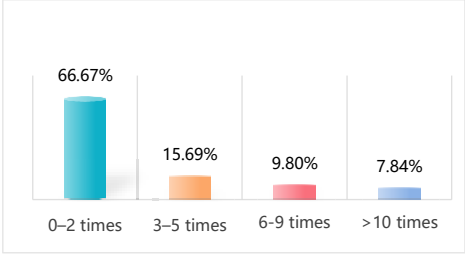


Figure 1a. Frequency of Cosmetic Use

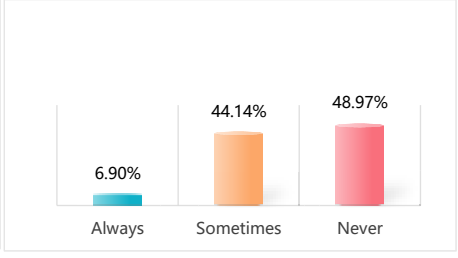


Figure 1b. Skin Test Practice upon First Cosmetic Use

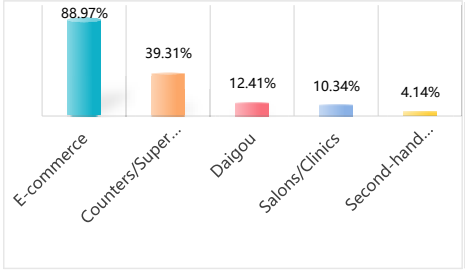


Figure 1c. Cosmetic Purchasing Channels

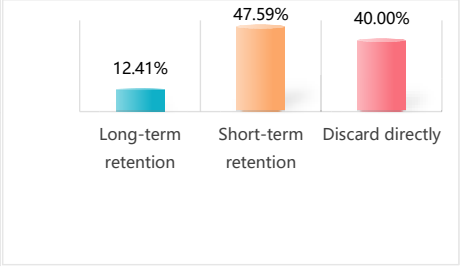


Figure 1d. Receipt Retention Practice for Cosmetics

3.3 Adverse Reaction Experiences

The experience of adverse reactions following cosmetic use and the corresponding management approaches are presented in Figure 2a and b, respectively. Data from the returned questionnaires indicated that slightly more than half of the respondents had experienced adverse reactions, and approximately half of those who experienced adverse reactions chose to seek medical treatment.

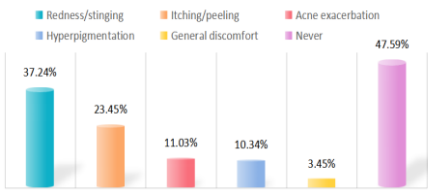


Figure 2a. Figure 2a Adverse Reaction Experience

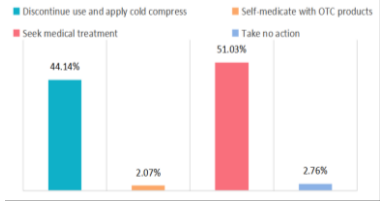


Figure 2b. Adverse Reaction Management

3.4 Monitoring Cognition Analysis

3.4.1 Cosmetic Definition Recognition

Product classification accuracy assessment across 12 common items revealed 22.1% (n=32) of respondents exhibited categorical confusion. Among participants attempting differentiation, 53.8% (n=78) and 29.7%(n=43) correctly identified disinfectant hand sanitizers and scar ointment as non-cosmetic, while misclassification occurred for anti-dandruff shampoo (36.6%, n=53), toothpaste (42.1%, n=61), facial cleanser (12.4%, n=18), perfume (11.7%, n=17), and whitening masks (6.2%, n=9).

3.4.2 Cosmetic Classification

The identification assessment for special-use cosmetics revealed categorical confusion in 20.7% (n=30) of respondents. Separately, 55.9% (n=81) and 61.4% (n=89) correctly identified hair dye and melasma treatment cream as special-use cosmetics, respectively. Meanwhile, depilatory cream, mascara, moisturizer, and regular lip balm were erroneously classified as special-use cosmetics by 60.0% (n=87), 18.6% (n=27), 11.7% (n=17), and 9.7% (n=14) of respondents, respectively.

3.4.3 Analysis of Awareness Regarding the Definition of Cosmetic Adverse Reactions and "the Measures"

Awareness regarding the implementation timeline and related specifics of the Measures was also found to be low. Analysis of the reasons for not reporting adverse reactions revealed that over 70% attributed it to unfamiliarity with the reporting procedure. Notably, nearly 85% of respondents considered it very necessary to conduct cosmetic safety education for the public. Specific data are presented in Table 1.

Table 1. Specific survey questions and statistical results regarding "**the Measures**"

Question	Option	Subtotal	Percentage
	Allergic reactions caused by using counterfeit products	28	19.31%

1.Awareness of the definition of cosmetic adverse reactions	Skin/physical damage caused by normal use of qualified products	89	61.38%
	Chemical injury from occupational exposure to raw materials	9	6.21%
	Unclear	19	13.10%
2.Awareness of"the Measures"	Have systematically studied	11	7.59%
	Know a little	57	39.31%
	Completely unaware	77	53.10%
3.Awareness of"the Measures" effective date	January 1, 2020	15	10.34%
	January 1, 2022	18	12.41%
	October 1, 2022	27	18.62%
	October 1, 2024	12	8.28%
	Do not know	73	50.34%
4.Awareness of responsible entity for cosmetic safety	Local People's Government	6	4.14%
	Cosmetic manufacturer	76	52.41%
	Cosmetic registrant/filing agent	40	27.59%
	Cosmetic retailer	6	4.14%
	Do not know	17	11.72%
5.The authority responsible for the national monitoring and management of cosmetic adverse reactions is( )	National Medical Products Administration	37	25.52%
	Provincial Drug Regulatory Department	34	23.45%
	National Cosmetic Adverse Reaction Monitoring Institution	50	34.48%
	Do not know	24	16.55%
6.Awareness the adverse reactions from cosmetic use should be reported	Yes	80	55.17%
	No	65	44.83%
7.Principle for reporting adverse reactions	Active collection	31	21.38%
	Report upon suspicion	19	13.10%
	Report upon discovery	48	33.10%
	Report after confirmation	27	18.62%
	Do not know	20	13.79%
8.Evaluation timeframe for severe reports (working days)	10 days	21	14.48%
	7 days	45	31.03%
	3 days	25	17.24%
	Do not know	54	37.24%
9.E-platform's duty upon learning of a reaction	Report within 3 days to retailer on platform	24	16.55%
	Report within 7 days to retailer on platform	31	21.38%
	Report within 3 days to manufacturer	16	11.03%
	Report within 7 days to manufacturer	12	8.28%
	Report within 7 days to registrant/filing agent	18	12.41%
	Do not know	44	30.34%
10.Scenarios constituting a severe adverse reaction (Multiple choice)	Temporary/permanent functional loss (e.g., scars, permanent hair loss)	103	71.03%
	Systemic injury (e.g., organ dysfunction, anaphylactic shock)	99	68.28%
	Requires or warrants hospitalization	91	62.76%
	Life-threatening or fatal	81	55.86%
	Do not know	24	16.55%

3.5 Statistical Analysis of Personal Reporting Channels for Cosmetic Adverse Reactions and Public Access to Safety Information

Effective monitoring of cosmetic adverse reactions relies on the collection of reports, which is contingent upon consumers' ability to both identify and report such events. Consequently, disseminating knowledge about adverse reactions and ensuring that consumers are aware of the proper reporting channels is essential. To consolidate and clarify the pathways through which consumers access information and submit reports, Principal Component Analysis (PCA) was applied to the two corresponding multiple-choice questions to extract fundamental insights. Initially, the suitability of the data for PCA was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. The accepted KMO benchmarks are: >0.9 (very suitable), >0.8 (suitable), >0.7 (middling), >0.6 (mediocre), and <0.5 (unacceptable). A significance level (p-value) below 0.05 for Bartlett's test indicates significant correlations among variables, confirming the data's appropriateness for PCA.

PCA was performed on the selected “personal reporting channels” options using SPSS 26. The KMO measure was 0.836 (>0.8), and Bartlett's test of sphericity yielded a significance level of $p < 0.001$ as shown in Table 2, indicating the suitability of the data for PCA. Following the general principle of eigenvalue >1 for component extraction, only Component 1 (eigenvalue=4.364) and Component 2 (eigenvalue=1.097) had eigenvalues exceeding 1 as shown in Table 3. These two principal components cumulatively explained 60.674% of the total variance. The rotated component matrix is presented in Table 4. Based on a loading threshold of >0.6 for classification, Component 1 included high-loading variables: “reporting to local municipal/county-level monitoring institutions” (0.792), “reporting to municipal/county-level regulatory departments” (0.716), and “reporting to the cosmetic registrant, filing agent, or domestic responsible person” (0.704). The variable “not knowing how to report” (-0.716, reverse-scored) also loaded highly. The common theme among these variables points towards the formal, official, and institutionalized reporting channels stipulated in “the Measures”, or conversely, the lack of awareness thereof. This component was therefore labeled “Awareness of “the Measures” Component 2 comprised high-loading variables: “cosmetic sales enterprises” (0.839), “cosmetic manufacturers” (0.824), and “hospital dermatology departments” (0.758). These variables primarily reflect the natural tendency of consumers to seek accountability or solutions for adverse reactions. This component was named “Solution-seeking Pathways.” The two dimensions are independent of each other, providing a concise and robust analytical framework for understanding public reporting behaviors.

Table 2. KMO and Bartlett's tests

KMO		0.836
Bartlett's Test of Sphericity	Approximate Chi-Square	535.943
	Degrees of freedom	36
	Significance	0.000

Table3. Total Variance Explained

Compent	Initial Eigenvalue			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	Variance %	Cumulative %	Total	Variance %	Cumulative %	Total	Variance %	Cumulative %
1	4.364	48.490	48.490	4.364	48.490	48.490	2.841	31.565	31.565
2	1.097	12.184	60.674	1.097	12.184	60.674	2.620	29.109	60.674
3	0.846	9.398	70.072						
4	0.678	7.531	77.603						
5	0.620	6.885	84.488						
6	0.488	5.427	89.915						
7	0.378	4.205	94.119						
8	0.287	3.186	97.306						
9	0.242	2.694	100.000						

Table 4. Rotated Component Matrix table*

Information Channel	Component	
	1	**2**
Reports to municipal/county regulatory depts	0.792	0.197
Reports to local monitoring institutions	0.716	0.282
Unfamiliarity with reporting procedures	-0.716	-0.235
Reports to registrants/filing agents	0.704	0.121
Market Supervision Bureau 12315	0.560	0.358
Cosmetic retailers	0.258	0.839
Cosmetic manufacturers	0.267	0.824
Hospital dermatology departments	0.138	0.758
ADR Monitoring Centers	0.470	0.588

***:** Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization. Rotation converged in 8 iterations

PCA was conducted on the selected "access pathways to cosmetic safety information" options using SPSS 26. The KMO measure was 0.777 (>0.7), and Bartlett's test of sphericity was significant ($p < 0.001$ as show in Table 5), confirming the data's suitability for PCA. The total variance explained and the component matrix are presented in Tables 5 and Table 6, respectively. Based on the component matrix, one principal component was extracted, with an eigenvalue of 2.534 >1, explaining 42.238% of the total variance (cumulative variance). All variable loadings were consistent in direction, with absolute values above 0.45, reflecting a clear continuum of "professional authority and credibility." This component was labeled "Authoritative, Credible, and Formal Channels." High-

loading variables included “campus lectures” (0.744), “consulting physicians” (0.727), and “product instructions” (0.713), indicating a strong public preference for such channels. This reflects a consistent attitude rather than a choice among specific options; for instance, an individual who trusts “campus lectures” is also highly likely to trust “consulting physicians” and “product instructions.” Trust in authoritative and formal channels appears to be holistic rather than segmented. Therefore, the correlation pattern among variables supports a single-dimension structure as shown in Table 7. A KMO value of 0.777 is sufficient for extracting a unidimensional construct, and the explained variance of 42.238% is within an acceptable range.

Table 5. KMO and Bartlett's tests

KMO		0.777
Bartlett's Test of Sphericity	Approximate Chi-Square	149.517
	Degrees of freedom	15
	Significance	0.000

Table 6. Total Variance Explained

Compent	**Initial Eigenvalue**			**Extraction Sums of Squared Loadings**		
	Total	Variance %	Cumulative %	Total	Variance %	Cumulative %
1	2.534	42.238	42.238	2.534	42.238	42.238
2	0.979	16.322	58.560			
3	0.819	13.650	72.210			
4	0.604	10.075	82.284			
5	0.547	9.118	91.402			
6	0.516	8.598	100.000			

Table 7. Component Matrix table*

Information Channel	**Component**
	1
Campus lectures	0.744
Professional physician consultations	0.727
Cosmetic package inserts	0.713
Regulatory agency official accounts	0.632
Official science short videos	0.586
Other channels	-0.450

*: Extraction Method: Principal Component Analysis.

3.6 Grounded Theory Analysis of Open-ended Questions

3.6.1 Data Collection Methodology

Based on textual data from regulations, literature, and operational documents, the questionnaire and interview guide were designed. Following the completion of the

surveys and interviews, the collected qualitative data from the returned questionnaires and interview transcripts were compiled. This data was then analyzed using grounded theory, in conjunction with collected typical literature.

3.6.2 Coding Procedures

Adhering to the principles of grounded theory qualitative methodology, an iterative comparative analysis and progressive coding of collected data were performed through the tripartite process of open coding, selective coding, and theoretical coding, which through systematic juxtaposition with extant literature reports led to the development of novel conceptualizations or redefinitions of key constructs and corresponding regulatory measures.

3.6.2.1 Open Coding Implementation

Notwithstanding the availability of qualitative analysis software, manual coding was deliberately employed due to both technical accessibility constraints and the manageable volume of textual data (Chongqing adverse reaction questionnaires), which permitted meticulous line-by-line semantic analysis that ultimately deconstructed the raw data into 104 discrete conceptual units through an iterative process maintaining maximal fidelity to original expressions, with subsequent comparative analysis reorganizing these concepts into 20 coherent categories reflecting emergent phenomena. Due to space constraints, part of the coding process is illustrated in Figure 3.

Data Organization	Initial Coding	Category	Conceptual Categories Forming the Categories
1. A relatively comprehensive cosmetic adverse reaction monitoring system has been established, implementing national policies and building local monitoring networks. According to recent statistics and risk analysis, the annual number of reported adverse reactions has increased, primarily involving skin allergies. The implicated products are mainly high-risk special cosmetics such as spot removers, sunscreens, and hair dyes. Key area monitoring has been implemented to strengthen sampling inspections on e-commerce platforms (e.g., Taobao, Pinduoduo) and offline beauty salons. Efforts to enhance public education, publicity, and improve complaint channels are underway.	a1: Well-established system; a2: Increased number of reports; a3: Adverse reactions mainly skin allergies; a4: High-risk products mainly special cosmetics like spot removers, sunscreens, hair dyes; a5: Key area monitoring, strengthened sampling on e-commerce platforms and beauty salons; a6: Enhanced education and publicity efforts; a7: Improved complaint channels.	A1: The three-tier reporting system is relatively well-established	a1: System is relatively well-established; a18: Our city has a three-tier reporting system.
4. Monitoring difficulties are increasing for new business formats (cross-border e-commerce, Taobao, live-streaming e-commerce, influencer products, etc.).	a14: Monitoring new business formats like e-commerce is difficult.	A2: The number of reports is increasing, with more cases involving children and the elderly annually. Reports mainly originate from medical institutions but are few in number and low in quality.	a2: Number of reports is increasing; a9: Cases involving children and the elderly are increasing year by year; a15: Reporting is mainly from medical institutions, representing only the tip of the iceberg; a27: Reports are few in number and low in quality.
20. The quantity of collected information is low, mainly due to personnel's lack of awareness and knowledge about cosmetic adverse reactions, an incomplete regulatory and institutional system, low coverage of network systems and testing equipment, a single version of the reporting form, and inefficient reporting channels.	a39: Low quantity of collected information; a40: Lack of awareness and knowledge; a50: Incomplete regulatory and institutional system.	A3: Strong professional nature of reporting, limitations of data entry assistance technology, overly detailed information required hampers submission and evaluation.	a25: Overly detailed information affects report submission and evaluation; a48: Varying levels of public knowledge, strong professional nature of reporting; a11: Limitations of data entry assistance technology; a28: Statistical differences in diagnoses between sentinel and non-sentinel medical institutions.
...	...	...	...

Figure 3. Partial coding process screenshot

3.6.2.2 Selective Coding Process

The 20 preliminary categories underwent intensive re-examination through constant comparative analysis against both existing literature and newly retrieved publications (approximately 100 additional sources identified during this phase), employing the paradigm model to establish relational linkages until theoretical saturation was conclusively determined when no further category development could be substantiated[10], as systematically demonstrated in Table 8 detailing the finalized paradigm analysis framework.

Table 8. Paradigm Model Analysis of Cosmetic Adverse Reaction Monitoring

<table>
<tr><th colspan="3">Causal Conditions</th><th>Intervening Conditions</th><th>Action/Interaction Strategies</th><th>Context</th><th>Phenomenon</th><th>Consequences</th><th>Core Category</th></tr>
<tr><td rowspan="2">A9</td><td rowspan="2">A8、A10</td><td rowspan="2">A12、A15</td><td rowspan="3">Measures for the Administration of Cosmetic Adverse Reaction Monitoring</td><td rowspan="3">A5、A6、A7、A16、A17、A18、A20</td><td rowspan="3">A14、A19</td><td>A1、A2、A4、A13</td><td>A3、A9、A11</td><td rowspan="4">AA1：”Top-suspended & bottom-blinded” regulatory dilemma with quantitatively insufficient yet steadily increasing low-quality reports, addressed through the “one-consolidation and three-reinforcements” optimization framework with procedural simplification for efficacy improvement.</td></tr>
<tr><td>Public “legal illiteracy”</td><td>Absence of accountable entities</td><td>Measures for Cosmetic Adverse Reaction Monitoring</td><td>Preliminary stage</td><td>Regulatory “triple difficulties”</td></tr>
<tr><td colspan="8">AA1 Contextual Narrative: Chongqing has established a three-tier cosmetic adverse reaction monitoring and reporting system. However, reports remain limited in both quantity and quality, despite a steady growth trend. Key challenges stem from regulatory shortcomings: incomplete laws and technical standards, inadequate and unevenly distributed sentinel units, a shortage of trained professionals, and insufficient accountability. These are compounded by the absence of responsible entities among registrants/filing agents, low public awareness of the relevant Regulations, and the rise of new business models. This confluence creates a “triple difficulty” in supervision: challenges in data collection, report submission, and regulating new formats—a situation characterized as “supervision suspended above, public blindness below, with missing responsible entities.”
To address this, a strategy is proposed focusing on policy implementation (“One Consolidation”), strengthened leadership, enhanced stakeholder awareness, and improved collaboration (“Three Reinforcements”). This is coupled with streamlining procedures by simplifying reporting forms and channels, moving from complexity to simplicity. The goal is to improve monitoring quality and efficiency, thereby ensuring public cosmetic safety.</td></tr>
</table>

Through iterative comparative analysis and progressive coding of collected data in juxtaposition with existing literature, this study has conceptualized two novel constructs: the “top-suspended and bottom-blinded” regulatory predicament stemming from deficient subject accountability, and the “one-consolidation and three-reinforcements” optimization framework coupled with “complexity-to-simplicity” transformation for quality-efficiency enhancement.

The “top-suspended and bottom-blinded” phenomenon fundamentally originates from inadequate policy dissemination and implementation, where monitoring personnel demonstrate insufficient regulatory literacy and weak accountability, compounded by minimal public awareness of cosmetic adverse reactions—evidenced by the startling statistic that registrants/filing agents, as primary responsible entities, submitted merely one report annually during 2023-2024, accounting for a negligible 0.01% of total reports [11], which starkly reflects both the current industry consciousness level and developmental status, with emerging business models further exacerbating regulatory challenges.

Conversely, the proposed “one-consolidation and three-reinforcements” framework (entailing consolidated policy implementation, strengthened leadership, heightened awareness, and enhanced interdepartmental collaboration) systematically addresses these issues through comprehensive process simplification—eliminating bureaucratic obstacles across the entire monitoring continuum from report submission, verification protocols, to evaluation methodologies—by establishing intelligent multi-channel

reporting systems and optimized signal extraction mechanisms that substantively improve both the quality and efficiency of adverse reaction surveillance.

3.6.2.3 Theoretical Coding

Building upon the systematic examination of core categories through constant comparative analysis with raw data, this study developed a comprehensive theoretical framework by identifying the intricate relationships between concepts and organizing substantive codes into a coherent storyline that captures three fundamental aspects of cosmetic adverse reaction monitoring in Chongqing: the regulatory challenges arising from insufficient accountability at different levels of the monitoring system, the paradoxical situation where limited reporting volume coexists with gradually increasing case numbers despite quality concerns, and the proposed solution framework emphasizing policy implementation reinforcement through strengthened leadership, enhanced awareness, and improved collaboration while streamlining procedures to boost overall effectiveness.

The validity of this theoretically constructed storyline was further confirmed through exhaustive literature review encompassing nationwide data, demonstrating its capacity to incorporate both documented challenges and proposed solutions currently existing in China's cosmetic adverse reaction monitoring systems beyond the Chongqing municipality.

4. Discussion

The current state of cosmetic adverse reaction monitoring in Chongqing is characterized by a challenging regulatory environment where supervision is suspended at the top, the public is uninformed at the bottom, and the absence of responsible entities makes regulation difficult. This has resulted in a situation of few reports with low quality, albeit with a steady increasing trend. Addressing this requires a strategy focused on implementation, triple-strengthening, and process simplification to enhance regulatory quality and efficiency.

4.1 Theoretical Construction and Significance

This study marks the first application of the grounded theory research methodology to the specific field of cosmetic management. It provides a preliminary theoretical framework for cosmetic adverse reaction monitoring, representing a valuable attempt and exploration in cosmetic management research. Simultaneously, it enriches the theoretical achievements in this field.

4.2 Practical Innovation

Through the analysis and comparison of existing problems within Chongqing's cosmetic adverse reaction monitoring system, this study systematically summarizes the key issues, explores their causes and potential solutions, and defines the characteristics of the current development stage: suspended top-level supervision, an uninformed public, absent responsible entities, and a pattern of few yet steadily increasing low-quality reports. The

proposed strategy of "implementation, triple-strengthening, and process simplification" to improve regulatory quality and efficiency provides concrete, actionable guidance for cosmetic adverse reaction monitoring in China.

5. Research Limitations and Future Prospects

The development of cosmetic adverse reaction monitoring involves numerous and complex issues. When designing questionnaire items, consideration was given to questionnaire length, resulting in insufficient homogeneous questions and relatively weak correlations. More accurate results could be obtained through further classification and separate questionnaire surveys.

Using classical grounded theory as the scientific research method, this study explored the development of cosmetic adverse reactions in Chongqing. However, due to limitations of time, energy and resources, there are many shortcomings in this research. For example, the entire article is based on data collection regarding problems and suggestions, and the preliminary theoretical conclusions need to be verified and refined in practice; the sample size collected was small; the study failed to investigate related issues in more provinces and cities. Future plans include seeking cooperation with drug regulatory authorities to incorporate registrants, filers, production and operation enterprises, collecting more samples from more provinces and cities, and continuing to deepen and enrich the concepts and categories proposed in this study for verification.

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Bibliometric Analysis of Research Trends in Mountain Remote Sensing Observation

Yajuan Tian[a,1], Yi Yang[b], Jiqiang Shi[a], Xing Wang[a] and Ying Lu[a]
[a] *National Science Library(Chengdu), CAS, China*
[b] *Institute of Mountain Hazards and Environment, CAS, China*

Abstract. Mountain remote sensing observation constitutes a critical technical method in mountain research. Over the last decades, researches on mountain remote sensing have become increasingly advanced and in-depth. With the continued development of science and technology and the complex changes in mountain environment, exploring current research hot spots and trends becomes an important issue. In this study, we mainly employ bibliometric analysis methods, and incorporates the advocacy of international authoritative organizations for the development of global mountain research, aiming to predict future trends in this field. It is expected that this work can provide support for scientific research development and planning management in this field.

Keywords. Mountain, Remote Sensing, References, Bibliometric Analysis

1. Introduction

Mountain remote sensing observation research is a frontier field that deeply integrates mountain science and geospatial information science. Its development relies on the innovation of remote sensing technology, multidisciplinary theoretical support, and the needs of mountain area development. It has formed a progressive path of "technological breakthrough—method innovation—application implementation". Earth observation remote sensing provides crucial data sources for accurately understanding and assessing the responses and adaptations of terrestrial ecosystems at a global scale.

International organizations such as the World Meteorological Organization (WMO) and the Committee on Earth Observation Satellites (CEOS) have successively formulated several satellite land surface climate research programs. The National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and other institutions have gradually launched satellite climate dataset production services [1]. Some countries started mountain remote sensing observation research relatively early, with a relatively mature technological system. The free and open service of remote sensing satellite data (such as Landsat, Sentinel, etc.) has laid the foundation for global observation and product systematization. Based on different satellite remote sensing

[1] Corresponding Author: Yajuan Tian, National Science Library (Chengdu), CAS, China; Email: tyj@clas.ac.cn

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observation platforms, various global multi-element remote sensing product datasets have been developed internationally, such as the US MODIS product series, the European CGLS series, China's Fengyun satellite remote sensing product series, and the Global Land Surface Satellite (GLASS) product series. The remote sensing datasets for key parameters of global change have been greatly enriched, laying a solid foundation for mountain remote sensing observation.

Due to the particularity of mountain terrain, remote sensing observation faces more technical challenges. For example, there is insufficient terrain adaptability. In terms of observation networks, long-term data have been accumulated relying on networks like the GLORIA alpine observation network and the FLUXNET flux network, providing support for mountain ecological process research. However, most sites deliberately avoid complex terrain, resulting in limited mountain representativeness of the observation footprint, making it difficult to quantify the impact of topographic effects on ecological processes. In product development, global remote sensing product series such as MODIS and CGLS have been formed, covering key parameters like surface reflectance and vegetation coverage. However, the spatial resolution is mostly at the hundred-meter to kilometer level, unable to accurately depict the strong spatiotemporal heterogeneity of mountains. Although there are products like GlobeLand30 with 30m resolution [2], limitations exist in scenarios such as refined monitoring of complex mountain terrain, short-term dynamic response, and identification of specific types [3]. In technological exploration, there are distinctive advancements in fields like glacier monitoring and alpine ecological response, such as using the ICESat-2 satellite lidar for high-precision glacier elevation monitoring. However, challenges like low data utilization due to canopy occlusion persist in complex mountainous forest areas. Existing data reserves remain extremely limited, and most mountain site observation setups tend to avoid the influence of mountain terrain, restricting the exploration of topographic effects in mountain processes and introducing significant uncertainty into current mountain process research.

To explore the trends in this field and identify research hotspots, this paper primarily employs bibliometric analysis. Bibliometric analysis has previously been applied to mountain research. For instance, Liu Zhengquan et al. used keyword timeline analysis and burst detection to study publications and citation numbers, countries and institutions engaged in research, co-citations and key literature, keyword categories, and research fields in flash flood research [4]. Gallardo-Salazar JL et al. studied thirty years of remote sensing analysis of forest decline related to climate change, with keyword analysis reflecting associations with different key forest decline phenomena like drought stress and climate change [5]. Liu Wenhao et al. studied the research hotspots and frontiers of mountain ecosystem services based on metrics including main research forces, core journals and papers, research hotspots and topics by using the methods of bibliometrics and text mining, and the results revealed that the hotspot worthy of attention in the near future is the assessment of mountain ecosystem services capacity and value[6]. Bian Jinhu et al. studied the various methods and resources used for monitoring Sustainable Development Goal (SDG) 15.4. RS monitoring methods on monitoring and assessment of mountain SDG indicators were introduced in detail based on bibliometric analysis [7]. However, there is currently few bibliometric analysis specifically on research hotspots in mountain remote sensing technology.

We surveyed global literature on mountain remote sensing observation research from the past decade, analyzed current hotspots in mountain remote sensing observation application research, and combined this with the development advocacy for global mountain research by international authoritative organizations to predict future

development trends in this field. This aims to provide references for scientific research development and planning management in this field.

2. Data and Methods

2.1 Data

The data for this paper is sourced from the SCIE database on the Web of Science platform, considering that SCIE papers are currently the most authoritative scientific achievement database widely recognized by global researchers, with guaranteed article quality and data accuracy, capable of comprehensively reflecting global scientific research progress.

Search strategy is designed as: TS= (Mountain* or alpine or Glacier* or Plateau) and ("Remote Sensing" or "Precision Monitoring" or "High-Resolution Monitoring" or "intelligent monitoring" or "geospatial data" or "geospatial big data"). Searching was conducted on 07 February, 2026. A total of 11,375 relevant papers were retrieved, including 100 ESI Highly Cited Papers. The keyword data from all papers totals 22,280 entries. After screening and deduplication, a total of 20,524 keyword data entries were obtained.

2.2 Methods

Derwent Data Analyzer (DDA) was employed as the analytical tool. Developed by Clarivate, DDA is a big data analytics platform that enables multi-perspective analysis of research hotspots from literature data, including keywords statistical analysis, , keyword changes analysis over the past three years, and emerging trend indicator analysis.

Additionally, we combined content interpretation of ESI (Essential Science Indicators) papers from the search results to understand current research focuses.

3. Results and Discussion

3.1 Hotspot Keywords in Mountain Remote Sensing Observation Research

Keywords reveal the research themes of papers. Statistical analysis of the frequency and changes of keywords can intuitively understand the research hotspots and their evolution over time in a specific research field.

By analyzing the keywords of papers in the field of mountain remote sensing observation applications, the high-frequency keywords in this field are shown in Table 1.

The top 1 keyword is "machine learning". The keywords "deep learning" (including "convolutional neural network") and "random forest" rank 3rd and 4th respectively, indicating that machine learning technology has been deeply integrated into mountain remote sensing technologies. Machine learning has significantly enhanced the accuracy and efficiency of mountain remote sensing monitoring. By integrating multi-source, high-resolution data and utilizing models such as Random Forest and XGBoost, it enables high-precision estimation and dynamic monitoring of key ecological parameters

like forest biomass, canopy coverage, and snow cover area. This provides robust data support for the scientific management and conservation of mountain ecosystems. Machine learning is not only an effective tool for solving technical challenges in mountain remote sensing but also a core driving force propelling the field towards intelligent perception and deep analysis.

Ranking 2nd is "climate change", showing that for research in this field, "climate change" is the most concerning topic. "Climate change" represents the most critical theme in mountain remote sensing research. Against the backdrop of global warming and the increasing frequency of regional climate anomalies, mountains act as the "sensitive sentinels" and "amplifiers" of global climate change. With its unique strengths of macroscopic, dynamic, and integrated monitoring capabilities, remote sensing technology has become an irreplaceable critical tool for obtaining core evidence of climate change, unraveling its underlying impact mechanisms, and guiding human adaptation actions in complex mountain environments.

Furthermore, "Soil moisture", "NDVI", "Landslide", "Glacier", "Tibetan Plateau"、"Precipitation", "Evapotranspiration", "Land surface temperature", "Land use", "Snow", and "Soil erosion", etc., are other objects of concern. These research targets forms the scientific foundation for achieving precise monitoring, simulation, and management of mountain regions.

Main remote sensing monitoring technologies include: "GIS", "MODIS", "Landsat", "Sentinel-2", "Google Earth Engine", "Sentinel-1", "UAV", "Lidar", etc.

Table 1. Hotspot Keywords in Mountain Remote Sensing Observation Applications

Keywords	Frequency
remote sensing	3616
machine learning	1331
climate change	737
deep learning	674
random forest	421
Tibetan Plateau	392
soil moisture	378
GIS	330
MODIS	282
landsat	243
Sentinel-2	218
NDVI	199
landslide	191
glacier	167
Google Earth Engine	157
precipitation	154
Sentinel-1	142
evapotranspiration	138
UAV	138
lidar	137
permafrost	135
land surface temperature	134
land use	121
snow	121
convolutional neural network	120
soil erosion	117

3.2 Changes in Research Keywords for Mountain Remote Sensing Observation Applications

By analyzing the development trends of keywords in the field of mountain remote sensing observation research, Table 2 shows keywords that first appeared in the past three years, and Table 3 shows keywords that no longer appeared in the past three years, reflecting, to some extent, changes in research hotspots.

As can be seen from Table 2, keywords that first appeared in the past three years include "Interpretable machine learning", "SHAP analysis", "XGBoost-SHAP", "Internet of things", "PLS-SEM", "YOLO", "Vectors", "stacking ensemble learning", etc.

Table 2. Newly Appearing Keywords in the Past Three Years

Keywords	Frequency
interpretable machine learning	12
SHAP analysis	10
XGBoost-SHAP	9
internet of things	8
PLS-SEM	7
YOLO	6
vectors	6
Yunnan Province	5
stacking ensemble learning	6
model interpretability	5
plant functional traits	5
algal bloom	5
Bayesian optimization	4
Yunnan-Guizhou Plateau	4
physics-informed machine learning	4
computational seismology	4
mountain flood forecasting	4
Sentinel-2 (S2)	4
spatial autocorrelation analysis	4
Landsat 9	4
terrestrial water storage anomalies	4
ERA5 reanalysis data	4

Table 3 lists keywords that no longer appeared in the past three years, including "Deforestation", "Fire severity", "Glacier delineation", "Sierra Nevada", "Triple collocation", "AMSR-E", "ASCAT", "atmospheric correction", etc. It can be seen that these research topics have faded from attention.

Table 3. Keywords that no longer appear in the past three years

Keywords	Frequency
deforestation	14
fire severity	13
glacier delineation	13
Sierra Nevada	11
triple collocation	11
AMSR-E	11
ASCAT	10
atmospheric correction	10
radar observations	10
Sentinel-2 MSI	10
spatial scale	10
USLE	10
landscape ecology	9
landscape change	9

ASTER GDEM	8
Gangotri Glacier	8
Himawari-8	8
invasive species	8
mortality	8
pansharpening	8
wind erosion	8

Emergence Indicators(EI) is a technology foresight tool produced by Alan Porter, Professor at Georgia Institute of Technology. EI analyzes and mines topic words from titles and abstracts through bibliometric methods, and calculates the Emergence Indicators based on Novelty, Persistence, Growth, and Community (research community engagement), to reflect emerging trends in this field.

Table 4 shows important emerging trend research topics in the field of mountain remote sensing observation applications. It can be seen that research on "SHAP analysis", "robust framework", "new hydrological insights", "water resource management", "spatial heterogeneity", "complex terrains", "early warning systems", "ecological conservation", "spatiotemporal dynamics", etc., are new themes that have gradually focused in the past decade and may become new research priorities in the future.

Table 4. Analysis of Emerging Trend Topics

Topic Term	EI Score	Record Count
SHAP analysis	8.537	57
robust framework	7.277	20
new hydrological insights	7.27	65
water resource management	6.524	150
spatial heterogeneity	5.434	194
complex terrains	5.361	68
early warning systems	5.238	33
ecological conservation	5.049	52
spatiotemporal dynamics	5.007	94
deep learning models	4.776	30
disaster prevention	4.775	31
nonlinear interactions	4.492	36
high-risk zones	4.324	38
data quality	4.054	41
interpretability	4.03	42

3.3 Focus Topic Analysis of ESI Papers

The Essential Science Indicators (ESI) database is a basic analytical and evaluation tool launched by the Institute for Scientific Information (ISI), a world-renowned academic information publisher, for measuring scientific research performance and tracking scientific development trends. ESI Highly Cited Papers refer to papers published in the past 10 years with citation counts ranking in the top 1% globally within their respective subject fields. They are important indicators for analyzing research frontiers in a particular discipline.

Through our investigation and analysis of highly cited papers (ESI papers) in this field, we found that over the past decade, the more focused directions in mountain remote sensing observation applications are as follows:

- Mountain Land Surface Parameter Remote Sensing Retrieval

Research focuses on developing new remote sensing sensors, platforms (such as UAVs, high-resolution satellites, photon-counting lidar), and multi-source data fusion methods (such as combining optical, thermal infrared, microwave remote sensing with reanalysis data) to retrieve various land surface parameters, such as soil moisture, fractional vegetation cover, evapotranspiration, vegetation indices, fraction of absorbed photosynthetically active radiation, land surface temperature, forest aboveground biomass, etc. This aims to assess the health status, function, and quality of ecosystems, providing scientific basis for ecological environment management and decision-making. Currently, mountain land surface parameter remote sensing retrieval technology has achieved the generation of long-term time series datasets at kilometer or even meter scales without gaps (e.g., global 1 km daily scale soil moisture).

- Evolution and Driving Mechanisms of Ecological Environment Quality

Research focuses on using remote sensing ecological indices, land use/cover change, etc., to assess the spatiotemporal evolution of regional ecological environment quality and explore its natural (e.g., climate) and anthropogenic (including policy and urbanization) driving mechanisms. This includes: quantifying ecosystem carbon budgets (e.g., GPP, NPP); assessing vegetation vulnerability and stress response, and the effectiveness of ecological engineering (e.g., returning farmland to forest and grassland); using methods independent of remote sensing technology, such as tree-ring growth models, to extend phenological records, verify, and analyze inconsistencies in remote sensing phenology products, which is also a subject of considerable research. Additionally, comprehensive application of models like InVEST (assessing habitat quality), FLUS (simulating future land use), soil erosion models, etc., to construct ecological security patterns, identify ecological sources and corridors, support territorial spatial planning, as well as monitoring and simulating key hydrological variables like surface water, soil water, evapotranspiration, and assessing their changes and impacts on water resource availability, are also research focuses.

- Application of Machine Learning and Deep Learning in Mountain Remote Sensing

Applying and developing advanced machine learning (ML) and deep learning (DL) algorithms for remote sensing image classification, parameter retrieval, predictive modeling (e.g., yield, disasters, runoff), and model optimization is a current hotspot. This includes: designing network architectures for specific geoscience problems, such as high-performance specialized models like Spatial Graph Convolutional Networks (SGCN) for road extraction, Global Context Spatial Attention Networks (GCSANet) for scene classification, and Spatio-Temporal Graph Convolutional Networks for landslide prediction; research on Explainable AI (XAI) using tools like SHAP values to interpret the decision-making process of ML models, enhancing model transparency and trustworthiness; multi-modal data and prediction: fusing multi-source data like remote sensing, meteorology, and topography to predict crop yield, runoff, geological disasters (landslides, floods); small-sample and data generation research: using Generative Adversarial Networks (GAN) to generate synthetic data to enhance model training in data-scarce fields (e.g., geological disasters).

- Development of Models, Algorithms, and Optimization Theories

Research on new remote sensing platforms (e.g., UAVs), new algorithms (e.g., change detection, time series analysis), data fusion methods, and specific domains (e.g., the Tibetan Plateau, biodiversity) is relatively focused. Among these, research utilizing

UAVs, near-space platforms, and microsatellite constellations to provide higher spatiotemporal resolution data, applications of cloud platforms like Google Earth Engine to extend research scope to global scale and long-term time series analysis, and the application of cutting-edge algorithms combining optical, microwave, and LiDAR are frontier hotspots in this field.

4. Advocacy from International Authoritative Institutions for Environment

United Nations agencies addressing climate change and promoting sustainable development, notably the United Nations Framework Convention on Climate Change (UNFCCC), United Nations Environment Programme (UNEP), and the United Nations Office for Disaster Risk Reduction (UNDRR) form a system responsible for scientific assessment, policy formulation, and action coordination in global climate governance. Their work is closely centered around the principle of "common but differentiated responsibilities". The global policy agendas and scientific reports issued by these organizations collectively constitute the core knowledge system and action framework for the global response to climate change and disaster risks. These reports, based on the consensus of top global scientists, systematically assess the facts, impacts, and mitigation pathways of climate change, provide authoritative scientific assessments and policy benchmarks, and establish common global goals and directions for action.

In November 2025, the Secretariat of the UNFCCC released the report of the UN Climate Change Conference—COP 30 Global Climate Action Agenda Outcome Report [8], in which the topics such as the application of artificial intelligence in climate governance in the Action Agenda were included for the first time. The Data-Driven EnviroLab and partners from CAMDA launched a new initiative, establishing a multi-year global data partnership. This partnership utilizes artificial intelligence, satellite observations, and open data to assess the specific performance and contributions of cities, companies, and regions worldwide in achieving global climate goals, thereby further enhancing the transparency and accountability mechanisms of global climate governance work. The world's first digital infrastructure for climate action was launched, which will help countries use Digital Public Infrastructure (DPI) and Digital Public Goods (DPG) to advance climate action, applying open digital tools to strengthen disaster response, energy, water resource management, and climate-resilient agriculture.

In September 2023, the UNFCCC Secretariat released a synthesis report on the first global stocktake technical dialogue [9]. It proposed that to enhance the resilience of mountain ecosystems, it is necessary to improve scientific understanding and monitoring capabilities of mountain ecosystems, strengthen scientific coverage of mountain ecosystems at regional and global levels, including monitoring and assessment of mountain areas, as well as impact and risk assessment; socioeconomic dimensions should be integrated into mountain spatial observation; and field surveys and remote sensing technology should be prioritized in mountain terrain monitoring to obtain data helpful for formulating mitigation and adaptation decisions.

On November 7, 2024, the UNEP released the Adaptation Gap Report 2024 (AGR 2024) online [10]. It proposed: establishing ecosystem risk and vulnerability assessment data monitoring systems has become an important means for ecological environmental protection, including natural resource monitoring, climate-smart monitoring, health sector risk assessment and monitoring, etc., promoting climate-smart infrastructure

construction, improving technical capacity for collecting data needed for monitoring and evaluation activities, and monitoring progress on adaptation actions and goals.

In 2025, the UNDRR released the 2025 Global Assessment Report on Disaster Risk Reduction [11]. The report proposed that innovative tools such as machine learning and artificial intelligence are helping to enable more accurate disaster prediction and decision-making. For example: using digital twins to reduce disaster losses and risks. A digital twin project jointly developed by the Banque de France, De Nederlandsche Bank, and the Hong Kong Monetary Authority virtually reconstructs parts of the economic and financial system to simulate disaster shock effects. Using fine-grained geolocation data, the system tracks flood risks and their transmission paths to the financial system in real-time, while also being able to assess the impact of disasters under different intensity scenarios. Mountainous areas have a high incidence of disaster risks, and these initiatives provide guidance for disaster risk early warning and management in mountainous areas.

5. Conclusion and Discussion

This study aims to trace the development of hotspot in mountain remote sensing observation research, and forecasting the future trends of this field. Analysis of literature keywords and ESI highly cited papers fully reveals the current focal research themes, while observations of international reports and policies allow us to identify the trajectory of future technological development.

Based on the above analysis, we argue that the following research directions will become the core priorities for the future development of this field:

- New Remote Sensing Sensors, Platforms, and Multi-source Data Fusion Methods

The Adaptation Gap Report 2024 points out that establishing ecosystem risk and vulnerability assessment data monitoring systems has become an important means for ecological environmental protection. Remote sensing technology, as a key technology for mountain ecological environment monitoring and protection, will continue to promote improvement for a considerable period. Research on UAV remote sensing, high-resolution satellites, lidar, photon-counting lidar, medium-resolution imaging spectrometers, Internet of Things technology, etc., are both current research hotspots and will be focal points for future development.

- Artificial Intelligence applied in Mountain Remote Sensing Technology

The COP 30 Global Climate Action Agenda Outcome Report included the application of artificial intelligence in climate governance in the Action Agenda for the first time. Domestically and internationally, efforts are continuously advancing climate-smart infrastructure construction. The application of machine learning (especially explainable machine learning) and deep learning in mountain remote sensing will continue to strengthen. Research on high spatiotemporal resolution seamless data generation through data fusion (e.g., combining optical, thermal infrared, microwave remote sensing with reanalysis data) and machine learning (e.g., random forest), image processing and enhancement techniques (spectral unmixing and spatial resolution enhancement, eliminating terrain shadow correction of remote sensing images; cloud removal methods; radiometric and geometric correction; image fusion and downscaling, etc.), digital twins and intelligent reasoning, etc., will continuously improve with the development of big

data and AI technology and will inevitably be hotspots in the development of mountain remote sensing observation technology.

- Mountain Ecological Environment Remote Sensing Monitoring and Assessment

The assessment of mountain ecological environments is an important content of mountain remote sensing observation research. Currently, research integrating remote sensing (e.g., fractional vegetation cover, vegetation indices, solar-induced chlorophyll fluorescence SIF), machine learning, and ecosystem process models to quantify the spatiotemporal changes of regional vegetation carbon sinks and the relative contributions of climate and human activities is increasing. Using long-term time series remote sensing data, combined with comprehensive indicators like RSEI (Remote Sensing Ecological Index) and land use/cover change (LUCC), to assess ecological changes in mining areas and watersheds, as well as the comprehensive application of models like In VEST (assessing habitat quality), FLUS (simulating future land use), and soil erosion models for "production-ecology-living" space conflict identification and ecological security pattern construction, are all research hotspots. As these studies mature, they will further enhance the assessment capacity of mountain ecological environments, providing meaningful support for global climate change theory research and national territorial spatial planning in various countries.

- Mathematical Models, Algorithms, and Optimization Theories Developing

Using new mathematical models and optimization algorithms to solve problems in geoscience, ecology, and broader scientific computing will be a future research hotspot. Technologies providing higher spatiotemporal resolution data through UAVs, near-space platforms, and microsatellite constellations, applications of cloud platforms like Google Earth Engine extending research scope to global scale and long-term time series analysis, and the application of cutting-edge algorithms combining optical, microwave, and LiDAR are representative of such technologies. Additionally, assimilating remote sensing data with crop models, hydrological models, etc., and using methods like random forest, XGBoost, and stacking ensemble learning to improve retrieval accuracy, forming new hydrological insights or supporting related theory optimization, will also be important development directions.

6. Limitations of this study

Although this study attempts to conduct a detailed analysis of the research hotspots and current research status of international mountain remote Sensing observation based on published research papers, it still has limitations in the following aspects: Firstly, the research data are mainly collected from the SCIE database. As a database that mainly collects papers from influential academic journals, it inevitably limits the full integration of research results from other types of papers in this analysis. Secondly, the data retrieval strategy adopted in this study is combined subject retrieval. In this retrieval mode, human factors exert a relatively significant impact on the formulation and selection of search terms, which may lead to the unavoidable risk of omitting some relevant research results. Finally, it should be noted that the bibliometric method analyzes research in a specific field from the perspective of paper bibliographies, and the relevant conclusions have

certain reference value for judging research hotspots in this field. However, a more accurate analysis should rely on the in-depth study and precise grasp of full papers.

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Artificial Intelligence for Environmental Protection: CiteSpace-Based Bibliometric Analysis

Dawei SHEN[1]

School of Marxism, Hohai University, Nanjing, China
ORCiD ID: Dawei SHEN https://orcid.org/0009-0000-0395-2312

Abstract. Artificial intelligence technology has triggered innovative changes in environmental protection. According to 455 valid articles within the Web of Science Core Collection from 2016 to April 10, 2026, this study employed CiteSpace 6.3.R1 to systematically study the artificial intelligence trends of its application in environmental protection so as to identify strategic research frontiers and collaboration gaps. It was found that since 2024, related research has increased significantly, and Chinese research results account for more than half of the total number of documents. Furthermore, the keyword cluster map indicated that considerable scholarly attention has been focused on the promoting role of artificial intelligence technologies in areas such as advancing environmental protection within domains such as air quality monitoring. Due to database and time limitations, the analysis results of this paper could be extended in future opportunities. However, this study provides a timely overview of bibliometric data.

Keywords. AI trends, Environmental protection, Bibliometric analysis, Research hotspots, ESG

1. Introduction

Artificial intelligence (AI) has garnered sustained and elevated attention from developed countries and regions worldwide. Due to the increasingly severe global climate change and environmental issues, artificial intelligence has been widely applied in this field. During this process, challenges and opportunities coexist. Under the increasingly strict carbon quotas and Environmental, Social, and Governance (ESG) reporting requirements, enterprises face huge compliance pressure. However, when managers implement intelligent environmental performance measurement systems, they often encounter problems such as the credibility of carbon emission data and the

[1] Corresponding Author: Dawei SHEN, Email: sdw@jsut.edu.cn

lack of data governance. The scarcity of resources and extreme climate events further exacerbate the vulnerability of supply chains, and there is an urgent need for data-driven strategic decision-making tools. Using the bibliometric analysis software CiteSpace 6.3.R1 to construct a knowledge map [1], from a macro perspective, we can grasp the development trajectory of AI for environmental protection, present prominent theme focuses, mainstream trends, and existing deficiencies, which is helpful in bridging the gap between AI technology and practical environmental management applications.

2. Data Sources and Research Methods

2.1. Data Sources

This study selected the SCI-EXPANDED and SSCI databases within the Web of Science Core Collection as the data source. Using the advanced search function of Web of Science, the search topics were set as "artificial intelligence" and "environmental protection", the document type was limited to "article", and the language was restricted to English. The search covered the period from 2016 to April 10, 2026, yielding 455 valid articles.

2.2. Research Methods

This study employed CiteSpace 6.3.R1 to generate scientific knowledge maps, aiming to analyze the underlying dynamic mechanisms of disciplinary evolution and to detect the frontiers of disciplinary development. A project was established by running CiteSpace 6.3.R1 with the following parameter settings: the time span was set from 2016 to 2026, with a time slice of one year; the node types were respectively set as institution, country, and keywords; the k value in the node selection module remained unchanged (k=25).

3. Research Overview

3.1. Annual Publication Volume Analysis

Academic research on artificial intelligence for environmental protection has shown growth since 2019, with a substantial increase in 2025, reaching an all-time high of 160 articles. Although the literature search for 2026 only covers data up to April 10, the number of articles has already reached 50, suggesting that the total for the entire year may potentially surpass the previous peak. It is anticipated that, driven by the rapid development of AI and the increasing emphasis on ecological and environmental protection, future research in this field will exhibit a relatively stable upward trend.

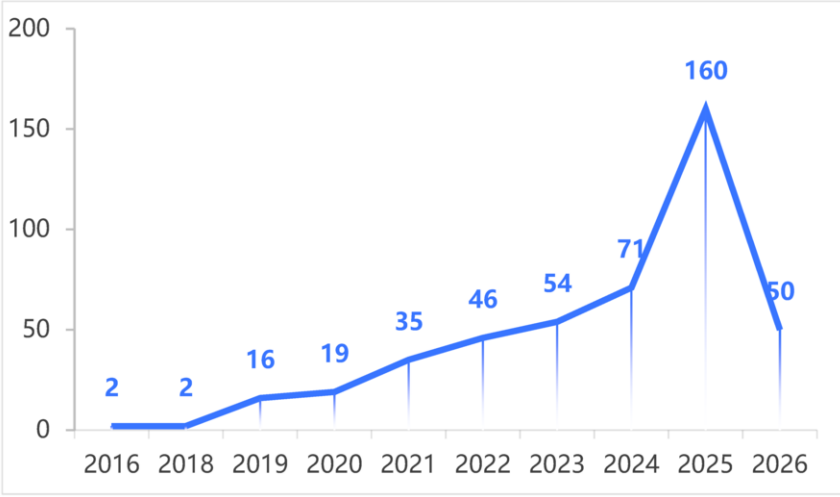


Figure 1. The papers from 2016 to 2026

3.2. Country/Institution Research Profiling

As shown in Figure 2, the institutional collaboration network map shows 242 nodes (N=242) and 163 links (E=163), with a density of only 0.0056. These data indicate that collaboration and exchange among institutions are relatively insufficient, and future research in the field of AI for environmental protection should strengthen multi-institutional cooperation. The density of the cooperation network among institutions in this field is only 0.0056, and the centrality of high-yield institutions approaches zero, indicating that the research forces are generally scattered and locally concentrated. This phenomenon is not accidental but a precise reflection of the structural characteristics of the cross-disciplinary field of artificial intelligence for environmental protection. Firstly, the disciplinary barriers prevent the AI research entities and environmental application entities from deeply integrating in their cooperation. Secondly, the local nature of environmental issues and the data island effect results in the research forces being highly dispersed at the geographical and institutional levels. The high-yield institutions have each formed relatively stable internal cooperation clusters, but there is a lack of effective connections between the clusters, and knowledge flow is blocked, and no cross-disciplinary or cross-regional knowledge circulation hubs have yet been formed. If we aim to promote the integration and breakthrough innovation in the field of AI for environmental protection, it is essential to build a bridge-like platform or collaborative mechanism that connects various isolated clusters.

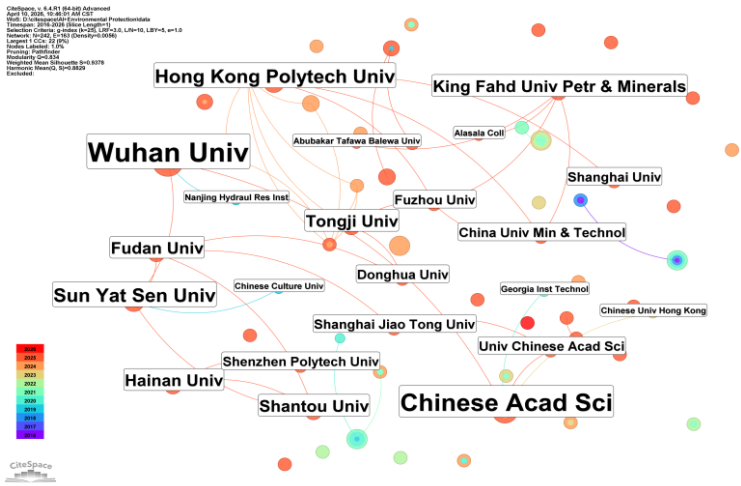


Figure 2. Institutional co-occurrence network

In Table 1, there are eight institutions with four or more publications in this field, namely Wuhan Univ, Chinese Acad Sci, Guangzhou Univ, Hong Kong Polytech Univ, Sun Yat Sen Univ, Duy Tan Univ, Huazhong Univ Sci & Technol, and COMSATS Univ Islamabad, among which six are from China.

Table 1. Top 8 institutions

Rank	Institutions	Count	Year
1	Wuhan Univ	9	2019
2	Chinese Acad Sci	7	2020
3	Guangzhou Univ	4	2024
3	Hong Kong Polytech Univ	4	2025
3	Sun Yat Sen Univ	4	2019
3	Duy Tan Univ	4	2019
3	Huazhong Univ Sci & Technol	4	2016
3	COMSATS Univ Islamabad	4	2021

In Table 2, in the research on AI for environmental protection, Chinese scholars have published the largest number of papers, totaling 230, which accounts for approximately 50.54% of the total publications. They are followed by scholars from the USA, India, South Korea, and Saudi Arabia, each with 25 or more publications. Among these countries, Chinese scholars started the earliest in this field. This may be associated with China's green development policies.

Table 2. Top 5 countries

Rank	Countries	Count	Year
1	CHINA	230	2016
2	USA	51	2019
3	INDIA	27	2019
4	SOUTH KOREA	25	2019
5	SAUDI ARABIA	25	2019

3.3. Reference Co-citation Network

The citation network of literature is a knowledge graph composed of cited references. Table 3 presents the data of highly cited literature in the research field of AI for environmental protection. The "Count" column indicates the total number of times this reference has been cited in the entire literature dataset (those papers imported into CiteSpace). The higher the count is, the more frequently it is mentioned in the papers within that research field. Generally, this indicates that the academic contribution and foundational status of this literature are higher. The "Centrality" column represents the degree to which this literature acts as a "bridge" in the network. The higher the value (usually greater than 0.1), the greater the contribution of this literature in connecting different research directions and promoting the integration of the field; however, no values greater than 0.1 appeared in this dataset, indicating that the knowledge flow within this field is not smooth, and each sub-topic is relatively isolated, lacking a strong integrator. As can be seen from Table 3, there are 11 references that have been cited together at least 5 times. Among them, the four papers−"the role of artificial intelligence in achieving the Sustainable Development Goals" [2], "artificial intelligence for sustainability: challenges, opportunities, and a research agenda" [3], "how does artificial intelligence affect green economic growth?-Evidence from China" [4], and "robots and jobs: evidence from US labor markets" [5]−have high influence.

Table 3. Top 11 Cited References

Rank	Count	Centrality	Year	Cited Reference
1	11	0.01	2020	Vinuesa R, 2020, NAT COMMUN, V11, P0, DOI 10.1038/s41467-019-14108-y
2	9	0.01	2020	Nishant R, 2020, INT J INFORM MANAGE, V53, P0, DOI 10.1016/j.ijinfomgt.2020.102104
2	9	0	2022	Zhao PY, 2022, SCI TOTAL ENVIRON, V834, P0, DOI 10.1016/j.scitotenv.2022.155306
2	9	0	2020	Acemoglu D, 2020, J POLIT ECON, V128, P2188, DOI 10.1086/705716
5	8	0	2021	Zhang CM, 2021, J IND INF INTEGR, V23, P0, DOI 10.1016/j.jii.2021.100224
6	6	0	2023	Tian HN, 2023, TECHNOL FORECAST SOC, V194, P0, DOI 10.1016/j.techfore.2023.122732
6	6	0.01	2024	Wang Q, 2024, J CLEAN PROD, V447, P0, DOI 10.1016/j.jclepro.2024.141298
6	6	0	2021	Ahmad T, 2021, J CLEAN PROD, V289, P0, DOI 10.1016/j.jclepro.2021.125834
9	5	0	2022	Liu J, 2022, SOCIO-ECON PLAN SCI, V83, P0, DOI 10.1016/j.seps.2020.101002
9	5	0	2022	Yang CH, 2022, RES POLICY, V51, P0, DOI 10.1016/j.respol.2022.104536
9	5	0	2024	Zhou W, 2024, ENERG ECON, V131, P0, DOI 10.1016/j.eneco.2024.107355

4. Visual Analysis of Research Focuses

4.1. Keyword Co-occurrence Analysis

Using CiteSpace, a keyword co-occurrence map was generated to reflect hot topics in research on AI for environmental protection. As shown in Figure 3, the map contains 325 nodes (N=325) and 533 links (E=533), with a link density of 0.0101. Different colors of nodes and links correspond to different years.

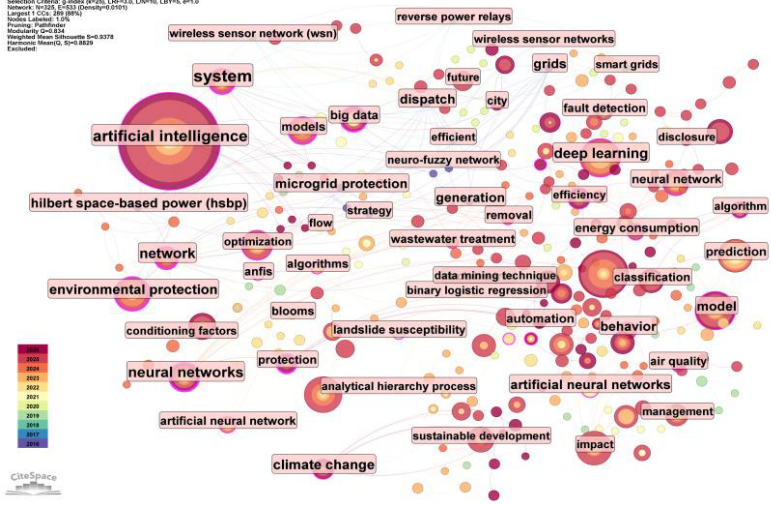


Figure 3. Keyword co-occurrence network

In Table 4, the top ten keywords in this field are AI, machine learning, deep learning, model, performance, prediction, impact, environmental protection, optimization, neural networks. For example, in terms of environmental protection, some scholars have proposed an advanced AI framework for environmental development and protection, with the aim of enhancing contemporary culture and the economy [6]. Some scholars have conducted research to explore the environmental protection practices of China's leading enterprises in dealing with various extreme climate events, and focused on analyzing the roles played by AI and government assistance in this process. [7].

Table 4. Top 10 high-frequency keywords

Rank	Count	Centrality	Year	Keywords
1	179	0.18	2016	artificial intelligence
2	46	0.01	2021	machine learning
3	29	0.12	2020	deep learning
4	27	0.16	2019	model
5	25	0.00	2019	performance
6	24	0.09	2019	prediction
7	22	0.05	2022	impact
8	21	0.23	2016	environmental protection
9	15	0.15	2022	optimization
10	14	0.30	2020	neural networks

4.2. Keyword Clustering Analysis

The keyword clustering map presents the research hotspots in a thematic manner, thereby revealing the key points of research in that field. The effectiveness of this map is usually evaluated by using the modular value (Q value) and the average silhouette value (S value), both of which have a range of [0, 1]. Specifically, a Q value greater than 0.3 indicates a significant clustering structure; an S value greater than 0.5 implies a reasonable clustering result; and if the S value exceeds 0.7, it suggests an efficient clustering with strong persuasiveness. [8]. The keyword clustering map of AI for environmental protection (see Figure 4) consists of 325 nodes (N = 325) and 533 connections (E = 533), with a network density of 0.0095. Its Q value reaches 0.834, which is much higher than the critical value of 0.3, indicating a significant clustering structure; the S value is as high as 0.9378, not only greater than 0.7 but also approaching 1, suggesting extremely high clustering efficiency.

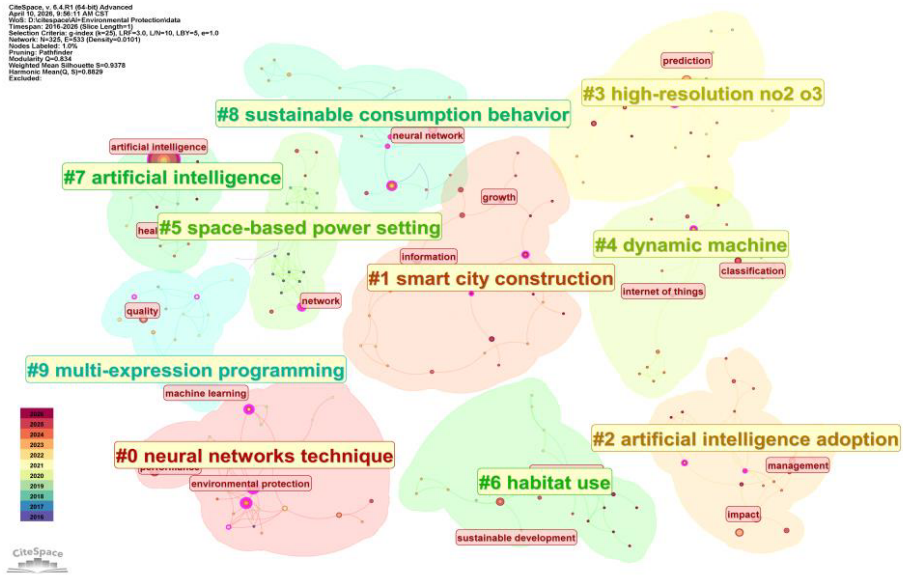


Figure 4. Keyword clustering map

Figure 4 presents ten clusters, namely neural networks technique (#0), smart city construction (#1), artificial intelligence adoption (#2), high-resolution no2 o3 (#3), dynamic machine (#4), space-based power setting (#5), habitat use (#6), artificial intelligence (#7), sustainable consumption behavior (#8), and multi-expression programming (#9). These ten clusters represent the key themes in academic research on artificial intelligence for environmental protection. With respect to neural network techniques, research has proposed a neural network-based predictive and control system for regulating building environmental parameters, with the objective of reducing unnecessary energy consumption in intelligent buildings [9]. With respect to smart city construction, some scholars have recognized the substantial potential of AI in the development of smart cities and the transformation of urban energy systems [10]. With respect to artificial intelligence adoption, the academic community generally

recognizes the significant role of the adoption of AI in environmental protection, and specifically examines and studies it from aspects such as the green transformation of high-energy-consuming enterprises [11], low-carbon agriculture [12], water pollution control [13], and the ESG performance of enterprises [14]. With respect to high-resolution no2 o3, artificial intelligence technology is conducive to the high-resolution monitoring, analysis and prediction of air pollutants (NO2, O3, etc) [15]. These clusters mainly deal with modern management issues, namely, what role artificial intelligence technology plays in the specific application of environmental protection, how it functions, what difficulties and challenges it encounters, and how they are addressed.

5. Conclusions

AI technology has been extensively applied to environmental protection, precipitating profound transformations within the domain. This paper employed CiteSpace to generate a series of knowledge maps, thereby elucidating the research landscape, salient thematic foci, and developmental trends pertaining to AI for environmental protection.

In the field of AI for environmental protection, scholarly output has exhibited exponential growth since 2024, and this upward trajectory is likely to persist in the future, driven by ongoing advances in artificial intelligence technologies and the escalating severity of global climate and environmental challenges. Among all countries and regions worldwide, China maintains a commanding lead in research on this topic, accounting for more than half of the total publication volume. However, the research forces are extremely unevenly distributed geographically and institutionally. There is no yet a close and coordinated relationship among various institutions. It is suggested to establish a cross-institutional cooperation platform or mechanism to promote the integration of knowledge and innovative research in this field. The keyword co-occurrence map reveals that the extant literature predominantly concentrates on the positive ramifications of AI technology for environmental protection and on their practical implementation within specific subfields. Furthermore, the keyword cluster map indicates that considerable scholarly attention has been directed toward the role of artificial intelligence technologies in advancing environmental protection within domains such as smart city construction, electric power systems, habitat use, and sustainable consumption behavior. The application of AI technology in environmental protection is becoming increasingly widespread and its role is becoming more prominent. It is suggested that a global performance evaluation system for AI in environmental protection be established to ensure that the relevant data is reliable during the period of rapid growth from 2024 to 2026.

This study has certain limitations. The data source is restricted to the SCI-EXPANDED and SSCI databases within the Web of Science Core Collection, which may result in incomplete analytical findings. Moreover, as research in this field continues to evolve, bibliometric analysis may not promptly capture the latest research advances and outcomes. Overall, the use of CiteSpace to generate scientific knowledge maps illustrating the current state and trends of research in artificial intelligence for environmental protection can assist scholars and artificial intelligence practitioners in conducting related research or making management decisions. In the future, against the

backdrop of the in-depth penetration of AI technology into ecology and environmental protection, emerging issues, new opportunities, and pathways arising from this development will receive broader attention.

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DCSR-Net: A Dual-Axis Context and Spatial-Channel Refinement Network for PV Segmentation in Remote Sensing Images

Yongkun NIE, [a] Junjie ZHU, [b] Yu CHEN, [a] Wen WENG, [a] Jintao ZHU, [b] Hao WU [b] and Jie ZHANG [c,1]

[a] *Huaneng (Fujian) Energy Development Co., Ltd. Clean Energy Branch. Fuzhou, China*

[b] *China Huaneng Clean Energy Research Institute Co., Ltd. Beijing, China*

[c] *College of Physics and Information Engineering, and Institute of Micro-Nano Devices and Solar Cells, Fuzhou University, Fuzhou, China*

ORCiD ID: Jie Zhang https://orcid.org/0009-0007-3954-0177

Abstract. The current methods for segmenting photovoltaic (PV) from remote sensing images still face problems such as complex backgrounds, dense array distributions, scale variations, and discontinuous boundaries. To address these issues, this paper proposes DCSR-Net, a PV segmentation network that integrates dual-axis contextual modeling with spatial-channel refinement. In particular, the Dual-Axis Context Retention Module (DCRM) is introduced to capture long-range spatial dependencies, while the Spatial-Channel Feature Refinement Module (SCFRM) is designed to enhance feature discrimination and boundary recovery in the decoding stage. Experiments on three public datasets, namely PV01, PV03, and PVP, demonstrate that DCSR-Net achieves superior performance and good cross-scene adaptability. Compared with representative methods, the proposed method obtains better results on multiple evaluation metrics, especially on the PVP dataset. Visual results further confirm its effectiveness in preserving structural continuity and reducing missed segmentation, missed detections, and boundary adhesion.

Keywords. photovoltaic segmentation, remote sensing imagery, spatial-channel refinement, semantic segmentation

1. Introduction

With the expansion of photovoltaic (PV) power generation scale, the maintenance cost of PV modules has also increased. How to efficiently count the location information, shape features and maintenance status of PV modules has become a key issue that needs to be urgently addressed. The precise segmentation and recognition of PV modules not only

[1] Corresponding Author: Jie Zhang, College of Physics and Information Engineering, and Institute of Micro-Nano Devices and Solar Cells, Fuzhou University, Fuzhou, China. Email: zhangjie@fzu.edu.cn

have significant application value in intelligent fault detection, but also can be combined with image segmentation and measurement technology to quickly assess the PV installed capacity of large-scale areas, providing important references for the future planning of PV power stations. Therefore, image segmentation technology has demonstrated its great practical significance in the daily monitoring, intelligent operation and maintenance, and construction planning of PV power stations [1,2,3].

In recent years, deep learning techniques have made remarkable progress in the field of computer vision. Through end-to-end learning, models can extract texture, shape, and context information of PV components, demonstrating stronger robustness in complex backgrounds and diverse scenarios. In response to the characteristics of small targets, multi-scale, and blurred boundaries of PV arrays, various improvement methods based on convolutional neural networks (CNN) have been proposed. Zhang et al. [4] introduced a multi-scale feature fusion mechanism based on the U-Net framework, which integrates semantic information from different levels to enhance the model's expression ability for PV components of different sizes, thereby effectively alleviating the performance degradation caused by scale changes in remote sensing images. Wang et al. [5] improved the DeepLabv3+ structure to address the problem of easy missed detection of small targets in high-resolution remote sensing images, significantly enhancing the segmentation performance of small target areas by strengthening feature expression capabilities. Yu et al. [6] introduced an asymmetric convolution-based multi-level feature fusion (MFF) module, effectively mitigating the influence of background noise and restoring lost detail information in deep features. Additionally, Shan et al. [7] introduced a boundary-aware branch to improve the problems of blurred and broken boundaries of PV arrays, further enhancing the segmentation accuracy.

Compared with traditional CNN methods, Transformer-based models focus more on the modeling of global context relationships and demonstrate stronger capabilities in long-range dependency modeling. Li et al. [8] constructed a PV array segmentation model based on the Mask2Former framework, which enhanced the understanding of the spatial distribution patterns of PV arrays by leveraging its global modeling capabilities, thereby achieving better segmentation results in complex scenarios. Xie et al. [9] designed a lightweight segmentation model based on SegFormer, which achieved multi-scale feature modeling through hierarchical Transformer encoders, reducing computational costs while maintaining accuracy. Additionally, to address the distribution differences of PV arrays in different regions, Wang et al. [10] proposed an improved model based on a multi-scale attention mechanism, which enhanced the model's generalization ability across resolution data by adaptively weighting features of different scales.

Although existing segmentation methods have shown significant progress in general scenarios, the segmentation task for PV module images still faces many challenges. Firstly, PV images usually contain complex backgrounds, and these backgrounds have certain similarities in texture and structure with PV modules, which can easily lead to mis-segmentation. Secondly, PV modules in remote sensing images typically present regular and fine-grained structural features, and due to imaging factors, the segmentation boundaries are prone to discontinuities or jagged issues.

To address the above issues, we propose a dual-axis context and spatial channel refinement integrated PV segmentation network, DCSR-Net, to enhance the model's discrimination ability for complex backgrounds and improve its expression ability for fine-grained structures, thereby achieving more accurate PV module segmentation. The main

contributions of this paper are as follows: The main contributions of this paper are as follows:

1. A novel PV segmentation network, termed DCSR-Net, is proposed by integrating dual-axis contextual modeling with spatial-channel refinement to address the challenges of dense array distribution, complex backgrounds, and boundary discontinuity in remote sensing-based PV segmentation.
2. A Dual-Axis Context Retention Module (DCRM) is introduced to efficiently capture long-range spatial dependencies, thereby enhancing global contextual representation and improving the structural consistency of PV segmentation.
3. A Spatial-Channel Feature Refinement Module (SCFRM) is designed to strengthen feature discrimination and improve the recovery of boundary details and structural information during decoding, leading to more accurate segmentation results in complex scenes.

2. Methodology

2.1. Overall Architecture of DCSR-Net

To address the issues of dense arrangement and significant scale variation of PV panels in the remote sensing segmentation task of PV panels, this paper proposes a dual-axis context and spatial channel refinement network. It adopts an encoder-decoder structure, with the encoder composed of six feature extraction units, gradually mapping the input image into high-dimensional multi-scale semantic features, and the number of channels increasing successively to 16, 32, 64, 128, 256, and 512. Each layer's feature extraction unit is based on lightweight convolution and residual connections, reducing computational cost while enhancing the ability to model local patterns. At the end of the encoder, a DCRM is introduced to enhance the global context expression ability of deep features.

During the decoding stage, DCSR-Net adopts a step-by-step upsampling and skip fusion approach to restore spatial resolution. Considering that PV arrays have highly regular arrangement and directional texture, a SCFRM is introduced in the decoding stage to adaptively fuse the features after fusion. Finally, the refined features are output as the segmentation result through a 3×3 convolutional layer.

2.2. Spatial-Channel Feature Refinement Module

In the PV panel segmentation task, the target regions typically have features such as regular arrangement and repetitive textures, while the background regions often contain interfering structures similar to PV panels, such as roads and building rooftops. Conventional convolution, due to its limited local receptive field, is prone to causing foreground fragmentation or boundary blurring during the decoding stage. Therefore, we designed the SCFRM, as shown in Fig.1.

Specifically, the input feature X is first subjected to average pooling along the width and height directions respectively in the spatial dimension to capture directional descriptions:

$$X_h = \mathrm{AvgPool}_w(X) \in \mathbb{R}^{C\times H}, \quad X_w = \mathrm{AvgPool}_h(X) \in \mathbb{R}^{C\times W} \tag{1}$$

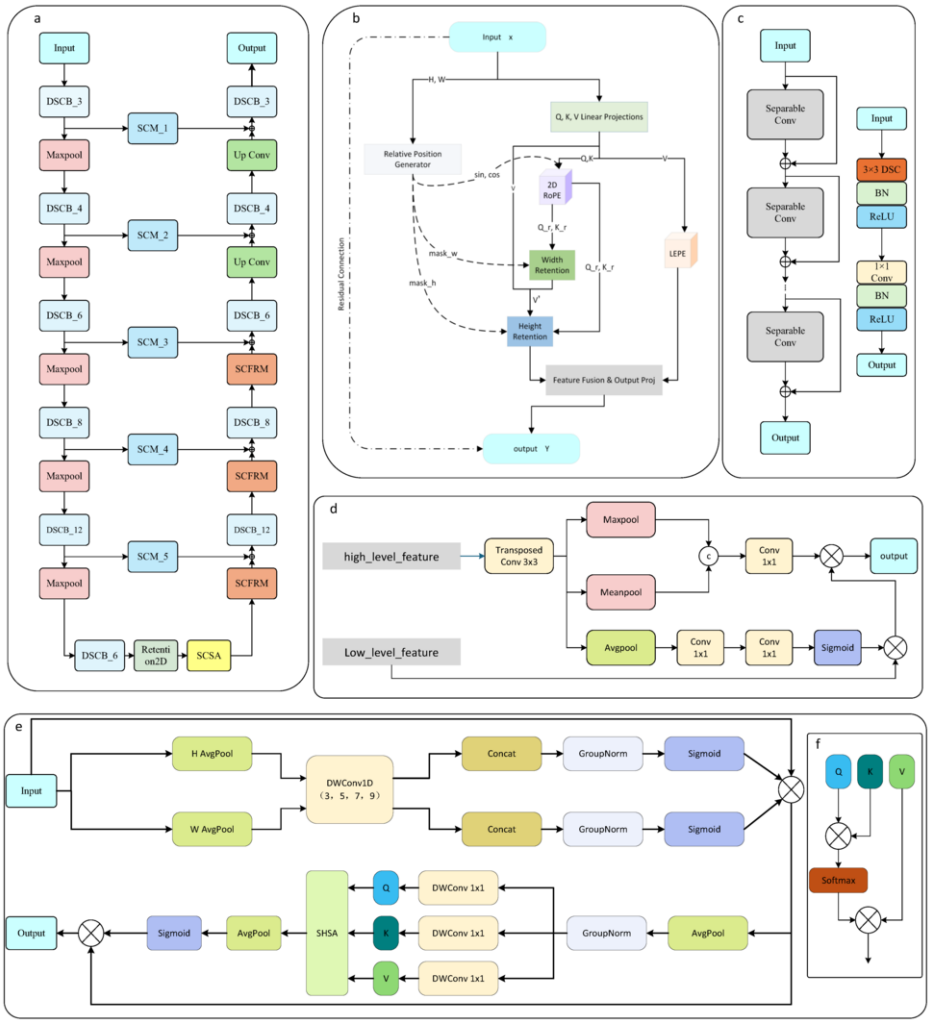


Figure 1. Overall Architecture of DCSR-Net. (a) DCSR-Net. (b) DCRM. (c) DSCB. (d) SCM. (e) SCFRM. (f) SHSA.

where AvgPool represents global average pooling. Subsequently, to balance local details and the global context, the channel dimension is divided into four groups, and one-dimensional depthwise separable convolutions with kernel sizes of 3, 5, 7, and 9 are respectively applied for modeling. Taking the height direction as an example, its spatial attention representation can be written as:

$$A_h = \sigma\left(\mathrm{GN}\left(\mathrm{Concat}\left(\phi_3(X_h^1), \phi_5(X_h^2), \phi_7(X_h^3), \phi_9(X_h^4)\right)\right)\right) \tag{2}$$

where $\phi_k(\cdot)$ denotes a 1D depthwise convolution with a kernel size of k, GN represents the group normalization operation, and σ is the gating function. Similarly, the spatial attention map in the width direction, A_w, can be obtained through an analogous process.

The spatially enhanced feature X_s is formulated as:

$$X_s = X \odot A_h \odot A_w \tag{3}$$

Based on spatial enhancement, SCFRM further models the channel relationship. Specifically, X_s is first downsampled and linearly mapped through 1×1 depthwise separable convolution to generate query (Q), key (K), and value (V) representations. Then, it passes through the SHSA module. Finally, the channel weights are generated by combining global average pooling with gated mapping, and the output feature Z is expressed as:

$$Z = X + \alpha\,(\sigma\,(\mathrm{AvgPool}(M)) \odot X_s) \tag{4}$$

where α denotes a learnable parameter.

2.3. Dual-Axis Context Retention Module

PV arrays usually exhibit strong structural consistency and directional continuity. However, conventional convolution operations are constrained by local receptive fields and thus have limited ability to capture long-range dependencies among distant pixels, which may result in discontinuous or semantically inconsistent segmentation. To address this issue, the proposed DCRM is introduced to model long-range spatial dependencies with relatively low computational cost, thereby improving the completeness and consistency of PV segmentation. The architecture of DCRM is shown in Fig. 1.

Given an input feature map $X_0 \in \mathbb{R}^{B\times C\times H\times W}$, it is first rearranged into $X \in \mathbb{R}^{B\times H\times W\times C}$. Then, three linear projections are applied to generate the query, key, and value features:

$$Q = XW_q, \qquad K = XW_k, \qquad V = XW_v, \tag{5}$$

where W_q, W_k, and W_v are learnable projection matrices. The channel dimension is evenly divided into h heads, and the dimension of each head is denoted by $d = C/h$.

To incorporate spatial positional information, rotary positional encoding is applied to Q and K:

$$\widetilde{Q} = \Theta(Q, \sin, \cos), \qquad \widetilde{K} = \Theta(K, \sin, \cos), \tag{6}$$

where $\Theta(\cdot)$ denotes the rotary transformation, and sin and cos are position-dependent encoding terms generated by the relative position module.

To avoid the quadratic complexity of full 2D attention, DCRM adopts an axial retention strategy by decomposing spatial dependency modeling into width and height directions:

$$\begin{aligned} A_w &= \mathrm{Softmax}\left(\frac{\widetilde{Q}_w \widetilde{K}_w^T}{\sqrt{d}} + M_w\right), \quad V_w = A_w V, \\ A_h &= \mathrm{Softmax}\left(\frac{\widetilde{Q}_h \widetilde{K}_h^T}{\sqrt{d}} + M_h\right), \quad V_h = A_h V_w, \end{aligned} \tag{7}$$

where M_w and M_h denote the head-wise distance-decay masks along the width and height directions, respectively.

To enhance local structural information, a locally enhanced positional encoding branch is introduced on the value features, and the final output is obtained through output projection and residual fusion:

$$V' = V_h + \mathrm{LEPE}(V), \qquad Y = X + \gamma \cdot \mathrm{Proj}(V'), \tag{8}$$

where $\mathrm{LEPE}(\cdot)$ is implemented by depthwise convolution, $\mathrm{Proj}(\cdot)$ denotes the output linear projection, and γ is a learnable scaling parameter.

3. Experiment

3.1. Datasets

To evaluate the effectiveness of the proposed method for PV image segmentation, experiments were performed on three datasets, PV01[11], PV03[11], and PVP [12]. These datasets present evident differences in spatial resolution and scene complexity, enabling a comprehensive assessment of the proposed model under varying target scales, illumination conditions, and complex backgrounds.

3.2. Experimental Settings and Evaluation Metrics

All experiments were conducted on a Windows 10 platform with an Intel Core Ultra 7 Processor 265KF CPU (3.9 GHz) and an NVIDIA RTX 4090 GPU with 24 GB memory. The proposed model was implemented using the PyTorch framework.

All images were resized to 512×512 for input consistency. Random flipping and random rotation were adopted for data augmentation during training. The loss function was defined as the sum of BCE loss and Dice loss, and stochastic gradient descent (SGD) was used for optimization. For fair comparisons, all competing methods were trained under identical hyperparameter settings, including a batch size of 8, 100 training epochs, and an initial learning rate of 0.04. A cosine annealing strategy was further employed to adjust the learning rate dynamically.Segmentation performance was evaluated using four metrics, namely mIoU, mPrecision, mRecall, and mF1-Score.

3.3. Comparative Experiments

To validate the effectiveness of the proposed model, comparative experiments were conducted against several representative semantic segmentation methods, including PSPNet [13], DeepLabV3+ [14], SegFormer [15] and MSLAUNet [16]. The quantitative results on the three datasets are presented in Table 1. Overall, DCSR-Net achieves competitive performance on PV01 and PV03, and shows a more evident advantage on the challenging PVP dataset. Specifically, on PV01, DCSR-Net obtains the Better results on evaluation metrics, with an mIoU of 94.78%. On PV03, where the performance gap among methods is relatively small, DCSR-Net still achieves the best mIoU (95.02%) and mF1-Score (97.44%). On PVP, DCSR-Net again delivers the best performance, reaching an mIoU of 93.43% and an mF1-Score of 96.58%, showing clear advantages over the

Table 1. Comparative experimental results on different dataset subsets.

Dataset	Model	mIoU (%)	mPrecision (%)	mRecall (%)	mF1-score (%)
PV01	PSPNet	94.47	97.19	97.10	97.14
	DeepLabV3+	94.23	96.89	97.14	97.01
	SegFormer	92.35	95.53	96.49	95.99
	MSLAUNet	94.74	97.15	**97.42**	97.28
	DCSR-Net (Ours)	**94.78**	**97.28**	97.33	**97.30**
PV03	PSPNet	94.66	97.02	97.48	97.24
	DeepLabV3+	94.58	96.89	97.52	97.20
	SegFormer	94.01	96.63	97.18	96.90
	MSLAUNet	94.92	**97.22**	97.54	97.38
	DCSR-Net (Ours)	**95.02**	97.18	**97.70**	**97.44**
PVP	PSPNet	90.94	95.22	95.17	95.20
	DeepLabV3+	90.93	95.11	95.28	95.19
	SegFormer	91.46	95.22	95.77	95.49
	MSLAUNet	92.47	96.02	96.08	96.05
	DCSR-Net (Ours)	**93.43**	**96.42**	**96.74**	**96.58**

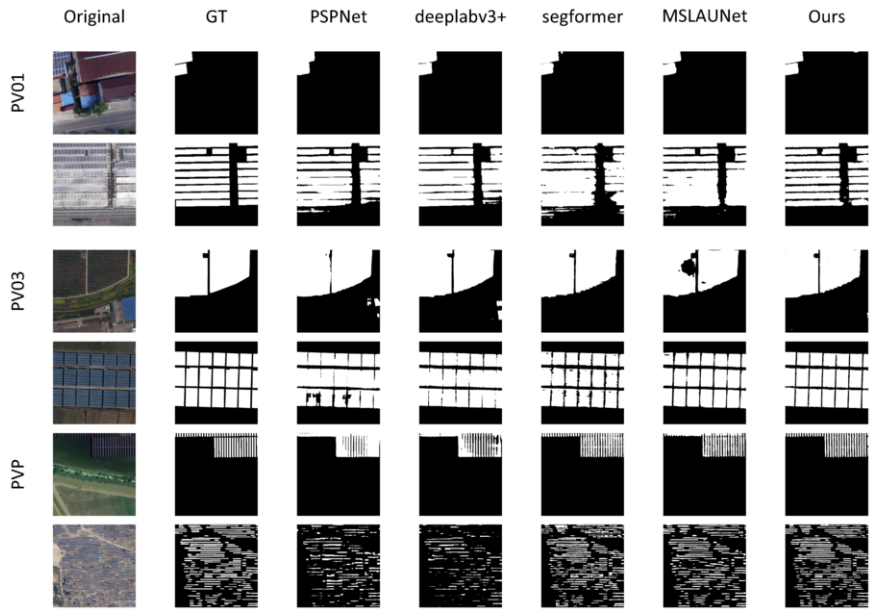


Figure 2. Visual comparison results of different methods on the PV01, PV03, and PVP datasets.

compared methods. The visual comparison results are shown in Fig. 2. On PV01, the compared methods tend to suffer from incomplete structures and missing boundary details, whereas DCSR-Net produces more complete and accurate segmentation results. On PV03, DCSR-Net better preserves structural consistency and reduces discontinuous pre-

dictions. On PVP, where background interference is more severe, the compared methods are more prone to missed detections and jagged boundaries, while DCSR-Net effectively suppresses background noise and yields more reliable segmentation results.

3.4. Ablation Experiments

Table 2. Ablation results of different modules on the dataset subsets.

Dataset	Model	mIoU (%)	mPrecision (%)	mRecall (%)	mF1-Score (%)
PV01	Baseline	94.12	96.91	97.00	96.95
	+SCFRM	94.42	97.24	96.99	97.12
	DCSR-Net	**94.78**	**97.28**	**97.33**	**97.30**
PV03	Baseline	94.77	97.04	97.58	97.30
	+SCFRM	94.74	97.10	97.48	97.29
	DCSR-Net	**95.02**	**97.18**	**97.70**	**97.44**
PVP	Baseline	93.16	96.13	**96.74**	96.43
	+SCFRM	93.23	96.32	96.62	96.47
	DCSR-Net	**93.43**	**96.42**	**96.74**	**96.58**

To investigate the effectiveness of the DCRM and SCFRM modules in the proposed DCSR-Net, ablation experiments are conducted on the PV01, PV03, and PVP datasets. As reported in Table 2, We construct the complete DCSR-Net model by sequentially stacking the modules to varying degrees. After introducing the SCFRM module alone, the mIoU and mPrecision of the model on the PV01 dataset increase by 0.30% and 0.33%, respectively, indicating that SCFRM can effectively enhance feature fusion and semantic representation capabilities, thereby improving segmentation performance. By constructing the complete DCSR-Net model, the model achieves the best results on all datasets, with mIoU values of 94.78%, 95.02%, and 93.43% on the PV01, PV03, and PVP datasets, respectively, demonstrating its superior segmentation capability.

4. Conclusion

This paper proposes DCSR-Net for PV segmentation by integrating dual-axis contextual modeling with spatial-channel refinement. By introducing DCRM and SCFRM, the proposed method enhances global context modeling and improves the recovery of boundary details and structural information, thereby improving segmentation accuracy in regular layouts and complex background scenes. Experiments on three public datasets demonstrate that DCSR-Net achieves superior performance and good cross-scene adaptability. Compared with representative methods, DCSR-Net obtains better results on multiple evaluation metrics, especially on the PVP dataset. Visual results further confirm its effectiveness in preserving structural continuity and reducing mis-segmentation, missed detections, and boundary adhesion. Meanwhile, DCSR-Net contains 7.950M parameters and requires 18.812G FLOPs, indicating that it maintains a relatively low model complexity while achieving competitive segmentation performance. Future work will focus on lightweight design and improved generalization in more challenging scenarios.

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Automated Cybersecurity Incident Response Mechanism Based on DeepSeek Agent

Guanghua Qiu, Zheng Wang, Chuyi Zou and Weibo Huang [1]
Guangdong University of Foreign Studies, Guangzhou, China

Abstract. With the rapid development of the digital economy, cyber threats have become increasingly complex and concealed. Traditional security responses suffer from high false positives, slow reaction, inability to handle unknown attacks, and personnel shortages with alert overload. To address these issues, this paper proposes an automated cybersecurity incident response mechanism driven by an intelligent agent based on the DeepSeek large language model, which takes the integration of Retrieval-Augmented Generation (RAG) technology, security knowledge graph, and intelligent agent as the core design concept. The mechanism adopts four-layer closed-loop framework and three-layer agent structure (reasoning, security, control). Experimental results show the proposed mechanism significantly outperforms traditional methods in response time, success rate, and false positive rate. This mechanism provides a practical solution for the intelligent transformation of security operations. However, it still has limitations in the generalization of unknown threats, resource consumption, and device compatibility, which will be the focus of future optimization and improvement.

Keywords. Cybersecurity Incident Response，Large Language Model，Intelligent Agent

1. Introduction

With the rapid development of the digital economy, cybersecurity threats have grown increasingly complex and pervasive, accompanied by frequent APT attacks, zero-day vulnerability exploits, and multi-stage coordinated assaults [1]. Cybersecurity offense and defense feature inherent information asymmetry, leaving defenders in a passive position. Meanwhile, industry challenges including the shortage of security personnel and massive alert overload further render conventional defense models inadequate for protecting enterprises and critical information infrastructure. Large Language Models (LLM) and agent technology have emerged as a key direction for intelligent cybersecurity automated response. Leveraging strong semantic understanding, multi-source data fusion and complex reasoning capabilities, the DeepSeek effectively overcomes the limitations of rule-dominated systems such as rigid logic and insufficient

[1] Corresponding Author: Weibo Huang, Center for Contemporary Education Technology, Experimental Teaching Center, Guangdong University of Foreign Studies, China; Email: 172564946@qq.com.

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comprehension, offering an innovative technical solution for automated cybersecurity incident disposal.

2. Study Status

Some scholars argue that rule-based response lacks adaptive capabilities and cannot address zero-day vulnerabilities and evolving attacks. They propose dynamically optimizing response strategies using deep reinforcement learning, which learns from historical and real-time interactions, automatically updates decision-making logic, and improves adaptability to unknown threats [2]. Other scholars contend that security knowledge bases should not be static and fixed; instead, they require multi-source data fusion, semantic extraction, and real-time updating to form a growing, reasoning-capable dynamic knowledge entity that supports adaptive threat response [3]. Meanwhile, some scholars point out that in modern network environments, the volume of alerts often exceeds the manual processing load. Analysts must screen, analyze, and develop response strategies within a limited time, and such a high-load state easily leads to the omission of critical threats while low-value alerts waste resources. The inefficiency of manual processing has become a major cause of delayed incident response [4].

The emergence of SOAR tools has alleviated the shortage of cybersecurity professionals. However, some studies suggest that unknown scenarios cannot be fully automated, meaning humans can never be completely excluded, as uncertainty is inherent in cybersecurity [5]. Some studies indicate that LLM agents possess autonomous reasoning, tool invocation, and contextual memory capabilities, breaking through the static bottlenecks of rule-based SOAR and enabling autonomous decision-making and adaptive response [6]. Meanwhile, other studies conclude that large model agents achieve a full-process closed loop of perception, analysis, response, and evolution, solving the problems of weak adaptability and inability to counter unknown threats in traditional schemes [7]. Furthermore, LLM agents can autonomously extract features from unstructured logs, reconstruct attack chains, and generate response strategies, with the ability of continuous learning and iterative optimization [8]. This research gap highlights the need for a more integrated and reliable intelligent response mechanism.

3. Framework Design of Agent-Based Automated Cybersecurity Incident Response Mechanism Based on DeepSeek

The core framework of the DeepSeek agent-based automated cybersecurity incident response mechanism adopts an interconnected, collaborative four-layer closed-loop architecture: data perception layer, intelligent decision-making layer, execution orchestration layer, and closed-loop optimization layer. The data perception layer, the foundation of the mechanism, collects multi-source security data (traffic, logs, alerts, etc.) via tools like ELK and Fluentd, then processes unstructured data into standardized structured data for subsequent use. As the core hub, the intelligent decision-making layer, centered on the DeepSeek security agent, integrates the large model, RAG, and knowledge graph to achieve incident parsing, threat assessment, strategy generation, device linkage, and memory iteration. The execution orchestration layer converts decision strategies into practical actions (IP blocking, host isolation, etc.) by connecting security devices through APIs and SDKs, feeding back execution results in real time.

The closed-loop optimization layer evaluates system effectiveness quantitatively, collects feedback data to fine-tune the model, update the knowledge base, and enhance adaptability. The four layers form a complete closed loop, addressing traditional security response drawbacks and realizing full-process intelligence, providing reliable technical support for automated security incident handling in complex networks. The overall workflow is shown in Figure 1.

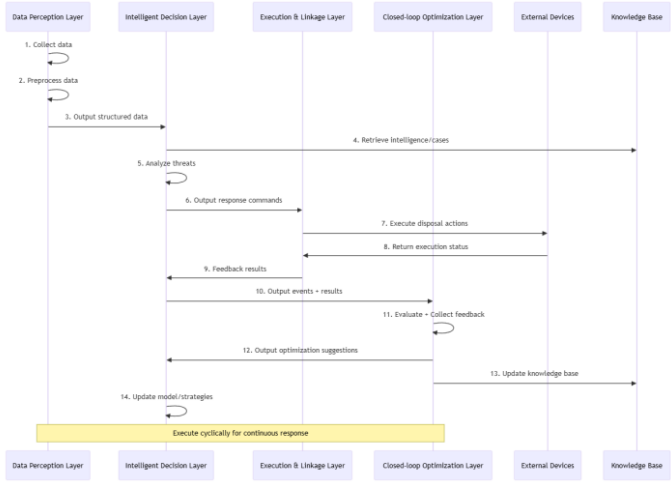


Figure 1. Automated Response Workflow for Cybersecurity Incidents Based on the DeepSeek Agent

With the upgrading of network security protection towards intelligence and automation, the DeepSeek security agent realizes efficient processing, intelligent analysis and closed-loop response of multi-source security data through a collaborative multi-layer architecture. Its core operation logic involves input-output definition, workflow modeling, core mechanism implementation and iterative optimization, forming a complete security protection system. This paper elaborates on its core content and internal logic from three core layers: reasoning, security and control. The DeepSeek security agent takes the DeepSeek as its core reasoning engine and adopts a three-layer architecture consisting of a reasoning layer, a security layer, and a control layer. The three layers cooperate and perform their respective duties to achieve automated response to cybersecurity incidents.

3.1. DeepSeek Security Agent — Reasoning Layer: Definition of Input, Output and Core Functions

As the basic support layer, the reasoning layer clarifies system input-output specifications and decomposes core functions. The system input is a multi-source security data set $X = \{x_1, x_2, \dots, x_n\}$, including four core data types: log data $x_{textlog} = \{t, s, c, m\}$ (timestamp, data source, log category, content), alarm data $x_{textalarm} = \{textid, l, a, d\}$ (alarm ID, level, type, details) pushed by SIEM/XDR platforms, traffic data $x_{textflow} = \{textsrc, textdst, textport, textproto, textbytes\}$ (source/destination IP, port, protocol, traffic size), and threat intelligence data $x_{textintel} = \{v, i, f, t\}$ (vulnerability number, malicious identifier, attack feature, update time). These data form the agent's data foundation.

The system output is an automated response result set $Y = \{y_1, y_2, y_3\}$: $y_1 = \{T, L, S, R\}$ (attack type, threat level, impact scope, false positive probability) as the decision basis; $y_2 = \{o_1, o_2, \backslash dots, o_k\}$ where each executable command o_j consists of $(\backslash texttype, \backslash textobj, \backslash textparam)$; $y_3 = \{P, E, F\}$ (response record, disposal evaluation, optimization suggestions) for closed-loop optimization.

The core function is the mapping $F: X \rightarrow Y$, decomposed into five interlocking functions: F_1 (data preprocessing $X \rightarrow X'$),F_2 (intelligent analysis $X' \rightarrow y_1$),F_3 (decision generation $y_1 \rightarrow y_2$),F_4 (execution linkage $y_2 \rightarrow y_3^p$), and F_5 (closed-loop optimization $y_3 \rightarrow \Delta\theta$), forming a complete functional chain from data input to iterative improvement.

3.2. DeepSeek Security Agent — Control Layer: Core Mechanisms and Optimization

The control layer, the core of intelligent decision-making and continuous optimization, includes four collaborative mechanisms: RAG retrieval, knowledge graph reasoning, hybrid-driven decision-making, and dual closed-loop optimization.

3.2.1 RAG Retrieval Mechanism

Adopting "vector retrieval + keyword retrieval", the RAG mechanism retrieves incident-related knowledge from the security knowledge base $K = \{k_1, k_2, \ldots, k_m\}$ (including CVE details, attack SOPs, etc.) to suppress large model hallucinations. Each $$k_i$$ is vectorized via BERT ($v_{k_i} \in \mathbb{R}^{\mathbb{d}}$) and stored in Milvus.

The retrieval process is standardized: convert$x' \in X'$to query vector v_q via BERT, calculate cosine similarity $\cos(v_q, v_{k_i}) = \frac{v_q \cdot v_{k_i}}{\|v_q\| \cdot \|v_{k_i}\|}$, filter with threshold $\alpha = 0.75$ to get K_c, match keywords (CVE number, attack type, etc.) to get K_r, sort K_r by similarity and input top 5 to the DeepSeek model, ensuring K_r relevance ≥ 85.

3.2.2 Knowledge Graph Reasoning

To realize the restoration of attack chains and the accurate assessment of threat impacts, a security knowledge graph $G = (V, E)$ is constructed in the control layer, where V is the set of nodes and E is the set of edges representing the associations between nodes. The specific definition of the knowledge graph is as follows:

- Node set $V = V_A \cup V_V \cup V_{Att} \cup V_{Action}$, where V_A denotes asset nodes (such as servers, terminals, and network devices), V_V represents vulnerability nodes, V_{Att} stands for attack nodes (such as attack methods and attack stages), and V_{Action} is the set of disposal action nodes;

- Edge set $E = E_{A-V} \cup E_{V-Att} \cup E_{Att-Action} \cup E_{A-A}$,where E_{A-V} represents the association between assets and vulnerabilities (e.g., "asset A has vulnerability V"), E_{V-Att} denotes the association between vulnerabilities and attacks (e.g., "attack Att exploits vulnerability V"), $E_{Att-Action}$ stands for the association between attacks and disposal actions (e.g., "disposal action Action can mitigate

attack Att"), and E_{A-A} represents the association between assets (e.g., "asset A is connected to asset B").

Based on the Graph Neural Network (GNN), the knowledge graph reasoning process includes five key steps to realize attack chain restoration and threat impact assessment:

1. Node initialization: Assign initial feature vectors to each node in the knowledge graph based on the attribute information of the nodes (e.g., vulnerability severity, asset importance);

2. GCN (Graph Convolutional Network) feature update: Update the feature vector of each node by aggregating the feature information of its neighboring nodes, and the update formula is $h_v^l = \sigma\left(\sum_{u \in N(v)} \frac{1}{\sqrt{\deg(v)\,\deg(u)}} h_u^{l-1} W^l + b^l\right)$, where h_v^l is the feature vector of node v at the l-th layer, $N(v)$ is the set of neighboring nodes of v, $\deg(v)$and $\deg(u)$ 0 are the degrees of nodes v and u respectively, W^l is the weight matrix at the l-th layer, b^l is the bias term, and σ is the activation function;

3. Attack path mining: Use the Depth-First Search (DFS) algorithm to mine the potential attack paths in the knowledge graph based on the updated node features, so as to restore the complete attack chain;

4. Impact scoring: Calculate the threat impact score of the attack chain using the formula $\text{Score} = \sum_{v_A \in \text{Path}} \left(\text{severity}(v_V) \times \text{importance}(v_A)\right)$, where v_A is the asset node in the attack path, v_V is the vulnerability node associated with the asset node, $\text{severity}(v_V)$is the severity of the vulnerability, and $\text{importance}(v_A)$ is the importance of the asset;

5. Result output: Output the restored attack chain and the corresponding threat impact score to provide support for subsequent decision-making.

3.2.3 Hybrid-Driven Decision-Making Logic

To balance the standardization of security disposal and the flexibility of handling complex scenarios, the control layer adopts a hybrid-driven decision-making mode combining rule-driven and large model-driven, and the decision-making logic is formally expressed as $y_2 = f_{\text{rule}}(y_1) + f_{\text{LLM}}(y_1, K_r, G_r)$, where f_{rule} is the rule-driven decision function, f_{LLM} is the large model-driven decision function, and G_r is the reasoning result of the knowledge graph.

The rule-driven stage is based on a pre-defined security disposal rule base $R = \{r_i\text{:IF } C_i \text{ THEN } O_i\}$, where C_i is the condition of the rule (e.g., "alarm level is critical and attack type is ransomware") and O_i is the corresponding disposal operation. Through forward reasoning, the basic disposal operation set O_{base} is obtained according to the

decision basis y_1.

The large model-driven stage uses the DeepSeek LLM to verify the rationality of the basic disposal operations in O_{base}, and supplements the supplementary disposal operation set O_{supp} for complex scenarios not covered by the rule base. To ensure the priority of disposal operations, the priority of each operation is calculated using the formula Priority $= 0.6L + 0.4\text{Score}$, where L is the threat level in y_1 and Score is the threat impact score from the knowledge graph reasoning. Finally, all disposal operations are sorted by priority and formatted into the standard executable command set y_2.

In the decision-making process, three core constraints must be followed: first, compliance, that is, all disposal operations must comply with relevant laws, regulations, and enterprise security policies; second, no interruption of core business, that is, the disposal operations shall not affect the normal operation of the enterprise's core business systems; third, no redundant actions, that is, to avoid repeated or unnecessary disposal operations to improve disposal efficiency.

3.2.4 Dual Closed-Loop Optimization Model

To realize the continuous iterative improvement of the DeepSeek Security Agent's performance, the control layer designs a dual closed-loop optimization model, which takes the minimization of the total errorL_{total} as the optimization objective. The total error is comprehensively considered from three dimensions: false alarm rate, disposal failure rate, and delay error, and the calculation formula is $L_{\text{total}} = 0.4L_{\text{false}} + 0.4L_{\text{dispose}} + 0.2L_{\text{delay}}$, where L_{false} is the false alarm rate, L_{dispose} is the disposal failure rate, and L_{delay} is the delay error (the difference between the actual disposal time and the expected disposal time).

The optimization process of the model is a continuous cycle, which mainly includes five key steps:

1. Feedback data collection: Collect the closed-loop data y_3 (response record, disposal evaluation, optimization suggestions) generated in the agent's operation process, and extract key error indicators;

2. Knowledge base update: Update the security knowledge base K

3. based on the feedback data, including adding new attack methods, updating vulnerability information, and supplementing disposal experience;

4. Model fine-tuning: Fine-tune the parameters of the DeepSeek LLM and the GNN model using the feedback data to improve the accuracy of intelligent analysis and reasoning;

5. Rule base optimization: Optimize the security disposal rule base R according to the disposal effect evaluation, including adding new rules for uncovered

scenarios, adjusting the conditions and operations of existing rules, and deleting invalid rules;

6. Effect verification: Verify the optimization effect using the preset threshold $\beta = 0.1$, that is, if the total error $L_{\text{total}} \leq 0.1$, the optimization is effective; otherwise, the optimization process is repeated until the total error meets the threshold requirement.

Through the above five steps, the dual closed-loop optimization model realizes the continuous iteration of the agent's performance, ensuring that the agent can adapt to the changing security environment and continuously improve the security disposal capability.

4. Conclusion

Traditional security operations and maintenance methods that rely on manual analysis and manual strategy configuration generally have problems such as delayed response, inconsistent judgment standards, and difficulty in controlling false positives and false negatives, which can no longer meet the high-frequency and sudden emergency needs of modern network security.

The automated cybersecurity incident response mechanism based on the DeepSeek agent designed in this paper combines the semantic understanding and reasoning capabilities of large models, external security knowledge base retrieval, attack correlation analysis, and standardized response processes. In actual tests, it can quickly complete alert parsing, threat determination, and device linkage response, effectively improving the consistency of threat analysis and judgment, shortening the overall time from threat discovery to blocking execution, and providing a feasible implementation path for the intelligent upgrading of existing security operation processes.

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Efficient Frontend for Microservice-Based Applications

Miloš BARDÁČ [a] and Martin BOBÁK [a,1]
[a] *Institute of Informatics, Slovak Academy of Sciences, Bratislava, Slovakia*
ORCiD ID: Martin Bobák https://orcid.org/0000-0002-2905-4999

Abstract. With the increasing number of microservice-based applications, which offer greater flexibility and easier integration of new modules or services, we observe emerging complications, including higher latency and increased communication complexity. Large data transfers, a growing number of services, and the diversity of data types lead to increased latency, resulting in a negative user experience. The paper analyzes and compares three architectural approaches for modern web applications: monolithic architecture, microfrontend architecture, and microservices architecture using the Backend for Frontend (BFF) pattern, aiming to identify the most suitable approach for mitigating these issues. The implemented solutions are deployed in a Kubernetes environment with an automated CI/CD pipeline and validated under various load levels. The results show that the BFF layer can reduce system latency and improve user interface responsiveness when handling larger data volumes. The monolithic architecture demonstrated lower resource demands, but its scalability is limited. The paper provides a practical perspective on the trade-offs between performance, scalability, and complexity of individual architectural approaches.

Keywords. Microservices, Microfrontend, Monolithic Architecture, System Scalability, Performance Evaluation

1. Introduction

Modern web applications are no longer represented by simple user interfaces communicating with a single server [1]. Growing demands for scalability, availability, and development speed have led applications to be decomposed into a larger number of independent components that continuously communicate with each other over the network.[2] In practice, we can observe an increasing number of new architectural approaches that attempt to optimize existing solutions in various ways. One of the main challenges is optimization of communication between the frontend and backend, particularly in systems with a larger number of independent services [3]. One of the most prominent solutions is the Backend for Frontend design pattern, which aims to optimize communication between the client and server through a specialized layer adapted to the frontend interface. Specifically, it involves shifting part of the data processing logic from the client to the server layer, which can reduce the amount of transferred data and the number of network requests. This approach has the potential to improve application performance and reduce latency [4].

[1]Corresponding Author: Martin Bobák, martin.bobak@savba.sk

2. Related Work

With the growing complexity of modern web applications, the question of latency between the frontend and backend is becoming increasingly discussed [5]. Many papers point out that changes to the system architecture have a fundamental impact not only on its performance and scalability [6], but also on user experience, application management, and the overall cost of the solution.[7] Studies most commonly focus on the implementation and subsequent comparison of various architectural types and approaches, aiming to highlight performance optimization challenges in the context of specific architectural solutions.[8] The literature most frequently refers to three fundamental approaches, each representing trade-offs between performance, maintainability, and solution complexity.

- **Monolithic architecture** represents a model in which all functional parts of the system — frontend and backend — are implemented as a single cohesive unit. Communication between these parts takes place at the internal process level, which results in lower latency, especially in smaller systems. However, in more complex systems, it significantly complicates maintenance and hinders the implementation of new features and system extensions.[9]
- **Microservices architecture** is driven by the principle of decomposing the server-side of the application into smaller, atomic units, each implementing a single specific business functionality. These units typically communicate using synchronous network protocols such as HTTP or RPC.[10] The advantage of this approach is the flexibility and resilience of the system, as individual services can be developed and deployed independently, and the failure of one service does not necessarily cause the failure of the entire system. Among the disadvantages, communication complexity is often discussed, frequently leading to higher latency compared to the monolith, as well as greater demands on operational and infrastructure coordination.[11]
- **Microfrontend architecture** also decomposes the system, but unlike microservices architecture, this decomposition takes place at the frontend level. It shares many characteristics with the microservices architecture. The most significant difference lies in the integration, where the user interface is dynamically assembled from individual components into a single whole on the client side at application load time.[12]

Research groups focusing on monoliths most commonly address migrating such systems to a microservices architecture, followed by an analysis and evaluation of the technical advantages and disadvantages these approaches bring to a specific system.[9] For example, a study from the Vienna University of Technology, which analyzes monolithic architecture, microservices, and microfrontends using Webpack Module Federation on an enterprise application built primarily with Angular, concluded that microfrontend architecture exhibits slower first-page load compared to the monolith without cached resources, but achieves equivalent performance once caching is applied.[7] Overall, the research demonstrated that distributed systems require greater development effort and CI/CD configuration, but are capable of eliminating otherwise obvious disadvantages. Another study compared monolithic architecture with microservices on applications built with Java Spring Boot and ASP.NET Core, measuring throughput, scalability, and resource utilization. Spring Boot demonstrated better performance for computationally in-

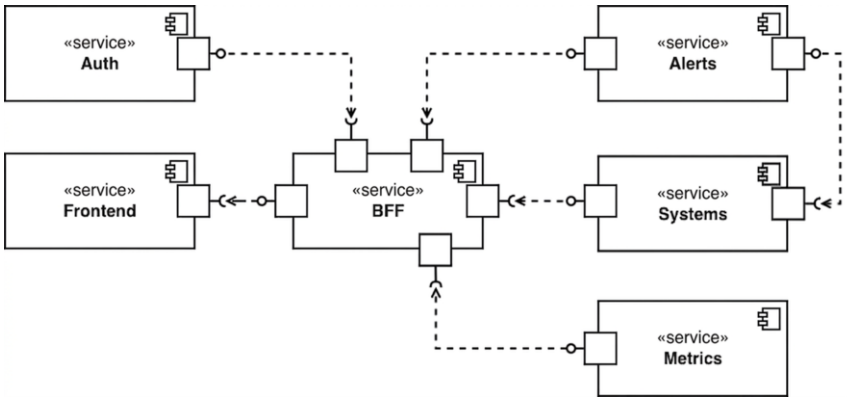


Figure 1. Microservices architecture with a centralized BFF layer

tensive operations, achieving up to twice the throughput in the monolith at low loads, while microservices excelled at scaling beyond 100,000 requests per day.[13] A further study from 2023 developed a tool for testing RESTful APIs in Backend for Frontend (BFF) microservices, monitoring communication between the BFF and backend services. The tool was primarily designed to detect erroneous server responses and thus potential security risks, demonstrating that incorrect implementation not only affects performance but can also significantly increase the vulnerability of the entire system.[14]

3. Microservices-Based Architecture Patterns

In this approach, the application itself is decomposed into smaller, independent units. Each unit should implement only a single business logic functionality and can be deployed, scaled, and developed independently at the level of individual developers, teams, or organizations.[15] An advantage of this approach is that individual parts of the application are not required to use the same technology stack, which may differ across teams. Furthermore, a failure in one part does not automatically result in a failure of the entire system.[16] Combined with the Backend for Frontend (BFF) architectural pattern, which optimizes communication between the frontend and backend, enables efficient aggregation of data from multiple microservices into a single call. BFF also allows responses to be tailored to specific frontend types, since web applications across devices often use interfaces with differing data structures, which significantly simplifies client calls and reduces overall client complexity.[14]

3.1. Backend for Frontend

A Backend for Frontend (BFF) is an additional system layer between the frontend and the server-side of the application (most commonly microservices), aggregating and delivering data to the user (see Figure 1). It addresses the situation in which the frontend must receive and process large amounts of data from multiple endpoints in order to render a page, significantly slowing page load time. The optimization lies in moving the data processing, filtering, and aggregation to the backend, which has greater computational power and better resource utilization. Furthermore, the BFF can retrieve data from multi-

ple sources in parallel and more quickly than the frontend, which communicates with the system over the public internet, resulting in increased latency, especially when transferring large amounts of data.[17] Data processed directly into a form usable by the frontend reduces the amount of unnecessary data and, given its reduced size, is simpler to transfer over the public network, thereby decreasing transfer time without requiring changes to the existing API structure. On the other hand, implementing this layer requires greater resource allocation and utilization, which plays a key role in the scalability and overall performance of the system. This solution is most suitable for systems that support multiple user interfaces, such as mobile phones, tablets, desktops, and televisions. The data structure often differs across these devices. Mobile devices typically require a smaller volume and simpler data, yet they often use the same API calls as other client types.[18] This problem can be easily addressed by implementing a dedicated BFF layer for each interface type, thereby tailoring the data to the specific interface.[19] A further advantage lies in the development of individual frontend parts, as the data processing logic is centralized on the server side. In smaller systems, this layer can be merged with the API gateway, simplifying solution management. However, as the number of BFF layers and different user interfaces grows, such a solution would increase complexity and produce precisely the opposite effect.

3.2. Microfrontend

Microfrontend architecture is similar to microservices. It decomposes the application into independent modules on the frontend. It shares many characteristics with microservices, including the potential for faster parallel development and greater deployment flexibility. Additionally, it brings complications related to maintainability, design consistency, and increased security requirements.[20] Its significant advantage is the ability to use different technologies across the entire project, which can be valuable in cases where a specific part requires a particular technology. Another important aspect is the preferences and technical expertise of the teams implementing and managing the application. Existing studies address this approach and demonstrate that frameworks such as Vue, React, and Angular can work together without disrupting the user experience. However, this requires more complex operations and a high degree of coordination.[21]

4. Results

Evaluation is focused on comparing the performance of the architectures at various load levels with different volumes of processed data. On the frontend side, the following metrics were monitored: 1) First Contentful Paint (FCP) — the time to render the first visual content, 2) Largest Contentful Paint (LCP) — the time to render the largest visual content, 3) Speed Index — the rate at which visual content is progressively rendered, 4) Total Blocking Time (TBT) — the time during which the browser's main thread was blocked. All of these metrics represent the time required to render content for the user and the overall application responsiveness. From the backend perspective, the primary focus was on comparing the approach with and without the BFF layer. Response time at a given number of virtual users, request throughput over a specific time period, and resource utilization under a given load were all evaluated.

Table 1. Comparison of architecture performance depending on the number of records.

Architecture	Record count	FCP [ms]	LCP [ms]	Speed Index [ms]	TBT [ms]
Monolith	100	797	4768	2413	130
Monolith	1 000	794	4775	2328	135
Monolith	10 000	795	4751	2967	191
Monolith	50 000	808	4755	5762	170
Microservices	100	796	4732	2408	127
Microservices	1 000	797	4750	2349	135
Microservices	10 000	796	4725	2860	186
Microservices	50 000	815	4672	6009	173
Microservices with BFF	100	794	4685	2392	146
Microservices with BFF	1 000	794	4625	2294	146
Microservices with BFF	10 000	798	4650	2474	207
Microservices with BFF	50 000	808	4681	3259	253
Microfrontend with BFF	100	796	4993	2541	203
Microfrontend with BFF	1 000	792	4933	2427	218
Microfrontend with BFF	10 000	791	4935	2444	297
Microfrontend with BFF	50 000	798	5035	3035	361

Table 1 presents a comparison of performance metrics for individual architectures at different numbers of database records. FCP and LCP values are nearly identical across all approaches, with the microservices architecture using the BFF layer achieving significantly better results by a few tens of milliseconds. On the other hand, the microfrontend solution is slightly underperformed compared to all other approaches. The difference is more visible in the Speed Index metric, where both BFF-enabled architectures achieve significantly better results. With larger data volumes, this represents nearly a two times improvement. On the other hand, elevated TBT values are observed when using BFF, indicating longer blocking during request processing.

Individual architectures are also compared in terms of computational resource utilization for the same scenario with varying numbers of virtual users. Table 2 shows that the monolithic architecture consistently achieves the lowest memory and CPU utilization. The microservices architecture demonstrated significantly higher resource consumption compared to the monolith, particularly at higher load levels. The highest resource demands among the examined solutions were observed for the microservices architecture with BFF, which at the the highest load achieves more than twice the CPU utilization compared to the monolithic architecture. The BFF layer also consumes considerably more memory even at lower loads.

Figure 2 illustrates the system utilization when the BFF reaches the computational limits of the hardware resources earlier than the implementation without it. Within the defined two-minute window, the system without this layer successfully handled nearly 8,500 more requests from 500 virtual users.

5. Conclusion

The paper demonstrates that modern distributed architecture patterns can significantly influence data processing behavior, user responsiveness, and system resource demands.

Table 2. Comparison of system resource utilization at varying numbers of virtual users

VU count	Resource	Monolith	Microservices without BFF	Microservices with BFF
1	CPU [cores]	0.085	0.232	0.351
	RAM [MiB]	194	219	602
10	CPU [cores]	0.167	0.273	0.402
	RAM [MiB]	219	272	733
50	CPU [cores]	0.516	0.383	0.737
	RAM [MiB]	223	266	768
100	CPU [cores]	0.905	1.516	2.706
	RAM [MiB]	382	696	954
200	CPU [cores]	1.730	3.342	3.748
	RAM [MiB]	731	851	991

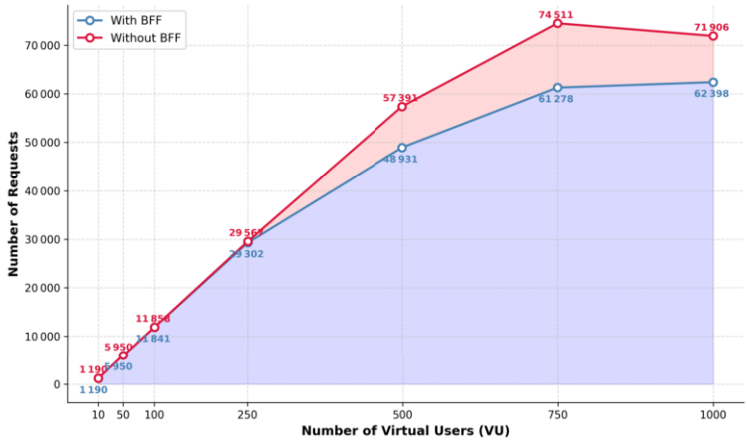


Figure 2. Number of successfully processed requests depending on the number of virtual users

The achieved results showed that individual architectural approaches involve different trade-offs between performance, scalability, and system complexity. The results confirmed the benefits of the Backend for Frontend layer, particularly when handling larger data volumes. On the other hand, it was shown that the BFF layer also brings considerably higher computational requirements and higher memory consumption. Thus, it is necessary to consider not only the system performance, but also the complexity of implementation, deployment, and management of the individual components.

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How Does Native Culture Shape Women's Fertility? Evidence from Guangdong Dialect Groups

Chunhua Gan[a,1] and Ruxin Li[b]
[a] *School of Management, Guangdong University of Science and Technology, China*
[b] *School of Psychology, Shenzhen University, China*

Abstract. Despite the national trend toward low fertility, Guangdong Province has consistently recorded higher birth rates. Drawing on the regional cultural characteristics of Guangdong, this paper examines how native culture shapes women's fertility through these mechanisms: cultural embeddedness, the safeguarding of clan culture, intergenerational family transmission, and the inertial effect of the one-child policy. Using questionnaire data and employing women's native dialects as a proxy for native culture, we uncover the following: (1) Compared to Hakka speakers, both Cantonese and Chaoshan groups show significantly lower fertility propensity, suggesting that Hakka culture carries the strongest fertility potential. (2) Guangdong's higher fertility is largely driven by its indigenous clan culture. Yet this fertility-safeguarding effect is pronounced only among Hakka women and is not significant for Cantonese or Chaoshan women. (3) In terms of intergenerational transmission, compared to Hakka women, those in Cantonese and Chaoshan groups show a weaker inheritance of the previous generation's high fertility pattern. Across all family sizes, the intergenerational transmission of high fertility regimes is significant only for women with two siblings. Only children in Guangdong do not have significantly lower fertility than those with siblings, except among young and urban women. These findings provide new insights for responding to China's low-fertility dilemma, calling for a coordinated culture-policy strategy adapted to local contexts, along with more institutional support for younger generations and only-child groups.

Keywords. Low Fertility; Native Culture; Native Dialect; Clan Culture; Guangdong

1. Introduction

Fertility trajectories worldwide are converging toward low levels. No industrialized nation has succeeded in sustaining the replacement-level fertility rate of approximately 2.1 children per woman [1]. However, nowhere is this trend more acute and paradoxical than in East Asia. What took several generations for some European countries to achieve—ultra-low fertility rates (total fertility rates below 1.3)—has been accomplished by Asian nations such as Japan and South Korea within one or two generations, stubbornly resisting extensive governmental pronatalist policy interventions [2]. China,

[1] Corresponding Author: Chunhua Gan, Guangdong University of Science and Technology–Management School, 99 Xihu Road, Dongguan, Guangdong, 523808, China. Email: gch0323@126.com
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the demographic colossus of East Asia, confronts a rapidly intensifying low-fertility crisis as well. The nation's total fertility rate (TFR) slipped beneath replacement in the mid-1990s and, after hovering near 1.6 for more than two decades, collapsed to a historic low of 1.07 in 2022 [3].

However, against the backdrop of a nationwide low fertility rate, significant differences in fertility rates exist across provinces. Figure 1 reveals that, among all provinces, Guangdong has been the most "fertile" in recent years. In terms of birth rate (typically defined as the number of births per 1,000 people within a year), with the exception of the seven provinces and regions—Tibet, Guizhou, Qinghai, Ningxia, Hainan, and Guangxi—where ethnic minorities constitute a high proportion of the population, Guangdong ranked first in 2022 and 2023 among all provinces. In contrast, Zhejiang, Beijing, and Chongqing—regions with economic levels comparable to Guangdong's—had birth rates that placed them in the lower half of Figure 1, while Jiangsu, Shanghai, and Tianjin ranked at the bottom.

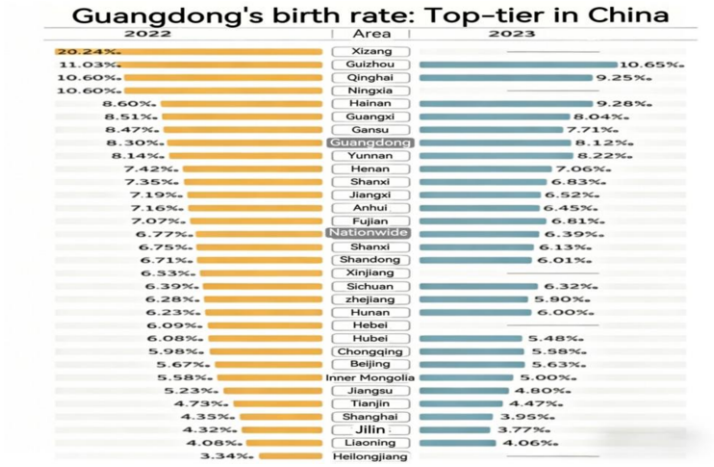


Figure 1. Birth Rates across China's Regions, 2022–2023

Data Source: NetEase Data Insights WeChat Official Account: "The Province with the Highest Birth Rate in China Doesn't Need to Encourage Childbirth," April 21, 2024

Under the same family planning policies, why do regions with similar economic levels exhibit such stark differences in birth rates? More importantly, given the context of a steadily declining national birth rate, why are people in Guangdong the most "fertile"? In response, some scholars argue that this is primarily due to cultural factors, as clan culture is more deeply rooted in southern regions than in the north [4]. However, this view cannot explain why birth rates in regions such as Jiangsu, Chongqing, and Shanghai—all located in the south—are significantly lower than those in Guangdong. Consequently, examining regional cultural disparities and their impact on fertility behavior simply by the geographical division between north and south is insufficient to account for this phenomenon. Instead, it is necessary to conduct in-depth research on the native culture of Guangdong, a region with a higher birth rate, to explore its cultural characteristics and the mechanisms through which they influence women's fertility, thereby identifying cultural pathways to address the low-fertility dilemma.

This study focuses on women in Guangdong, as they directly bear the costs of childbearing and are often the final decision-makers on fertility. Their individual attitudes, reproductive histories, and socioeconomic characteristics offer a more direct

and quantifiable link to fertility outcomes. Against this backdrop, this paper aims to make the following contributions. First, based on the characteristics of Chinese clan culture and the specific impact of the one-child policy, it analyzes the unique cultural shaping mechanisms underlying China's low fertility—namely, the embedding mechanism of native culture, the weakening of the safeguarding mechanism of clan culture, the intergenerational transmission mechanism within families, and the inertial effect mechanism of the one-child policy. Second, taking Guangdong Province as the example, it compares the cultural characteristics of different dialect regions and, empirically tests the impact of these cultural mechanisms on women's fertility. By providing "Guangdong-style" evidence, it identifies cultural forces conducive to promoting fertility.

2. Literature Review, Theoretical Framework and Research Hypotheses

2.1 Literature Review on the Shaping Factors of Low Fertility

Many studies attribute low fertility to economic factors, identifying industrialization, urbanization, and modernization as macro-level drivers of fertility decline, while rising direct child-rearing costs and the "motherhood penalty" [5] serve as micro-level drivers [6]. Policies such as public childcare, improved maternity benefits, and mother-friendly work arrangements were advocated to enhance fertility rates [7]. Yet East Asian countries have achieved only limited success despite adopting similar measures [8]. Consequently, academic research has shifted its focus toward a cultural lens.

Regarding the cultural mechanisms shaping low fertility, the existing literature has emphasized the following dimensions:

(1) The Cultural Embedding Mechanisms of Native Cultures

The Second Demographic Transition (SDT) theory attributes the emergence of low fertility to a values revolution in postmodern society, a shift in individual attitudes from family-centered values to self-actualization and personal freedom [9]. However, among industrialized nations, some have fallen into the low-fertility trap while others maintain fertility rates consistently above 1.5. In response, SDT emphasizes the diversity of fertility patterns, as cultural divergences across societies lead to varying fertility levels [10]. For example, James Feyrer et al. found that fertility rates in English-speaking and non-English-speaking countries have diverged significantly since the 21st century, with the former generally exceeding 1.5 and the latter mostly falling below this level. This is primarily because a society's cultural values and norms are embedded in individuals' lives through media such as language, thereby shaping attitudes and behaviors toward childbearing. Their research reveals that cultural norms in non-English-speaking countries generally reject out-of-wedlock childbearing and feature extremely unequal gender divisions of household labor, resulting in very low rates of non-marital childbearing and slow progress in developing non-family-based child-rearing support systems [11]. However, these studies are primarily based on Western contexts and are difficult to align with China's unique cultural environment.

(2) Intergenerational Transmission Mechanism of Family Fertility

As childbearing is the foundation of family reproduction, extensive research demonstrates that reproductive behavior exhibits significant intergenerational transmission effects within families, manifested as a consistent positive correlation

between the number of a woman's siblings and the number of her own children [12,13]. This transmission effect persists across different historical stages of demographic transition [14]. Socialization is considered the primary influencing factor, driven by the context in which individuals grow up during childhood and adolescence, as parents transmit family values, fertility preferences and attitudes [15-16].

It is worth noting that in China, family planning policies have significantly disrupted intergenerational transmission effects. The implementation of the one-child policy for over three decades has rendered the traditional high-fertility patterns of Chinese families unsustainable. Furthermore, influenced by their parents' fertility behaviors, the one-child generation tends to continue the pattern of having fewer children, making low fertility a form of "inertia" [17].

(3) The Weakening of the Safeguarding Mechanism of Clan Culture

The one-child policy has not only directly facilitated the intergenerational transmission of low fertility but has also undermined the foundations of traditional clan culture. China, as the birthplace of Confucianism, has long nurtured a deep-rooted clan culture, whose core values "continuing the family line, raising children for old-age support, and believing that more children bring more blessings" have guided the reproductive decisions of most families[18]. Clan culture is typically symbolized by ancestral halls and genealogies: the ancestral hall serves as a collective "living room" and a repository of family memory; the genealogy records the family lineage, enabling members to trace their roots. Through clan reunions and intergenerational support, clan culture forms a stable social network that ensures care for both the young and the elderly [19]. Consequently, it provides cultural safeguards for high fertility [20]. However, industrialization and urbanization have triggered large-scale rural-to-urban labor migration, leading to the disintegration of clan communities. Meanwhile, the long-term implementation of the one-child policy has shifted younger generations' fertility attitudes toward "fewer children, better quality, and just one child," causing clan-based views to fade [21]. Even after the policy's phaseout, these attitudes persist, making low fertility intentions endogenous and irreversible [22]. The policy also fostered a "one-child culture": the one-child generation exhibits lower fertility intentions than those with siblings, and later-born one-children show even lower intentions [23].

In summary, while China's low fertility shares common features with Western countries—such as structural changes driven by industrialization—it also exhibits unique characteristics arising from the interplay between clan cultural traditions and family planning policies. Consequently, the study of fertility-shaping mechanisms should be closely tied to native cultural and policy contexts.

2.2 Analysis of the Characteristics of Native Culture in Guangdong

(1)A Dialect as the Calling Card of Native Culture

As the language of a particular region, dialect is a unique expression of regional cultural DNA, carrying the history and traditions of a specific area or community. It integrates indigenous values and behavioral norms, serving as a symbolic consensus through which locals share knowledge and foster a sense of unity [24]. Frequent communication in dialect subtly shapes one's values to fit the community's traditions. Specifically, the native dialect, as the first language acquired in childhood, leaves a lasting imprint on how one cognitively perceives social identities.

The primary daily communication languages in Guangdong Province include Cantonese, Hakka dialect, and Chaoshan dialect (also called Teochew), in addition to public-setting Mandarin. Among these, Cantonese is mostly spoken in the greater Guangzhou area and western Guangdong, used just as much in official contexts as in everyday private conversations. Hakka dialects are mainly concentrated in Meizhou, Shaoguan, Huizhou, and other northeastern areas. The Chaoshan dialect is primarily used in southeastern Guangdong, including Shantou, Shanwei, Jieyang, and Chaozhou. Based on these dialect categories, this paper classifies Guangdong's native culture into four types: Cantonese culture, Hakka culture, Chaoshan culture, and foreign culture (corresponding to Mandarin and migrants' dialects). Due to the complexity of foreign cultural elements, its characteristics are not discussed in depth here. It should be noted that there is a close connection between native culture and clan culture. Given the deep entrenchment of clan culture in China, all native cultures contain clan elements, which vary in vitality and manifestation.

(2) Characteristics of Cantonese Culture

With over 120 million speakers worldwide, Cantonese is the most widely spoken dialect in the province, giving Cantonese culture the broadest geographical reach [25]. As the Cantonese region is situated at the southernmost tip of China, it has historically served as a frontier for China's engagement with the outside world. As a pioneer of modern China's maritime culture, it is characterized by strong openness, inclusivity, and high receptiveness to foreign ideas and technologies—evident in the numerous loanwords in Cantonese. This constant absorption and integration of foreign cultures have placed native culture in a state of perpetual flux. Though once home to a strong clan-based tradition, rising migration and urbanization since reform and opening-up have gradually eroded its local clan villages and cultural norms.

(3) Characteristics of Hakka Culture

The Hakka are a Han ethnic group with a unique cultural identity, formed as Central Plains Han people migrated south in waves due to war and famine, eventually assimilating with local residents. Nowadays, they are primarily distributed in the mountainous border region of Guangdong, Fujian, and Jiangxi provinces, constituting about a quarter of the province's population [26].

Hakka culture has preserved clan traditions relatively intact, bearing typical agrarian cultural characteristics. During their arduous southward journey, clan solidarity became the core of the Hakka spirit which is vividly embodied in Hakka roundhouses. Resembling concentric circles, roundhouse residents often share common ancestry. The Hakka ancestral hall is typically at the roundhouse center, housing ancestral tablets and genealogies. When significant clan events occur—son's birth or marriage—clan members gather in the ancestral hall to celebrate, strengthening family identity. The Hakka dialect is a key hallmark. Hakka people have long adhered to the adage, "Rather sell our ancestors' fields than sell our ancestors' language" [27], ensuring the dialect's transmission to today. Additionally, the Hakka have rich life-cycle customs from birth to death, including rituals for birth, coming-of-age, marriage, and funerals [28].

(4) Characteristics of Chaoshan Culture

The Chaozhou-Shantou region on Guangdong's eastern coast has a semi-enclosed geography (mountains north, sea south) that fuses maritime and Central Plains

agricultural cultures. The former yields openness and business acumen; the latter, clan ties, distinct gender divisions, and a stronger son preference than in Cantonese or Hakka regions [29]. Yet, expanding foreign trade, local labor outflows, and rising migrant populations are steadily corroding these cultural traditions.

2.3 Hypotheses Proposed

Based on existing findings and cultural variations across Guangdong's regions, this study proposes the following hypotheses to examine the impact of the aforementioned cultural mechanisms on women's fertility in Guangdong and the cultural forces shaping its high birth rate.

(1) Given that existing research on cultural embeddedness mechanisms has been predominantly conducted in Western contexts, to test the effect of this mechanism within the cultural setting of Guangdong, we propose the first hypothesis. H1: A woman's native dialect influences her fertility behavior, and the effects exhibit heterogeneity.

(2) To verify the existing assertion that Guangdong's high fertility largely stems from a robust clan culture, we propose the second hypothesis. H2: Native clan culture has a positive influence on women's high fertility.

(3) To examine the family intergenerational transmission effect and the inertial effect of the one-child policy in Guangdong, we propose the third hypothesis. H3: The greater the number of siblings, the stronger a woman's tendency toward high fertility; conversely, being an only child (i.e., having zero siblings) has a negative impact on high fertility.

3. Research Design

3.1 Sample

Data were collected using an online questionnaire distributed to women aged 18 to 49 between January and February 2024. The questionnaire comprised four sections: personal background, fertility outcomes, cultural identity, and migration experiences. A disproportional stratified random sampling method with equal allocation was employed. Stratification was based on the four geographical regions of Guangdong—the Pearl River Delta, eastern Guangdong, western Guangdong, and northern Guangdong. Within each regional stratum, respondents were selected using computer-generated random numbers from the sampling frame until approximately 150 valid responses were obtained from each region, ensuring a broad mix of cultural and socioeconomic backgrounds. This disproportional allocation was intentionally chosen to ensure sufficient sample sizes per region for meaningful cross-regional comparisons, not to mirror Guangdong's actual female population distribution. To boost generalizability, the sample intentionally included both native inhabitants and migrants from outside Guangdong. After removing invalid responses, the final sample included 539 observations.

3.2 Variable Selection

(1) Independent Variable: Native dialect. The variable"native dialect" served as a proxy for native culture and was coded as follows: "1" = "foreign dialects and Mandarin", "2" = "Cantonese dialect", "3" = "Chaoshan dialect", and "4" = "Hakka dialect".

(2) The Other Independent Variable: The Number of Siblings. It was coded as follows: "1" for no siblings, "2" for one sibling, "3" for two siblings, and "4" for three or more siblings.

(3) Dependent Variable: The Number of Children Born. As China replaced its one-child policy with the universal two-child policy in 2015, this variable was coded as "0" for women with 0 or 1 child (reflecting low fertility propensity consistent with One-Child policy), and "1" for those with 2+ children (reflecting high fertility propensity).

(4) Control Variables: Three kinds of factors were taken as control variables to improve the reliability of the analysis.

Individual characteristics (age, household registration, educational attainment, and economic income). Among these variables, "household registration" was coded as follows: "0" for rural identity, "1" for urban identity. "Educational attainment" was assigned values of 1, 2, 3, 4, and 5, corresponding to middle school or below, high school, associate degree, bachelor's degree, and master's degree or above, respectively. "Annual income (yuan)" was measured as follows: "1" = below 6 thousand, "2" = 6 thousand to 12 thousand, "3" = 12 thousand to 24 thousand, "4" = 24 thousand to 36 thousand, "5" = 36 thousand to 50 thousand, "6" = above 50 thousand, and "7" = no income.

Clan cultural background. It was coded as "1" if a clan hall existed in the community, and "0" otherwise.

The duration of migration. It was measured as "0" for "no migration", "1" for "less than 10 years", "2" for "10 years and over."

3.3 Baseline Model Construction

This study uses a binary logistic regression model as the baseline, given that the dependent variable "number of children born" is coded as binary. By comparing odds ratios across groups, this method quantifies the marginal effects of the independent variables on the log-odds while controlling for confounders, thereby illustrating how the explanatory variables influence the likelihood of fertility outcomes. The equation is formulated as follows:

$$ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta 1\ \mathrm{CULi} + \beta \mathrm{i}\ \mathrm{Xi} + \varepsilon \qquad (1)$$

In the above equation, p denotes the probability that the dependent variable takes a value of 1; $\beta 0$ is a constant value; CULi represents the type of native culture; β_k means the regression coefficient of the kth independent variable. This study focuses primarily on the estimate of $\beta 1$, using its sign, magnitude, and statistical significance to assess the net effect of native culture on fertility behavior.

All analyses were conducted using SPSS 26.0. The odds ratio (OR) served as the primary indicator of the direction and strength of the independent variable's influence: OR > 1 denotes a positive effect (larger OR, stronger effect); OR < 1 denotes a negative effect (closer to 0, stronger effect); and OR = 1 denotes no significant effect. Statistical significance was set at $\alpha = 0.05$, with $p < 0.05$ considered significant.

4. Empirical Results

4.1 Baseline Regression Test: the Effect of Native culture on Women's Fertility

In Table 1, Model 1 serves as a benchmark model, which includes the control variables and the dependent variable. By including dialects as the independent variables, we constructed a nested model (Model 2). Given that Hakka culture exhibits stronger clan-based traits in the cross-cultural comparison presented in Section 2, the Hakka group is used as the reference to examine the relationship between native dialects and women's fertility. The regression results are shown in Table 1.

Table 1 Baseline regression results: native dialects and women's fertility

Variables	**Model 1**			**Model 2**		
	OR	**95% CI**	***p***	**OR**	**95% CI**	***p***
Age	1.140	[0.096, 0.174]	<0.001***	1.151	[0.108, 0.185]	<0.001***
Residence	0.772	[-0.728, 0.194]	0.266	0.760	[-0.753, 0.206]	0.247
Educational attainment	0.754	[-0.550, -0.040]	0.021**	0.807	[-0.480, 0.040]	0.047**
Annual income	0.654	[-0.643, -0.256]	<0.001***	0.637	[-0.680, -0.281]	<0.001***
Clan culture	1.108	[-0.329, 0.559]	0.639	1.174	[-0.316, 0.641]	0.491
Duration of migration	0.974	[-0.283, 0.238]	0.841	0.923	[-0.357, 0.196]	0.558
Foreign dialect/Mandarin				0.607	[-1.157, 0.099]	0.110
Cantonese				0.301	[-1.890, -0.652]	<0.001***
Chaoshan				0.540	[-1.302, -0.032]	0.076*
Nagelkerke R^2	39.9%			42.8%		
Hosmer-Lemeshow	p = 0.710			p = 0.105		

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

The regression results for Model 2 indicate a Hosmer-Lemeshow test p-value of 0.105, suggesting good model fit, and this model explains 42.8% of the variance in the dependent variable, with 2.9% higher than in Model 1.Compared to Hakka speakers, Cantonese group shows a significantly lower fertility propensity (OR = 0.301, 95% CI [−1.890, −0.652], p < 0.001). Similarly, the foreign dialect/Mandarin group (OR = 0.607, 95% CI [−1.157, 0.099], p = 0.110) and the Chaoshan group (OR = 0.540, 95% CI [−1.302, −0.032], p = 0.076) also exhibits lower fertility propensity, though the effect for the Chaoshan group was only marginally significant. These findings demonstrate that native culture, as embedded in one's mother tongue, indeed influences women's fertility behavior, and that the effects vary across dialects. Among all the native cultures examined, Hakka culture exhibits the strongest "fertility potential", thus confirming Hypothesis 1.

4.2 Robustness Test

To test the robustness of the above findings, we recoded the dependent variable—number of children born as follows: 0 children = "1", 1 child = "2", 2 children = "3", and ≥3 children = "4". An ordered logistic (ologit) Model 3 is therefore employed as indicated in Table 2. By retaining the Hakka group as the reference, we find similar results to those of the above regression, with significantly negative effects for Cantonese group (B= -0.944, p<0.001) and Chaoshan group (B=-0.328, p=0.065). This confirms that alternative measurement does not affect the conclusions of the regression analysis, and the estimation results are robust.

Table 2 Robustness test results

Variables	Model 3		
	B	Wald χ^2	*p*
Age	0.185	127.964	<0.001***
Residence	-0.295	2.142	0.143
Educational attainment	-0.288	7.078	0.008**
Annual income	-0.306	13.746	<0.001***
Clan culture	0.061	0.096	0.757
Duration of migration	-0.076	0.423	0.515
Foreign dialect/Mandarin	-0.485	3.368	0.166
Cantonese	-0.944	13.232	<0.001***
Chaoshan	-0.328	1.242	0.065*
Nagelkerke R^2	42.8%		

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

4.3 Moderation Effect Test of Clan Culture

Since dialects alone capture only a limited set of cultural elements, they cannot fully explain the complex mechanisms through which native culture shapes fertility—particularly the role of clan culture, a key component. To address this, we introduce an interaction term between dialect and the presence of a clan hall into the analytical model to examine the moderation effect of clan culture on women's fertility.

Using foreign dialect and Mandarin group as the reference, Table 3 presents the regression results. Model 4 includes control variables and the dependent variable, while Model 5 adds the interaction term to Model 4. The results from Model 5 show that, relative to the reference group, the interaction between Hakka and clan culture has a significant positive effect on fertility at the 90% confidence level. In contrast, the interaction between Chaoshan dialect and clan culture exhibits a marginally significant negative effect. These findings suggest that Hakka clan culture promotes higher fertility among women, whereas clan cultures in other regions do not show such a fertility-safeguarding effect. Thus, Hypothesis 2 is partially confirmed. The partial confirmation implies that clan culture, as proxied by ancestral halls, does not universally support high fertility, or that the presence of an ancestral hall alone is insufficient to sustain clan culture.

Notably, Cantonese culture has a significant negative effect on fertility (OR = 0.516, 95% CI [-1.501, -0.193], p = 0.025). After introducing the interaction term, although its odds ratio is positive (OR = 1.104), it is far from statistically significant (p = 0.994), and the overall effect remains negative. This suggests that clan culture helps mitigate, to some extent, the negative impact of Cantonese culture.

Table 3 Moderation effect test results

Variables	Model 4			Model 5		
	OR	95%CI	*p*	OR	95%CI	*p*
Age	1.152	[0.110,0.184]	<0.001***	1.155	[0.111,0.186]	<0.001***
Residence	0.754	[-0.762,0.205]	0.235	0.752	[-0.758,0.208]	0.235
Educational attainment	0.820	[-0.444,0.060]	0.116	0.835	[-0.446,0.063]	0.156
Annual income	0.637	[-0.720, -0.275]	<0.001***	0.638	[-0.726, -0.280]	<0.001***
Clan culture	1.159	[-0.338,1.357]	0.528	1.556	[-0.341,1.361]	0.265
Duration of migration	0.916	[-0.344,0.246]	0.521	0.933	[-0.347,0.241]	0.616
Cantonese	0.516	[-1.501, -0.193]	0.025**	0.478	[-1.493, -0.196]	0.015**
Chaoshan	0.940	[-0.674,0.844]	0.856	0.880	[-0.679,0.847]	0.833

Variables	Model 4			Model 5		
	OR	95%CI	*p*	OR	95%CI	*p*
Hakka	1.737	[0.220,0.382]	0.066*	1.669	[0.224,0.379]	0.076*
Cantonese*Whether or not there is a clanhouse				1.104	[-1.162,1.215]	0.994
Chaoshan*Whether or not there is a clanhouse				0.263	[-3.283,0.067]	0.088*
Hakka*Whether or not there is a clanhouse				1.583	[-1.005,0.809]	0.069*
Nagelkerke R^2	42.8%			43.4%		
Hosmer-Lemeshow	*p* = 0.637			*p* = 0.241		

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

4.4 Baseline Regression Test: the Effect of Sibling Number on Women's Fertility

In Table 4, Model 2 serves as the baseline model. Model 6 extends Model 2 by adding the number of siblings as an independent variable, with women having three or more siblings as the reference group, to examine the effect of sibling number on women's fertility. Model 6 explains 44.2% of the variance in the dependent variable, which is 1.4% higher than in Model 2.

Table 4 Baseline regression results: the number of siblings and women's fertility

Variables	Model 2			Model 6		
	OR	95%CI	*p*	OR	95%CI	*p*
Age	1.151	[0.108,0.185]	<0.001***	1.149	[0.106,0.184]	<0.001***
Residence	0.760	[-0.753,0.206]	0.247	0.792	[-0.719,0.278]	0.338
Educational attainment	0.807	[-0.480,0.040]	0.047**	0.778	[-0.514,0.002]	0.059*
Annual income	0.637	[-0.680, -0.281]	<0.001***	0.636	[-0.694, -0.285]	<0.001***
Clan culture	1.174	[-0.316,0.641]	0.491	1.171	[-0.372,0.702]	0.512
Duration of migration	0.923	[-0.357,0.196]	0.558	0.899	[-0.429,0.184]	0.447
Foreign dialect/mandarin	0.607	[-1.157,0.099]	0.110	0.617	[-1.146,0.150]	0.131
Cantonese	0.301	[-1.890, -0.652]	<0.001***	0.317	[-1.809, -0.516]	<0.001***
Chaoshan	0.540	[-1.302, -0.032]	0.076*	0.537	[-1.281,0.020]	0.081
0 siblings				0.955	[-1.011,0.697]	0.919
1 siblings				0.711	[-1.928,0.282]	0.252
2 siblings				1.943	[0.035,1.343]	0.026**
Nagelkerke R^2	42.8%			44.2%		
Hosmer-Lemeshow	*p* = 0.105			*p* = 0.328		

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

With Hakka as the reference dialect group, Cantonese and Chaoshan women show significantly lower fertility propensity (OR = 0.317 and 0.537, respectively), suggesting that, compared to Hakka women, those in the Cantonese and Chaoshan groups inherited the previous generation's high-fertility pattern to a lesser extent.

When comparing sibling-size groups, women with two siblings exhibit a significantly higher propensity for high fertility than those with three or more siblings (OR = 1.943, 95% CI [0.035, 1.343], p = 0.026). This indicates that a larger sibship does not necessarily translate into higher fertility; rather, families of origin with three children show a stronger fertility transmission effect compared to larger families. However, whether this reflects an "optimal" family size needs to be further tested against smaller family sizes.

Regarding only children, being an only daughter (zero siblings) does not significantly affect the number of children born compared to women from families with three or more siblings (p = 0.919), suggesting no distinct "only-child culture" in Guangdong region.

4.5 Heterogeneity Test

Given that the impact of sibling number on fertility behavior may vary depending on a woman's socioeconomic status or age group, this study introduces household registration status and age group as grouping variables. Through heterogeneity analysis, we examine disparities in intergenerational transmission effects and the inertia of one-child policy across different subgroups.

(1) Urban versus Rural Heterogeneity

Table 5 presents regression results stratified by women's household registration status (rural vs. urban). Model 7 corresponds to women with rural registration, and Model 8 to those with urban registration.

With Hakka as the reference group, both urban and rural Cantonese women exhibit significantly lower fertility propensity (OR = 0.242, CI[-1.146,-0.980], p = 0.002 for urban; OR = 0.321, CI[-1.131,-1.050], p = 0.013 for rural), suggesting that the negative effect of Cantonese culture on fertility is robust across residence. For the Chaoshan group, however, a notable urban–rural divergence emerges: urban Chaoshan women show a marginally significant negative effect (OR = 0.388, CI[-1.011,0.413], p = 0.058), whereas the effect among rural Chaoshan women is far from significant (OR = 0.664, CI[-1.769,-0.503], p = 0.421). This pattern suggests that clan-based fertility norms may have eroded more rapidly in rural Chaoshan communities due to labor outmigration, leaving urban Chaoshan women as the primary carriers of the remaining cultural distinction. Collectively, these results reinforce the finding that Hakka culture maintains the strongest intergenerational transmission of high-fertility norms across both urban and rural settings.

Across sibling-size groups, urban women with two siblings show a significantly higher fertility propensity than other sibling groups (OR = 2.425, 95% CI [0.101, 0.284], p = 0.038). This suggests that, even in urban settings, native culture and family-of-origin structure continue to shape fertility behavior, with three-child families remaining the most conducive to fertility transmission.

Notably, being an only daughter has different effects by registration status. Among urban women, only-daughter status has a marginally significant negative effect on fertility (OR = 0.751, 95% CI [−1.275, −0.089], p = 0.083), whereas no significant effect is found for rural only daughters. This suggests that the inertial effect of the one-child policy is stronger among urban only daughters, likely because clan culture is weaker in urban than in rural areas.

Table 5 Heterogeneity results: urban and rural

Variables	**Model 7 (*N* =255)**			**Model 8 (*N* =284)**		
	OR	**95%CI**	***p***	**OR**	**95%CI**	***p***
Age	1.151	[1.112, 1.202]	<0.001***	1.149	[1.121,1.205]	<0.001***
Educational attainment	0.685	[-0.719,0.274]	0.064*	0.924	[-0.723,0.279]	0.665
Annual income	0.513	[-0.598,-0.791]	0.003**	0.731	[-0.601,-0.802]	0.029**
Clan culture	0.967	[-0.500,-0.345]	0.925	1.326	[-0.503,-0.346]	0.411
Duration of migration	0.958	[-0.689,0.709]	0.839	0.810	[-0.690,0.711]	0.290

Variables	Model 7 (*N* =255）			Model 8 (*N* =284）		
	OR	95%CI	*p*	OR	95%CI	*p*
Foreign dialect/mandarin	0.909	[-0.487,0.204]	0.841	0.358	[-0.392-0.014]	0.026**
Cantonese	0.321	[-1.131,-1.050]	0.013**	0.242	[-1.146,-0.980]	0.002**
Chaoshan	0.664	[-1.769,-0.503]	0.421	0.388	[-1.011,0.413]	0.058*
0 siblings	0.626	[-1.278,0.007]	0.767	0.751	[-1.275,-0.089]	0.083*
1 siblings	0.746	[-1.368,0.008]	0.527	0.646	[-1.279,0.010]	0.285
2 siblings	1.512	[-1.146,0.326]	0.343	2.425	[0.101,1.284]	0.038**
Nagelkerke R^2	48.6%			43.0%		
Hosmer-Lemeshow	$p = 0.364$			$p = 0.314$		

Note: ***p < 0.01, **p < 0.05, *p < 0.1.

(2)Age Heterogeneity

To examine generational differences in how sibling number affects fertility behavior, the respondents are divided into three age groups: 18–30 (coded "1"), 30–40 (coded "2"), and 40–49 (coded "3"). These groups reflect distinct generations shaped by varying social policies, moral norms, and cultural environments, which may influence fertility attitudes and behaviors.

As shown in Table 6, Model 9 corresponds to ages 18–30, Model 10 to ages 30–40, and Model 11 to ages 40–49. Among women aged 30–40, the Cantonese (OR = 0.406, 95% CI [−1.809, −0.516], p = 0.035) and Chaoshan groups (OR = 0.410, 95% CI [−1.281, 0.020], p = 0.053) exhibit significantly lower fertility propensity than the Hakka reference group. Among women aged 40–49, the Cantonese group also shows significantly lower fertility propensity. These results suggest that Hakka's positive association with high fertility has persisted over time.

Regarding intergenerational transmission, women aged 30–49 with two siblings have a significantly higher fertility propensity than other sibling groups (OR = 3.789, p = 0.005). This effect is not significant for other age or sibling groups, indicating that the high-fertility pattern of the natal family exerts the strongest influence on women born between 1975 and 1995.

Turning to only-daughter status, among the 18–30 cohort (born in the 2000s), only daughters had a marginally significant lower fertility propensity than women with three or more siblings (OR = 0.167, 95% CI [−1.004, 0.721], p = 0.098). In the other two age groups, being an only child had no significant effect. Thus, the low-fertility propensity among post-2000s only daughters is the most pronounced across all age and sibling groups.

In addition, several control variables also show significant effects among women aged 18–30: longer migration duration (OR = 0.156, 95% CI [−0.514, −0.430], p = 0.042), higher educational attainment (OR = 0.303, 95% CI [−0.726, 0.282], p = 0.008), and higher economic income (OR = 0.572, 95% CI [−0.605, −0.808], p = 0.021) are all associated with significantly lower fertility propensity. It is also noticed that, among women aged 18–30, Cantonese culture exerts an exceptionally strong negative effect on fertility (OR = 0.091, CI[-1.815, -0.521], p = 0.064), reducing the odds of high fertility by approximately 91% relative to their Hakka peers. The youngest cohort's divergence likely reflects that Cantonese-speaking areas coincide with the Pearl River Delta, where exposure to globalized individualist values, delayed marriage norms, and career-oriented lifestyles is most intense.

Table 6 Heterogeneity results: age groups

Variables	Model 9 (N =182)			Model 10(N =220)			Model 11 (N =137)		
	OR	CI	*p*	OR	CI	*P*	OR	CI	*p*
Educational attainment	0.303	[-0.726, 0.282]	0.008**	0.781	[-0.718, 0.279]	0.197	0.934	[-0.731, 0.285]	0.749
Annual income	0.576	[-0.605, -0.808]	0.103	0.679	[-0.598, -0.796]	0.071*	0.572	[-0.611, -0.772]	0.021**
Clan culture	0.915	[-0.508, -0.352]	0.921	1.067	[-0.498, -0.325]	0.847	1.532	[-0.512, -0.349]	0.314
Duration of migration	0.156	[-0.514, -0.430]	0.042**	1.071	[-0.610, 0.339]	0.719	0.876	[-0.692, 0.721]	0.560
Foreign dialect/Mandarin	1.084	[-1.151, 0.155]	0.938	0.964	[-1.141, 0.147]	0.937	0.364	[-1.155, 0.148]	0.123
Cantonese	0.091	[-1.815, -0.521]	0.064*	0.406	[-1.809, -0.516]	0.035**	0.272	[-1.779, 0.358]	0.051*
Chaoshan	0.074	[-1.304, 0.015]	0.129	0.410	[-1.281, 0.020]	0.053*	0.802	[-1.081, 0.008]	0.787
0 siblings	0.167	[-1.004, 0.721]	0.098*	0.531	[-1.011, 0.697]	0.301	1.907	[-1.005, 0.703]	0.435
1 sibling	0.333	[-1.843, 0.212]	0.350	0.714	[-1.912, 0.224]	0.400	0.495	[-1.841, 0.289]	0.206
2 siblings	0.681	[0.022, 1.204]	0.759	3.789	[1.177, 1.208]	0.005**	1.036	[1.157, 1.006]	0.946
Nagelkerke R^2	47.0%			48.2%			49.6%		
Hosmer-Lemeshow	p = 0.163			p = 0.154			p = 0.146		

Note: ***p < 0.01, **p < 0.05, *p < 0.1

Taken together, the results from Tables 4–6 indicate that, overall, there is no strict positive association between sibling number and fertility. However, women with two siblings exhibit a significantly higher fertility propensity than those with more siblings. Furthermore, although only daughters in Guangdong do not generally display a lower fertility propensity, this tendency is evident among urban only daughters and those aged 18–30. This suggests that even in a high-fertility region like Guangdong, an "only-child culture" persists in certain subgroups. Thus, Hypothesis 3 is largely supported; its partial non-confirmation across the entire region underscores the distinctiveness of native cultures within Guangdong and their heterogeneous effects on fertility.

5.Conclusions and Discussion

5.1 Conclusions

Using survey data from women in Guangdong Province, this study employed native dialects as proxy for native culture to examine its influence on women's fertility. The three proposed hypotheses are empirically tested, leading to the following conclusions.

First, owing to differences in indigenous cultural characteristics, the impact on women's fertility varies significantly across dialect groups. Compared to Hakka speakers, Cantonese speakers exhibit a significantly lower fertility propensity, while Chaoshan speakers also show a lower propensity, though the effect was only marginally significant. Women whose native language is Mandarin or other provincial dialects also display lower fertility tendencies, yet the effects were not statistically significant. Taken together, these results show that women raised in a Hakka cultural context have the highest fertility propensity, suggesting that Hakka culture carries the strongest fertility potential. Contrary to Shen's conclusion that southern China's higher fertility rates (relative to the north) stem from regional differences in grain cultivation [4], this study finds that in Guangdong, not all dialect areas exhibit high fertility preferences—even though they are all located in the south. Given the fertility heterogeneity within the province, relying solely on a north–south geographic divide to predict fertility levels is inaccurate.

Second, Guangdong's stronger indigenous clan culture (compared to other regions) provides a cultural basis for its higher fertility, confirming Feng's association of high birth rates with clan influence [21]. Nevertheless, the protective effect of clan culture on women's fertility varies by regional cultural context. Compared to the foreign

dialect and Mandarin groups, Hakka clan culture significantly promotes high fertility; in contrast, indigenous clan cultures in Cantonese and Chaoshan regions do not exhibit a similar effect. The stronger pro-fertility influence of Hakka clan culture stems from its emphasis on clan solidarity and its deep integration into daily life. This suggests that clan culture has weakened unevenly across Guangdong and cannot be sustained by ancestral halls alone.

Third, from the perspective of intergenerational transmission, women with two siblings exhibit a significantly higher fertility propensity. This suggests that within Guangdong, families with three children are the most likely to transmit a "genetic" predisposition for high fertility. It also indicates that the consistent implementation of the current universal Three-child policy will help sustain Guangdong's high fertility rate.

Fourth, Unlike Yu and Liang's claim that the one-child policy created an inertial effect—whereby the one-child generation, influenced by their parents' reproductive behavior, showed much lower fertility intentions than those with siblings [17]. This study finds that the one-child women in Guangdong did not exhibit significantly lower fertility than those with three or more siblings. This finding indicates that although the inertia of the one-child policy may serve as a primary driver of low fertility in other regions, such a conclusion cannot be simply extended to Guangdong. Yet, urban only daughters and those under 30 showed significantly lower fertility, pointing to an "only-child culture" in certain localities. Hence, while the low-fertility legacy of the one-child policy is not prominent in Guangdong overall, it remains a concern in specific subgroups.

5.2 Discussion

Based on the findings, for China to address the low-fertility predicament, fertility policies should be tailored to local cultural contexts rather than applied uniformly. In areas with deeply entrenched clan traditions, family-based incentives and intergenerational sharing of child-rearing responsibilities can be effective; in regions with looser clan ties and larger migrant populations, establishing a comprehensive public childcare system and a flexible employment system for mothers is advisable. Additionally, beneficial clan values—such as those promoting family unity and intergenerational continuity—can be reinforced through dialects, media, and folk activities. Finally, institutional support should be strengthened for youth and only-child groups by integrating a pro-fertility cultural narrative into education and offering policy incentives for employment, marriage, and parenting.

This study is limited by its relatively small sample size and the absence of longitudinal data. Although we controlled for multiple confounders, reverse causality cannot be ruled out. Variable definitions were simplified—using native dialects as the only indicator of native culture and clan halls as the only indicator of clan culture—and external cultures were not analyzed in depth. These drawbacks may compromise the accuracy of the findings. Future work should broaden the regional coverage, employ multi-wave data to track cultural dynamics, and rigorously address endogeneity to improve practical applicability.

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A Review of Key Technologies for Green and Low-Carbon Construction and Operation of Converter Stations in High Altitude Areas

Xiaofeng ZHANG [a,1], Wei DING [a], Yunxiao BAI [a], Ziyi FAN [a], Xinyan QIN [a]
[a] *China Energy Engineering Group Guangdong Electric Power Design Institute Co., LTD., Guangzhou, Guangdong 510663, China.*

Abstract. In response to China's "dual carbon" development goals, advancing the green and low-carbon construction of power systems is of significant importance. As critical energy conversion hubs within power systems, converter stations offer considerable potential for improving energy efficiency and reducing carbon emissions. Constructing converter stations in high-altitude, cold regions such as Tibet allows for leveraging the local climatic conditions to dissipate heat from core areas like valve halls, thereby significantly reducing operational energy consumption. Compared with plain regions, the unique environmental conditions in these areas impose differentiated technical requirements for achieving green and low-carbon development of converter stations. This study adopts a life-cycle perspective to analyze the sources of carbon emissions from converter stations in high-altitude regions, categorizing them into four areas: building energy consumption, electrical equipment, cooling systems, and other systems. Based on this analysis, the paper reviews the application of low-carbon technologies in five key areas: building structure and layout, electrical equipment selection, intelligent control and management, auxiliary system optimization, and collaborative technological innovation. These insights aim to provide guidance for the low-carbon planning and design of converter stations in high-altitude regions in the future.

Keywords: Converter station, low-carbon technology, carbon emissions, high altitude

1. Introduction

The "3060" carbon peaking and carbon neutrality target has been included in the national development strategy. As the main source of carbon emissions, the energy sector needs to accelerate low-carbon transformation to promote the construction of green power systems [1,2]. Carbon emissions of the power system account for a high proportion of the energy industry, and as the core hub of power conversion, the carbon emissions of the converter station account for a significant proportion of carbon emissions. Therefore, promoting the low-carbon construction of the converter station is

[1]Corresponding author: Xiaofeng ZHANG, China Energy Engineering Group Guangdong Electric Power Design Institute Co., LTD., Guangzhou, Guangdong 510663, China; Email: 2361971992@qq.com.

crucial to the green development of the power system and the implementation of national policies.

Converter station buildings primarily house large electrical equipment and have special functional requirements. In addition to comprehensive and office buildings, key functional structures include valve halls, control rooms, indoor DC fields, converter transformers, and filtering reactors with firewalls. During operation, the office buildings, valve hall equipment, and control rooms are the main sources of energy consumption and carbon emissions.

Converter stations in high-altitude areas face higher construction and operational demands due to their climate and special functional requirements. However, there is currently a lack of comprehensive guidelines for low-carbon technologies throughout the lifecycle of converter stations, and research on overall low-carbon technologies for converter stations is still scarce. This paper focuses on the outer building envelope of converter stations in high-altitude areas and examines the structures housing large electrical equipment, such as valve halls. The main sources of carbon emissions in the entire construction and operational process are analyzed, and the application of related low-carbon technologies is reviewed. The paper also explores the future prospects and pathways for the low-carbon transformation of converter stations, providing technical ideas for low-carbon planning and design in similar buildings.

2. Sources of Carbon Emissions in the Construction and Operation of Converter Stations in High-Altitude Areas

2.1. Construction Process

From an overall construction perspective, building a converter station in a high-altitude area presents greater challenges, leading to significantly higher costs. Particularly in terms of equipment and material transportation, the unique geographical and climatic conditions mean that transporting large quantities of building materials, equipment, and fuel (via trucks, helicopters, or rail) incurs higher transportation carbon emissions [3]. Additionally the harsh environment requires the use of more durable and cold-resistant materials for equipment and buildings. Valve halls, for example, require stricter airtightness and thermal insulation, which increases both material consumption and potential carbon emissions during production and transport. These factors jointly influence the carbon emissions during the construction process of converter stations in high-altitude areas, necessitating the application of effective low-carbon technologies and measures. The monetary inputs and emissions of partial transmission infrastructure projects is shown as Fig. 1 [4].

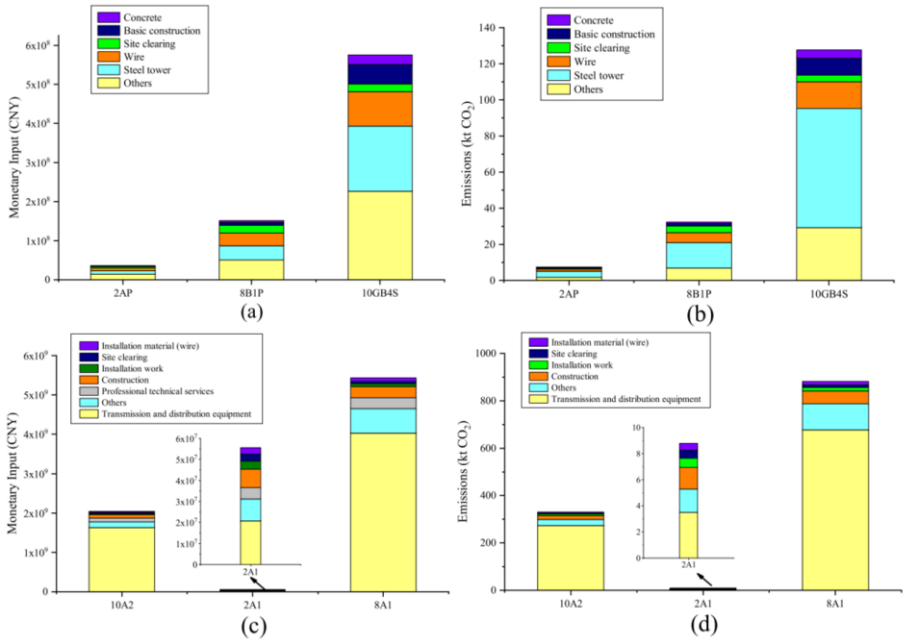


Figure 1. The monetary inputs and emissions of partial transmission infrastructure projects [3].

2.2. Operational Process

Carbon emissions during the operation of the transfer station mainly come from energy consumption [5], and the proportion of direct emissions caused by the leakage of SF6 and other materials is extremely low. The core characteristics of energy consumption are as follows: building energy consumption is the basic energy consumption type, which refers to the energy consumption of maintaining basic functions such as temperature and humidity in the building and does not include large-scale electrical equipment, covering the main control building, The energy consumption of air conditioning, HVAC and lighting systems in complex buildings, GIS rooms and other places(see Fig. 2).

However, the unique energy consumption mode of electrical equipment plants such as valve halls and transformer rooms needs to be paid attention to, especially the valve hall, which is the core of electrical energy conversion, which has a large number of built-in power electronic equipment. , it is necessary to strictly control the temperature (10℃-50℃, usually maintained around 30℃), humidity (10%-60%) and other environmental parameters within a specific range, while ensuring the requirements of micro-positive pressure and fresh air filtration; the harsh climate with low humidity and large temperature difference in high-altitude areas requires stricter architectural design and equipment configuration to meet the room [6]. The internal environment requires that the energy consumption of HVAC and lighting is greatly increased, and the carbon emission pressure is aggravated. Large-scale electrical equipment such as current transformers and transformers are the core of energy consumption and loss [7]. During its voltage and current adjustment, the control system will generate additional energy consumption. The power loss of 2%-4% of the current transformer and the iron loss and copper loss of the transformer are in the form of thermal energy. Release, and the

dynamic and static losses of equipment have a more prominent impact on energy efficiency under high load [8-10]. Furthermore, the cooling system of the flow switching station is a crucial component for maintaining the operating temperature of the equipment. Both the air-cooled and water-cooled methods require electricity, and energy consumption increases under high loads. While the automated control system and redundant backup power supply have a relatively low energy consumption ratio, they still require careful attention and fine-grained energy management [11-12].

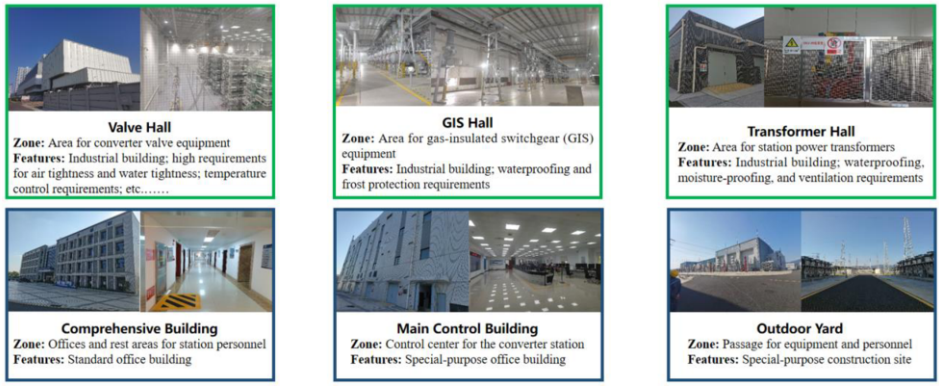


Figure 2. Main Buildings, Areas, and Features of the Converter Station

3. Application of Low-Carbon Technologies in Converter Stations

Based on the detailed analysis of the sources of carbon emissions in converter stations, specific carbon reduction technologies can be applied to mitigate emissions. Many converter stations, substations, and other power stations have already adopted innovative technologies to open new paths for the low-carbon development of converter stations.

3.1. Building Structure and Layout

High-altitude conversion station buildings have strict requirements for insulation, heat resistance and ventilation performance. The design of building size coefficient, main structure and enclosure materials is the core of ensuring the realization of functions [13]. Relevant research confirms that aluminum-magnesium-manganese board has excellent insulation performance and is suitable for cold areas; cadmium telluride photovoltaic panel curtain wall replaces traditional glass curtain wall, which can realize the integrated emission reduction of photovoltaic buildings [14,15]. It should be noted that the outer wall of the valve hall of the current exchange station is mostly made of steel, and it needs to be matched with suitable insulation materials [16-18]. The architectural layout and planning of the conversion station play a decisive role in the design of the power system. Typical cases show that the valve hall of Tonglit high-voltage current exchange station adopts face-to-face layout, and the AC filter is changed from "I" shape to "T" shape, reducing the area of 7,340 square meters and improving the transmission efficiency [19-21].

It can be seen that the architectural layout and orientation of the transfer station have a profound impact on the land area, construction cost, materials and operating energy consumption [22]. Its structure and energy-saving measures of enclosure materials are connected with ordinary buildings, and the core is to improve the thermal performance. Therefore, the design of high-altitude transfer stations should be selected according to geographical characteristics and follow the energy-saving standards of the enclosure structure.

3.2. Selection and Layout of Electrical Equipment

Electrical equipment is the core operating component of the current exchange station. Appropriate selection can effectively improve energy efficiency and reduce carbon emissions. In 110kV and above urban indoor substations, GIS equipment with SF_6 as the insulating medium is widely used [23]. The compact structure and modularity of equipment such as GIS can help current exchange stations achieve compact design, and the structure of current transformers and AC filters will also affect the compactness of equipment [24]. Under the premise of ensuring function and compatibility, compact layout can reduce resource consumption and is closely related to building layout design. However, SF6 will produce toxic decomposition products under high pressure, and its global warming potential value is 23,900 times that of CO_2 [22]. It is feasible to use environmentally friendly alternative media such as SF_6/N_2 mixed gas (see Fig 3). This technology has been used in power transmission lines. In summary, designing a low-carbon electrical system in combination with the needs of the installation site, equipment materials and service life is an important means for the low-carbon construction of high-altitude current exchange stations.

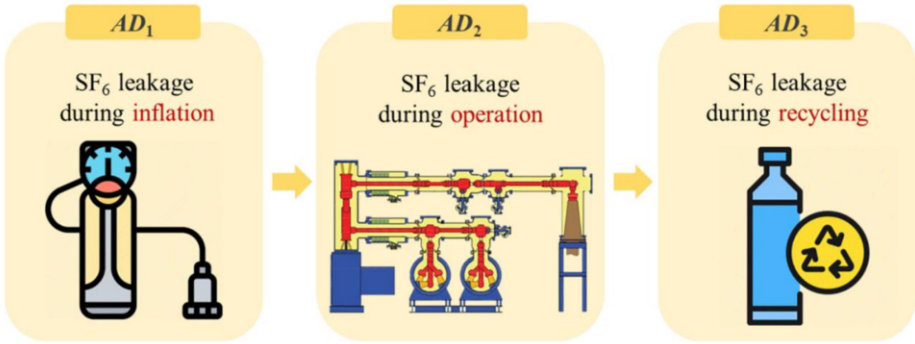


Figure 3. Carbon emissions of SF6 during the use of the equipment [25].

3.3. Intelligent Control and Operational Management

There is a wide variety of equipment in converter stations, making it difficult to achieve unified manual management and control. The introduction of technologies such as computers and artificial intelligence is the key to improving management efficiency [26]. Currently, computer technology can precisely regulate voltage and current to ensure the efficient output of the power system, but the application of intelligent control in auxiliary systems is limited. In relevant research, the energy-saving plan formulated by Qi and others achieved an annual power saving of over 2.53 million

kilowatt-hours by adjusting air conditioning parameters seasonally and managing equipment through an APP, demonstrating significant energy-saving results [27]. Sun applied BIM technology to converter stations, optimizing the control system through data from the operation and maintenance phase to facilitate energy conservation and carbon reduction [28]. In high-altitude areas, the equipment and auxiliary systems in converter stations have higher loads and greater energy consumption, offering greater potential for improvement in intelligent management and control as well as energy-saving optimization.

3.4. Adaptation and Optimization of Auxiliary Systems

The auxiliary system takes the cooling and ventilation system of electrical equipment as the core, and the relevant research proposes a variety of optimization solutions: Ruan et al. [29] combined with the climate of the Hami converter station, put forward three schemes of cooling outside the converter valve and select the optimal solution; Zhang [30] found that the cooling performance of the air conditioning system of the high-pressure converter station improves with the increase of air humidity; Gou [31] utilized simulation software to optimize the air distribution in the valve hall and determine the operating parameters of the air conditioning system. For high altitude areas, the adaptive system can cope with the harsh environment and ensure the stability of the equipment.

3.5. Synergy and Innovation of Multiple Technologies

The functions of the current exchange station are diverse, and its low-carbon construction in high-altitude areas needs to rely on multidisciplinary emission reduction technology. At present, the green current station has comprehensively applied building transformation, compact equipment layout, cooling system innovation, BIM technology, photovoltaics and other measures, and these multi-field technologies have become the driving force of innovation. In the future, the integration of assembly construction, automated control, renewable energy and other technologies will profoundly promote the low-carbon development of high-altitude switching stations and the construction of green power systems.

4. Conclusion and Outlook

With the intensification of global climate change, energy conservation and carbon reduction have become central issues in the development of the power industry [32]. As key facilities for power transmission and conversion, the energy consumption and carbon emissions of converter stations in high-altitude regions have a significant impact on the carbon footprint of the entire power system.

Currently, high-altitude converter stations have significant potential for energy conservation and carbon reduction. Through existing energy-saving technologies, green building designs, and intelligent management, low-carbon transformation can be achieved to some extent. This requires alignment with government policies and regional planning, establishing a scientific development path to provide the necessary environmental support for the low-carbon transformation of converter stations in high-altitude regions.

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Correlation Power Analysis Against the Secret Key Seed of SLH-DSA

Xin LI[a], Yang CAO[b,1], Zhibo DU[b], Fan ZHANG[a] and Jing PENG[a]
[a] *China Railway Chengdu Institute of Science and Technology Co., Ltd, Chengdu 610041, China*
[b] *School of Cybersecurity, Chengdu University of Information Technology, Chengdu 610225, China*

Abstract. To address the severe threats posed by quantum computing to traditional cryptographic systems, post-quantum cryptography has emerged as a vital solution. Among these advancements, SLH-DSA, a stateless hash-based digital signature algorithm, stands out for its robust mathematical security. However, its physical implementation security remains insufficiently explored. To address this critical gap, this paper proposes a Correlation Power Analysis attack targeting the $SK.seed$ of SLH-DSA. Through rigorous data flow analysis, the linear diffusion θ step and nonlinear transformation χ step of the underlying SHAKE256 hash function are identified as primary side-channel leakage points. Consequently, the XOR values from the θ step's column parity computation and the nonlinear outputs of the χ step are selected as intermediate variables for the attack. Utilizing a Hamming weight model, we construct a hypothetical power consumption model and design a precise side-channel leakage function. By calculating the Pearson correlation coefficient between the hypothetical and measured power traces, the attack successfully recovers $SK.seed$. Simulation results demonstrate full key recovery using merely 50 power traces, validating the high effectiveness and feasibility of the proposed method. Ultimately, this work exposes physical vulnerabilities in SLH-DSA implementations, providing crucial insights for designing SCA-resistant countermeasures in future PQC deployments.

Keywords. Post-quantum cryptography, SLH-DSA algorithm, Side-channel analysis, Correlation power analysis

1. Introduction

The recent NIST standardization of Post-Quantum Cryptography (PQC) has directe d research toward physical implementation security [1]. While mathematically secure, S LH-DSA's deployment on resource-constrained devices presents significant side-chann el analysis (SCA) risks, mirroring vulnerabilities found in its predecessor, SPHINCS+ [2-3]. Crucially, SLH-DSA's stateless nature dictates the on-demand, PRF-based compu tation of temporary keys. The frequent mixing of the $SK.seed$ with public addresses du ring repetitive SHAKE256 operations inherently generates a highly exploitable power l eakage surface.

Despite this vulnerability, existing side-channel research predominantly targets latt ice-based schemes [4-13], leaving SLH-DSA's PRF derivations largely unexplored. As

[1] Corresponding author: L3mory@protonmail.com

$SK.seed$ constitutes the absolute root of trust, its physical extraction catastrophically c ompromises the signature's unforgeability.

To bridge this gap, we propose a tailored Correlation Power Analysis (CPA) attack targeting the SLH-DSA $SK.seed$. Data flow analysis isolates the SHAKE256 permuta tion's linear θ and nonlinear χ steps as critical leakage sources. Utilizing a Hamming we ight model and Pearson correlation, our experiments achieve full key recovery with mer ely 50 traces. These results expose severe physical vulnerabilities in SLH-DSA, providi ng a vital foundation for future hardware countermeasures.

2. Preliminaries

2.1. SLH-DSA Algorithm Description

Unlike traditional stateful schemes, SLH-DSA achieves statelessness by eliminating local key counters. Instead, it dynamically computes the required keys during each signature via a PRF using the $SK.seed$ and address structure $ADRS$.

As shown in Equation (1), the SLH-DSA secret key comprises four n-byte elements ($n = 16$ in this study). Specifically, $SK.seed$ serves as the foundational secret seed, while $SK.prf$ generates random factors during message hashing to thwart specific attacks. Additionally, $PK.seed$ ensures domain separation to prevent hash interference, and $PK.root$ functions as the public verification anchor.

$$SK = SK.seed \parallel SK.prf \parallel PK.seed \parallel PK.root \tag{1}$$

To ensure statelessness, SLH-DSA dynamically computes all temporary keys on demand using $SK.seed$. For SHAKE-based parameter sets, this underlying PRF is defined in Equation (2):

$$PRF(PK.seed, SK.seed, ADRS) = SHAKE256(PK.seed \parallel ADRS \parallel SK.seed, 8n) \tag{2}$$

2.2. SHAKE256 Algorithm Description

SHAKE256 [14], an extendable-output function based on the sponge construction, relies on the $Keccak-f$ permutation to iteratively process a 1600-bit internal state S. During SLH-DSA execution, padded input messages are divided into $r = 1088$ bit blocks, absorbed into the state matrix via XOR, and subjected to multiple permutation rounds.

The Keccak state S is a $5 \times 5 \times 64$ matrix where each bit is uniquely addressed by coordinates (x, y, z). Specifically, $x, y \in \{0, \dots, 4\}$ denote the row and column indices, while $z \in \{0, \dots, 63\}$ specifies the offset within one of the 25 64-bit Lanes.

$Keccak-f[1600]$ consists of 24 iterative rounds, and each round of $Keccak-f$ permutation includes five steps: θ, ρ, π, χ, and ι.

The θ step provides linear diffusion via column parity computation. As detailed in Equations (3)-(5), it calculates the column parity sum $C[x, z]$, derives the intermediate value $D[x, z]$ from adjacent columns, and XORs the result back into the state matrix:

$$C[x, z] = A[x, 0, z] \oplus A[x, 1, z] \oplus A[x, 2, z] \oplus A[x, 3, z] \oplus A[x, 4, z] \tag{3}$$

$$D[x, z] = C[(x-1) mod 5, z] \oplus C[(x+1) mod 5, (z-1) mod 64] \tag{4}$$

$$A'[x,y,z] = A[x,y,z] \oplus D[x,z] \tag{5}$$

As $Keccak-f$ only nonlinear layer, the χ step utilizes logical AND and NOT operations to update the state. This transformation is applied independently across each row of the matrix, as defined in Equation (6):

$$\mathrm{A'[x,y,z]} = \mathrm{A[x,y,z]} \oplus ((\mathrm{A}[(\mathrm{x}+1)\ mod\ 5, y, z] \oplus 1) \cdot \mathrm{A}[(\mathrm{x}+2)\ \mathrm{mod}\ 5, \mathrm{y}, \mathrm{z}]) \tag{6}$$

2.3. CPA

CPA recovers secret keys by exploiting the correlation between a device's instantane ous power consumption and the Hamming weight of processed data. The attack compri ses four standard steps:

(1) Execute N cryptographic operations, recording power traces T_i and corresponding plaintexts M_i.

(2) Select a key-and-plaintext-dependent intermediate variable V. Compute its hypot hetical value $V_i(sk_{guess})$ across all key candidates sk_{guess} and apply a leakage model t o estimate power consumption.

(3) Calculate the Pearson correlation between the estimated and actual power traces.

(4) Recover the secret key by selecting the candidate $sk_\{guess\}$ that maximizes this correlation.

3. CPA Security Analysis Against SLH-DSA

SLH-DSA achieves statelessness by dynamically computing temporary keys via a SHAKE256-based PRF. Given its $r = 1088$-bit bitrate, the 512-bit padded input is fully absorbed into the Keccak state matrix in a single block prior to the $Keccak-f$ permutation.

Per the established padding rules, data fills the matrix sequentially across the z, x, and y axes. Thus, the 512-bit input occupies the first eight Lanes, with the exact mapping detailed in Table 1.

Table 1 Mapping of Input Data in Keccak State Matrix

Data	Length(Bytes)	Corresponding Lane Coordinates (x,y)	Visibility from Attack Perspective
PK.seed[0:7]	8	Lane(0,0)	Known
PK.seed[8:15]	8	Lane(1,0)	Known
ADRS[0:7]	8	Lane(2,0)	Known
ADRS[8:15]	8	Lane(3,0)	Known and controllable
ADRS[16:23]	8	Lane(4,0)	Known
ADRS[24:31]	8	Lane(0,1)	Known
SK.seed[0:7]	8	Lane(1,1)	Known
SK.seed[8:15]	8	Lane(2,1)	Known

3.1. Leakage in θ Step

The $Keccak-f$ permutation begins with the θ step, providing linear diffusion via column parity sums $C[x]$ (the XOR sum of all five Lanes per column). As defined in Equations (7) and (8), with all other Lanes functioning as padded constants, column $x = 4$ isolates $ADRS[16:23]$ in $Lane[4,0]$, while $x = 2$ isolates $SK.seed[8:15]$ in $Lane[2,1]$.

$$\begin{aligned} C[4] &= Lane[4,0] \oplus Lane[4,1] \oplus Lane[4,2] \oplus Lane[4,3] \oplus Lane[4,4] \\ &= ADRS[16:23] \oplus 0 = ADRS[16:23] \end{aligned} \tag{7}$$

$$\begin{aligned} C[2] &= Lane[2,0] \oplus Lane[2,1] \oplus Lane[2,2] \oplus Lane[2,3] \oplus Lane[2,4] \\ &= 0 \oplus SK.seed[8:15] = SK.seed[8:15] \end{aligned} \tag{8}$$

Substituting $C[2]$ and $C[4]$ into Equation (4) yields Equation (9), with ROT denoting right rotation. Given the known $ADRS[16:23]$, the intermediate value $D[3]$ isolates $SK.seed[8:15]$ as its sole unknown, making it a critical leakage target.

$$D[3] = C[2] \oplus \mathrm{ROT}(C[4], 1) = SK.seed[8:15] \oplus ADRS[16:23] \tag{9}$$

For $x = 3$ and $y = 0$, Equation (5) yields Equation (10). Because the updated state $A'[3,0]$ integrates the known $ADRS[8:15]$ with the $SK.seed$-dependent $D[3]$, its Hamming weight inherently correlates with device power consumption. Consequently, we designate $A'[3,0]$ as the target intermediate variable, employing a Hamming weight leakage model to recover the final 8 bytes of $SK.seed$.

$$A'[3,0] = A[3,0] \oplus D[3] = ADRS[8:15] \oplus SK.seed[8:15] \tag{10}$$

3.2. Leakage in χ Step

As $Keccak-f$'s only nonlinear layer, the χ step computes Lane outputs based on row-adjacent neighbors. After the θ, ρ, and π transformations, $SK.seed$ shifts from $Lane[1,1]$ to $Lane[1,0]$. Applying Equation (6) yields Equation (11), with A_π denoting the post-π state matrix. Specifically, $A_\pi[2,0]$ supplies the known $SK.seed[8:15]$ (recovered in Section 2.3), while $A_\pi[3,0]$ provides the controllable $ADRS$.

$$\begin{aligned} A_\chi(1,0) &= A_\pi(1,0) \oplus \left(\neg A_\pi(2,0) \oplus A_\pi(3,0)\right) \\ &= SK.seed[8:15] \oplus (\neg ADRS[8:15]) \end{aligned} \tag{11}$$

Because the intermediate state $A_\chi[1,0]$ integrates both $ADRS[8:15]$ and $SK.seed$, its Hamming weight directly correlates with device power consumption. Thus, we select $A_\chi[1,0]$ as the target intermediate variable and employ a Hamming weight model to recover the first 8 bytes of $SK.seed$.

4. CPA Attack on SLH-DSA

To implement the CPA attack during the θ step and χ step, the specific operations are carried out in the following order:

1) Select A'[3,0] in the θ step as the attack intermediate variable V, whose calculation formula is shown in Equation (12). Select $A_\chi(1,0)$in the χ step as the attack intermediate variable, whose value is shown in Equation (13):

$$V = A'[3,0] = A[3,0] \oplus D[3] = ADRS[8:15] \oplus SK.seed[8:15] \tag{12}$$

$$V = A_\chi(1,0) = A_\pi(1,0) \oplus \left(\neg A_\pi(2,0) \wedge A_\pi(3,0)\right) \tag{13}$$

2) Executing SLH-DSA N times with fixed $SK.seed$ and $PK.seed$, we capture power traces T_i (spanning SHAKE256's initial θ and χ steps) alongside addresses ADRS_i to construct (T_i, ADRS_i) pairs for leakage modeling.

3) Enumerating all candidates $sk_{\mathrm{guess}} \in \{0, \ldots, 255\}$ for each SK.seed byte, we apply Equation (14)'s Hamming weight model to V_i to derive the hypothetical leakage $H_{i,sk_{\mathrm{guess}}}$.

$$H_{i,sk_{guess}} = HW\left(V_i, sk_{guess}\right) \tag{14}$$

4) Using Equation (15), the candidate sk_{guess} yielding the maximum absolute Pearson correlation is extracted as the correct key byte. Iterating this across all positions fully recovers $SK.seed$.

$$\rho\left(sk_{guess}\right) = \frac{\sum_{i=1}^{N}\left(H_{i,sk_{guess}} - \bar{H}\right)(T_i - \bar{T})}{\sqrt{\sum_{i=1}^{N}\left(H_{i,sk_{guess}} - \bar{H}\right)^2}\sqrt{\sum_{i=1}^{N}(T_i - \bar{T})^2}} \tag{15}$$

5. CPA Attack Experiment on SLH-DSA

To evaluate the proposed CPA attack, we implement a Python-based side-channel s imulation platform modeling the PRF's power consumption during SLH-DSA executio n. In our experiments, the target $SK.seed$ is fixed to 0x780d9f3c70cd4f9e9700dc49e49 ea7cf.

5.1. CPA Attack

Attacking the 8th byte of $SK.seed$, we correlate all candidates $sk_{\mathrm{guess}} \in \{0, \ldots, 255\}$ against the measured traces. As shown in Fig. 1, the global maximum ρ = 0.8625 at $sk_{\mathrm{guess}} = 0x97$ perfectly matches the preset $SK.seed$. This fully validates the proposed θ-step CPA method for accurate key recovery.

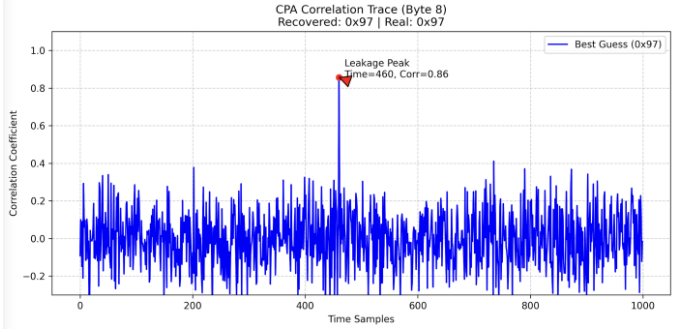


Figure 1. Correlation Power Trace for Byte 8.

5.2. Analysis of Attack Experiment Results

Following the θ and χ step CPA experiments detailed in Section 4, all 16 bytes of $SK.seed$ were successfully recovered. The extracted results perfectly align with the

preset target key, conclusively demonstrating the effectiveness, feasibility, and high accuracy of the proposed CPA method against SLH-DSA.

6. Conclusion

Addressing SLH-DSA's physical vulnerabilities, this paper identifies SHAKE256's θ and χ steps as critical leakage points through SK.seed data flow analysis. We propose a tailored CPA attack that achieves full key recovery with merely 50 traces, demonstrating high efficiency. This study highlights real-world PQC threats and provides a theoretical basis for future masking and countermeasures.

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Research on Fuzzing Mutation Strategy Based on Particle Swarm Optimization

Yuting XIAO[a], Jun LI[b], Zhibo DU[a1] , Kang YANG[b] and Huixin LI[b]
[a] *School of Cybersecurity, Chengdu University of Information Technology, Chengdu 610225, China*
[b] *System of Systems and Artificial Intelligence Laboratory, AVIC Chengdu Aircraft Design & Research Institute, Chengdu 610041, China*

Abstract. To address the limitations of conventional fuzzers in mutation strategy, including weak adaptability and inefficient operator scheduling, this paper proposes an improved particle swarm optimization (IPSO)-based mutation strategy for fuzzing. The non-deterministic mutation stage is modeled as an optimization problem, where the selection probabilities of mutation operators are treated as optimization variables. A nonlinear exponentially decaying inertia weight model is designed to dynamically balance exploration and exploitation, and a Beta-distribution-based stochastic perturbation is introduced to enhance search diversity. Furthermore, a fitness function that integrates path coverage increment and the number of interesting seeds is constructed to guide the adaptive evolution of mutation operator scheduling. Experimental results on six representative benchmark programs show that, compared with AFL and MOpt, the proposed method achieves a 5%–8% improvement in path coverage over MOpt and up to 280% over AFL, while increasing the number of interesting test cases by up to 3×. These results demonstrate the effectiveness and robustness of the proposed method in improving fuzzing efficiency.

Keywords. Fuzzing; Particle Swarm Optimization (PSO); Mutation Operator; Vulnerability Discovery

1. Introduction

With the increasing complexity of software systems, ensuring software security has become a critical challenge. Fuzzing has emerged as an effective vulnerability detection technique due to its high automation and scalability [1-3]. Coverage-guided fuzzing, represented by AFL [4], utilizes runtime feedback to guide input mutation. However, AFL's Havoc stage selects mutation operators uniformly at random, ignoring their varying effectiveness and resulting in inefficient exploration.

To improve fuzzing efficiency, existing studies have proposed several adaptive strategies, which can be broadly categorized into three types. First, seed scheduling methods such as AFLFast [5] and FairFuzz [6] prioritize inputs that are more likely to explore rare paths. Second, hybrid approaches, including Driller [7] and Angora [8], integrate fuzzing with techniques such as symbolic execution to enhance path discovery. Third, mutation operator scheduling methods directly optimize operator selection probabilities, among which MOpt [9] introduces Particle Swarm Optimization (PSO) for

[1] Corresponding author: duzb@cuit.edu.cn

adaptive adjustment. Despite these advances, limitations remain. Seed scheduling and hybrid methods focus on input selection rather than mutation behavior, while MOpt's linear inertia weight lacks flexibility in balancing exploration and exploitation, making it prone to premature convergence. Moreover, the absence of effective perturbation mechanisms limits its robustness in dynamic fuzzing environments.

To address these issues, this paper proposes an Improved Particle Swarm Optimization (IPSO)-based mutation strategy. The method adopts a nonlinear exponentially decaying inertia weight to better balance exploration and exploitation, and introduces a Beta distribution-based perturbation mechanism to enhance search diversity and avoid local optima. The main contributions are as follows:(1) Proposing a dynamic adjustment strategy for inertia weights based on non-linear exponential decay, effectively resolving the imbalance between exploration and exploitation in mutation space searches; (2) Introducing a Beta distribution-based random perturbation mechanism to mitigate the issue of premature convergence; and (3) Integrating the proposed algorithm into the fuzzing workflow and validating its effectiveness through standard benchmark suites.

2. Preliminaries

2.1. Mutation-Based Fuzzing

Fuzzing is categorized into generation-based and mutation-based methods. While generation-based fuzzing offers high precision through protocol-specific construction, it is often hindered by complex implementation and limited versatility [10].

In contrast, mutation-based fuzzing utilizes a set of legitimate seed files and applies mutation operators—such as byte flipping, shifting, and data insertion—to generate new test cases. Its primary advantage lies in using high-quality seeds as a baseline, allowing for subtle modifications that preserve valid input structures while probing for deep-seated logical vulnerabilities. Despite some inherent "blindness" and the production of redundant samples, its capacity for stochastic exploration provides high heuristic value and efficiency in uncovering elusive software bugs and complex edge-case risks.

2.2. Mutation Operators

Mutation operators are the core mechanism for exploring new execution paths by modifying input seeds [11]. In traditional fuzzers like AFL, these operators follow a progressive logic from granular changes to structural disruptions, categorized into four types:

Bit-level and Byte-level Mutations: These provide the finest granularity. Bitflip (inverting 1‑32 bits) triggers logic branching and probes state machines, while Byteflip disrupts identifiers (e.g., file headers) to test format validation and fault tolerance.

Arithmetic and Numerical Mutations: Used for bypassing range validations, Arithmetic operators perform integer addition/subtraction (range [1, 35]) to simulate fluctuations around thresholds. Interesting Values replace data with edge cases (e.g., 0, -1, or memory limits) to induce overflows, out-of-bounds errors, or division-by-zero exceptions.

Semantic and Dictionary-based Mutations: These leverage prior knowledge to bypass syntactic parsing. Insertion and Overwriting use predefined tokens or dictionary entries to ensure mutated cases (like SQL or XML) remain grammatically valid, enabling deeper exploration of business logic.

Block Manipulation: This focuses on structural reorganization rather than simple data modification. Block Deletion tests robustness against missing data, while Block Cloning constructs extreme inputs to trigger memory safety failures like buffer overflows. This mechanism is critical for uncovering vulnerabilities in complex protocol parsing.

3. Research on Mutation Strategy Based on Particle Swarm Optimization

3.1. Overview of Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a heuristic global stochastic search algorithm that simulates the foraging behavior of bird flocks. In a D-dimensional search space, each particle represents a potential solution to the problem. Particles update their positions and velocities by dynamically tracking two extreme values: the individual historical optimal position (p_{best}), discovered by the particle itself during the iteration process, and the global historical optimal position (g_{best}), currently identified by the entire population. The state of a particle is jointly determined by its position vector x_i and velocity vector v_i. During each iteration, the velocity and position of a particle are adjusted according to the following formulas:

$$v_{id}^{t+1} = \omega v_{id}^{t} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 \left(p_{gd} - x_{id}\right) \quad (1)$$

$$x_{id}^{t+1} = x_{id}^{t} + v_{id}^{t+1} \quad (2)$$

where t denotes the current iteration; d represents the dimensionality of the particle space; v_{id} and x_{id} denote the velocity and position components of particle i in the d-th dimension at iteration t, respectively; ω is the inertia weigh; c_1 and c_2 are acceleration coefficients; r_1 and r_2 are random variables uniformly distributed in [0,1]; and p_{id} and p_{gd} denote the personal best position of particle i and the global best position of the swarm, respectively.

3.2. Improved Particle Swarm Optimization Algorithm

Standard Particle Swarm Optimization (PSO) algorithms typically employ a fixed linear decreasing strategy for inertia weights. While this approach exhibits some effectiveness in addressing simple problems, it proves overly rigid when confronted with the complex and dynamically shifting tasks inherent in fuzzing mutation scheduling. As the number of iterations increases, linearly decreasing weights cause the particle swarm to lose population diversity in the later stages of the search. This makes the swarm highly susceptible to becoming trapped in local optima−stalls caused by high-yield mutation operators−leading to a phenomenon known as "premature convergence". Once the PSO algorithm falls into a local optimum, the mutator struggles to explore deeper code branches within the target program.

To address the issues of premature convergence and susceptibility to local optima within complex search spaces, this study proposes a nonlinear enhancement strategy for dynamically adjusting the inertia weight. By constructing an inertia weight model based on exponential functions and incorporating a random factor following the Beta

distribution, self-adaptive regulation of the search process is achieved. The expression for the improved inertia weight is defined as follows:

$$\omega = \omega_{min} + (\omega_{max} - \omega_{min}) \cdot e^{-\frac{t}{t_{max}}} + \sigma \cdot B(p, q) \quad (3)$$

where t and t_{max} t_max denote the current and maximum iteration numbers, respectively; ω_{max} and ω_{min} represent the initial maximum and final minimum values of the inertia weight; $e^{-\frac{t}{t_{max}}}$ is the exponential decay term, which determines the nonlinear rate at which the weight decreases over time; σ is the perturbation strength coefficient; and $B(p, q)$ denotes a random variable following a Beta distribution.

The exponential decay term allows ω to remain relatively large in the early stage of the algorithm, ensuring strong global exploration capability and enabling rapid traversal of the operator search space. As t increases, ω decreases nonlinearly, shifting the search process toward local exploitation and improving the precision around optimal operator combinations. In addition, the introduction of the stochastic term $\sigma \cdot B(p, q)$ enables real-time adjustment of the inertia weight. Leveraging the flexible skewness of the Beta distribution, this mechanism injects dynamic perturbations into the particle velocity, enhancing the ability to escape local optima in later iterations and significantly improving the robustness of the algorithm.

3.3. Implementation Details

This study integrates the Improved Particle Swarm Optimization (IPSO) algorithm into the Havoc stage of fuzzing by modeling mutation operators as particles in a high-dimensional vector space. The self-adaptive evolution of the operator scheduling strategy follows a closed-loop "feedback-adjustment-retest" cycle, divided into four phases:

Initialization Phase: Each mutation operator is modeled as a particle, and the set of operators forms a particle swarm. The particle position distribution is used as the probability distribution for operator selection to guide test case mutation. Following MOpt, the number of swarms (N_p) is set to 5, with 18 particles per swarm. The initial velocity v_0 is 0.1, and both p_{best} and g_{best} are initialized to 0.5. The inertia weight ranges from 0.4 to 0.9 (ω_{max} = 0.9, ω_{min} = 0.4), and the adjustment factor σ is set to 0.3.

Execution and Scheduling Phase: Particle coordinates are normalized into a probability distribution. The fuzzing engine uses this distribution to prioritize high-weight mutation strategies, generating test cases for target program execution.

Feedback and Evaluation Phase: The algorithm monitors runtime feedback, including path coverage and the number of interesting seeds, to compute fitness values.

$$F = \lambda_1 Cov + \lambda_2 Int \quad (4)$$

where Cov denotes the increment in path coverage, and Int represents the number of generated interesting test cases. λ_1 and λ_2 are weighting coefficients, set to λ_1 = 0.7 and λ_2 = 0.3 in this study.

Particle Swarm Update Phase: Velocity and position vectors are iteratively updated based on feedback. This evolutionary mechanism allows the swarm to converge toward an optimal state, dynamically guiding mutation paths to enhance vulnerability detection efficiency through tailored mutation patterns.

4. Experiment

This chapter evaluates the IPSO algorithm's efficacy across key metrics: path coverage, "interesting" seed generation, and vulnerability discovery

4.1. Experimental Setup

Experiments were conducted on 64-bit Ubuntu 22.04.4 LTS. To ensure statistical significance, each target underwent five independent 12-hour trials.The test suite includes six representative open-source programs—readelf, nm, size, cxxfilt, w3m, and jhead—covering binary parsing, symbol demangling, and document/image processing.

4.2. Analysis of Experiment Results

（1）Evaluation of Path Coverage Efficiency

After 12 hours of fuzzing, the results in Table 1 show that IPSO_AFL consistently outperforms AFL and MOpt across all six programs, demonstrating strong stability and adaptability. Compared with AFL, IPSO_AFL achieves substantial improvements, with path coverage on readelf, size, and nm increasing by 80%–290%, indicating more effective exploration of new execution paths. Relative to MOpt, IPSO_AFL maintains steady gains on most programs, suggesting that the proposed nonlinear inertia weight mechanism better adapts to dynamic search requirements than the linear strategy. Notably, on cxxfilt, IPSO_AFL reaches 11,074 paths, significantly exceeding AFL (5,897) and MOpt (2,278), highlighting its ability to avoid premature convergence and explore deeper paths.

Target Program	AFL		Mopt		IPSO_AFL	
	Paths Discovered	Coverage	Paths Discovered	Coverage	Paths Discovered	Coverage
readelf	2972	9.62%	4995	12.67%	**5385**	**13.22%**
size	530	3.55%	1912	6.00%	**2061**	**6.21%**
nm	1202	5.19%	2209	6.85%	**2384**	**7.10%**
cxxfilt	5897	9.37%	2278	5.21%	**11074**	**10.25%**
w3m	1154	3.72%	2307	4.19%	**2597**	**4.60%**
jhead	606	2.10%	1097	2.04%	**1156**	**2.23%**

Table 1. Comparison of Path Coverage Performance.

(2) Generation of Interesting Test Cases

The experimental data presented in Table 2 indicate that IPSO_AFL consistently ranks first in the number of "interesting" test cases generated across the vast majority of target programs. Compared to the baseline AFL, IPSO_AFL demonstrated a several-fold increase across all test targets. Specifically, for size, nm, and w3m, the number of generated interesting cases was 3.0x, 1.6x, and 2.1x that of AFL, respectively. These results demonstrate that the self-adaptive mutation strategy effectively eliminates the inherent "blindness" of the testing process. By generating test samples with a higher success rate in triggering new execution paths, the proposed method maximizes the mutation yield within a constrained time budget.

Target Program	Interesting Test Case		
	AFL	Mopt	IPSO_AFL
readelf	1349	**2127**	2086
size	152	429	**469**
nm	319	488	**537**

cxxfilt	1078	432	**1202**
w3m	97	166	**211**
jhead	213	202	**214**
Total	3208	3844	**4719**

Table 2. Comparison of Interesting Test Case Generation.

5. Conclusion

This paper addresses the poor adaptability and low efficiency of traditional fuzzing mutation strategies by proposing an Improved Particle Swarm Optimization (IPSO) scheduling approach. By mapping mutation operators to a high-dimensional particle space and leveraging path coverage and interesting seeds as feedback, we achieve self-adaptive evolution of operator selection probabilities. The introduction of non-linear exponentially decaying inertia weights effectively balances global exploration with localized refinement. Furthermore, the Beta-distributed stochastic perturbation empowers particles to escape local optima, mitigating premature convergence. Experimental results demonstrate that IPSO significantly enhances fuzzing efficiency and the discovery of effective test cases. Future research will focus on refining fitness function designs and integrating this strategy with seed scheduling to further optimize resource allocation.

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A Review of Research Progress on Forest Land Cover Classification Model Based on Remote Sensing Images

Linyan MA[a], Weijie ZHONG[b], Qiang WANG[c], Lili CHEN[d], Yanhua ZHANG[e], Jin WANG[a,1] Shuya LIU[a], Fengke DOU[b], Xiuqin SUN[b], Haiying GUAN[f]
[a] *Research Institute of Resources and Environment Innovation, Shandong Jianzhu University, Jinan 250101, China;*
[b] *Shandong Coal Field Geological Survey and Research Institute, Jinan 250100, China;*
[c] *Shandong Provincial Forestry Protection and Development Service Center, Jinan 250114, China;*
[d] *Chengyang district natural resources service center, Qingdao, 266000, China;*
[e] *Marine development center of Changyi, Weifang 261300, China;*
[f] *Wuzhiyuan (Nanjing) Biotechnology Co., Ltd, Nangjing 211221, China*

ORCiD ID: Jin Wang https://orcid.org/0000-0002-4366-9236

Abstract. This review systematically examines forest land cover classification models based on remote sensing imagery, categorizing approaches by classification units, label requirements, and feature attributes. The research highlights the significant advantages of deep learning techniques (including CNN, RNN, GAN, and ViT) in improving classification accuracy and efficiency, while also exploring the transition from traditional machine learning to deep neural network-based classification. The analysis identifies the critical bottlenecks including data scarcity, limited model generalization, and computational constraints when mapping complex terrains or high density vegetation. Future efforts would focus on optimizing algorithms for complex terrains and high density vegetation, developing lightweight models, and overcoming bottlenecks in transfer learning and model efficiency to enable practical deployment in resource constrained settings.

Keywords. Forest land cover types, Classification models, Deep learning, Neural networks

1. Introduction

Forests are vital regulators of global ecological processes and climate change. While remote sensing imagery remains the gold standard for monitoring these dynamics due to its extensive coverage and temporal diversity, the field is undergoing a rapid paradigm shift. In recent years, forest land cover classification has advanced significantly through the integration of multi-source data and sophisticated algorithms, transitioning from traditional statistical methods to complex deep learning architectures. These innovations

[1] Corresponding Author: Jin Wang, wangjin21@sdjzu.edu.cn.

have drastically improved classification granularity and provided critical technical support for dynamic resource management [1,2,3].

Despite this rapid progress, particularly in the deployment of deep neural networks, there is a conspicuous lack of recent, focused surveys that synthesize these modern advancements specifically for forest land cover. Most existing reviews either address general land use or are outdated, failing to account for the latest breakthroughs in spatial-temporal modeling and high-resolution feature extraction. To bridge this gap, this study provides a comprehensive review of remote sensing-based forest classification models. By evaluating the shift toward deep learning and identifying current technical bottlenecks, this research aims to provide the scientific insights necessary for the precise management and sustainable development of global forest resources.

2. Overview of Forest Land Cover Classification Models and Algorithms

Forest land cover classification models are essential for accurately identifying and distinguishing various types of surface cover, providing precise data for forest resource monitoring. Given the diversity of image classification techniques, different approaches lead to varying classification outcomes. As illustrated in Figure 1, this study categorizes forest land cover classification methods across three dimensions: the need for labeled samples, the minimum classification unit, and the feature space attributes. It is important to note that these three classification dimensions in this study may overlap to some extent.

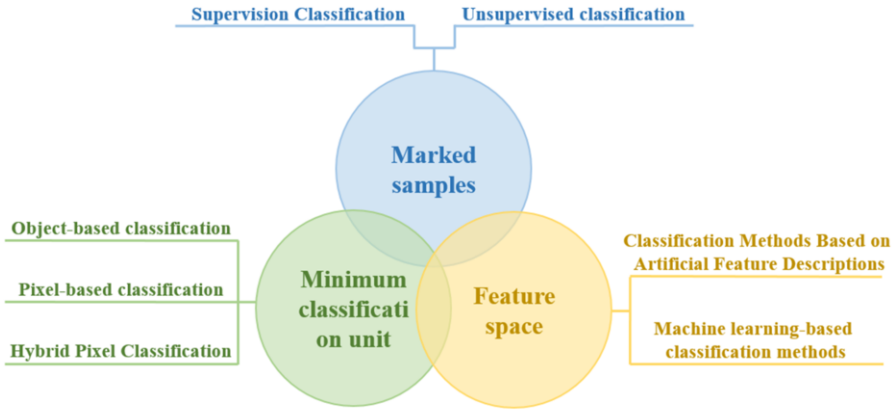


Figure 1. Classification Method of forest land cover types.

2.1. Classification method based on the division of classification units

2.1.1. Pixel-based forest land cover classification

Pixel-based classification is a method where each pixel in the image is treated as the smallest unit for classification, and it is assigned to a specific class based on its spectral characteristics. Common approaches include pixel-binary methods, vegetation indices, unsupervised classification, and supervised classification. While pixel-based classification is straightforward, intuitive, and easy to implement, making full use of the spectral information in the image, it overlooks the spatial relationships between pixels.

This can result in the "salt-and-pepper" effect, where the classification output is discontinuous and contains a significant amount of noise [4].

2.1.2. Object-based forest land cover classification

Object-based classification is an image classification approach that involves identifying and extracting object features from remote sensing images to achieve classification. In this context, "objects" refer to geographic entities or regions within the remote sensing image that consist of pixels with similar characteristics. This method takes into account spatial features of land cover, such as texture, shape, and contextual information, leading to more accurate and continuous classification results. Additionally, object-based classification is effective in addressing issues like "spectral confusion" and "spectral ambiguity" [5]. Image segmentation is a critical step in object-based classification, but the choice of segmentation algorithm and the tuning of its parameters can significantly impact the classification results. Furthermore, the object-based classification approach tends to have a relatively high computational complexity, requiring more resources and processing time [6].

2.1.3. Forest Land Cover Classification Based on Hybrid Pixels

Mixed pixels refer to a phenomenon where a single pixel contains multiple land cover types. It is a common challenge in remote sensing, especially in heterogeneous landscapes, where the sensor's resolution cannot fully distinguish between the different types of land cover within a single pixel [7]. The presence of mixed pixels significantly impacts the accuracy of remote sensing image classification, as traditional pixel-based classification methods struggle to handle pixels that contain multiple land cover types. To address this issue, various mixed pixel decomposition techniques have been proposed. Linear spectral unmixing is the most widely used approach, which relies on a linear mixing model to solve a system of linear equations and determine the abundance of each land cover type. This technique is particularly useful for complex features, such as linear or small-scale objects, providing more accurate information that supports their identification and analysis. As a result, mixed pixel classification has become a key research area in remote sensing image processing, with significant potential for diverse applications.

2.2. Sample-based classification method

2.2.1. Supervised Classification Model

Supervised classification is a high-accuracy statistical classification approach that relies on prior knowledge of predefined classes. The core idea is to first select training samples from known classes within the training areas. Then, using these labeled samples, relevant feature variables (such as pixel brightness mean, variance, etc.) are extracted, which are subsequently used to construct discriminant functions and classification criteria. A comparison of the advantages and disadvantages of several commonly used supervised classification methods can be found in Table 1.

Table 1. Supervised classification method of forest land cover types

Supervision Classification Method	Definition	Applicability	Advantages	Disadvantages
Minimum Distance Method	The minimum distance classification method calculates the distance between the spectral mean vector of an unknown pixel and the spectral mean vector of each class to determine its class membership.	This approach is well-suited for scenarios with high computational speed requirements.	It is computationally efficient, does not assume specific data probability distributions, and requires a minimal number of training samples [11].	The classification accuracy is limited, and the method is sensitive to time constraints. Additionally, it demands significant storage space and processing time [11].
Parallelepiped method	This classification method divides the multidimensional feature space into non-overlapping subspaces corresponding to different class categories by setting a series of partitioning points along each axis [8].	It is particularly useful in scenarios where quick preliminary classification results are needed, such as initial classification tasks or large-scale classification problems.	The approach is computationally efficient and provides fast classification speed [11].	The classification accuracy is limited, and the method is susceptible to noise, which may lead to discrepancies with the actual distribution of the land cover types [11].
Maximum likelihood estimation	This method assumes that the training sample data follows a Gaussian distribution in spectral space, where classification is determined by the contour of the sample's probability density. The pixel is then assigned to the class with the highest membership probability based on the calculated likelihood [9].	It is suitable for a variety of data types and domains, particularly in scenarios where high-precision classification results are required.	The method is grounded in solid theoretical principles, offering stable performance and high classification accuracy [12].	It is computationally intensive, requires a large number of samples, is sensitive to outliers, and is limited by the assumptions made in the model [11].
Support Vector Machine	This method separates different classes of samples by identifying an optimal hyperplane, and for nonlinear problems, it can map the data into higher-dimensional space using kernel functions for more effective classification [10].	It excels in binary and multiclass classification problems, high-dimensional data, and small sample scenarios.	The approach offers strong generalization capabilities and robust performance [11].	It is computationally complex, sensitive to parameter tuning, and faces challenges in handling multiclass classification tasks [14].
Decision tree method	The method involves hierarchical, stepwise comparisons based on the feature values of each pixel as the reference.	It is commonly applied in multi-class classification problems, feature selection, and handling missing data.	This approach is capable of handling various data types, offers fast classification, and can address multi-output issues, utilizing a white-box model [13].	This approach is prone to overfitting, struggles with predicting continuous fields, and is sensitive to initial conditions. Additionally, it tends to overlook the interdependencies between feature values [15].

2.2.2. Unsupervised classification model

Unsupervised classification is a land cover classification technique that relies on the intrinsic statistical properties of the image and the distribution patterns of natural point clusters for class differentiation, without the need for prior knowledge of the categories. In the absence of specific knowledge or expertise regarding the classification area, this method solely depends on the distribution characteristics of natural point clusters and the information inherent in the remote sensing data to carry out the classification process [14]. In other words, this technique does not rely on known information about specific land cover types but instead leverages the intrinsic statistical properties of the image [15].

2.3. A Feature Space-Based Classification Method for Land Cover Types

2.3.1. Classification Methods Based on Artificial Feature Descriptions

In classification methods based on manual feature description, visual interpretation was one of the earliest techniques used for forest land cover type classification. Visual interpretation requires interpreters to integrate the characteristic information presented in the forest cover images and identify and label different land cover types [16]. While visual interpretation can achieve high classification accuracy, it has several limitations: for instance, it demands that the interpreter possess in-depth knowledge and experience of the study area's land cover; the manual digitization process is inefficient, time-consuming, and lacks timeliness.

2.3.2. Machine learning-based classification methods

As a nonlinear algorithm, ANNs are well-suited for parallel processing of vast amounts of data and exhibit strong fault tolerance and resistance to interference. In recent years, with the rapid advancements in remote sensing technology, ANN-based algorithms have gained significant attention in the remote sensing field, achieving notable improvements in accuracy for tasks such as image classification and object recognition [17]. Particularly in forest land cover classification, ANNs have been widely applied and extensively researched due to their ability to automatically extract features and reduce reliance on manually designed features, offering a significant advantage in enhancing classification performance [18].

The Back Propagation Neural Network(BP) is one of the most representative and deeply studied algorithms in the field of artificial neural networks. With its exceptional flexibility and powerful nonlinear fitting capabilities, BP neural networks have demonstrated significant advantages in remote sensing image processing. This algorithm effectively handles the common nonlinear relationships present in remote sensing imagery, addressing key issues in remote sensing classification. As a result, BP networks enable rapid and accurate identification and extraction of land cover information, a capability that traditional remote sensing classification methods often struggle to achieve [19].

3. Land Cover Type Classification Model Integrating Deep Learning Techniques and Neural Networks

3.1. An Introduction to Deep Learning Technologies

Deep learning, proposed by Hinton and colleagues, is a deep neural network algorithm within the field of machine learning, with a core focus on representation learning. It aims to mimic the functioning of the human brain to deeply understand and interpret complex data, including but not limited to images, sound, and textual information. In the context of remote sensing, deep learning has been applied to model and analyze intricate spatial and spectral patterns in remote sensing data, offering significant improvements in tasks such as image classification, object detection, and change detection. By leveraging hierarchical feature learning, deep learning algorithms are capable of extracting high-level representations from raw data, leading to enhanced accuracy and automation in remote sensing applications.

3.2. The Application of Deep Neural Networks in Remote Sensing Image Classification

In many image scene classification tasks, traditional machine learning methods have been able to achieve certain levels of performance [20]. However, these methods often rely heavily on manually designed features and domain expertise, which limits their generalization ability and robustness, presenting challenges in a variety of contexts [21]. In contrast, deep neural networks, an extension of neural network techniques, have garnered increasing attention due to their ability to address these limitations. What sets them apart is their efficiency in extracting features of target objects, accurately capturing both shallow and deep elements of the image. This advantage makes deep neural networks particularly effective and suitable for applications such as forest cover type classification, where the complex and nuanced nature of remote sensing data requires robust feature extraction and high classification accuracy [22].

3.2.1. Convolutional Neural Networks (CNN)

Convolutional Neural Networks (CNNs) are composed of several key layers, including convolutional layers, pooling layers, and activation layers, with the design of the convolutional kernels being particularly crucial. For example, small-sized convolutional kernels are typically used to extract local features, while the number and weight of the kernels are selected based on the complexity of the forest texture recognition task [23]. Existing research has shown that CNNs offer significant advantages in forest land cover classification, and applying CNNs to remote sensing land cover classification has become a hot topic in current research. Compared to other methods, CNNs possess powerful feature representation capabilities and higher classification accuracy [24,25]. CNNs are capable of automatically extracting multi-level feature information directly from remote sensing images, including low-level features such as local textures and edges, as well as high-level semantic features. This significantly enhances feature extraction, Wei Zhang et al. utilized pre-trained deep Convolutional Neural Networks (CNNs) as core feature extractors, enabling the automatic learning and capturing of highly discriminative initial feature maps from high-resolution remote sensing imagery [26].

3.2.2. Recurrent Neural Networks (RNN)

Recurrent Neural Networks (RNNs), by incorporating neurons with feedback mechanisms, RNNs effectively capture contextual relationships within time-series data. In remote sensing image processing, RNNs demonstrate significant advantages in temporal modeling and analysis, leveraging their inherent capacity to handle variable-length time-series data. This ability enhances the accuracy of remote sensing image classification. Time-series data from remote sensing images, collected over multiple periods, can reveal dynamic patterns of land cover changes. These temporal correlations provide valuable discriminative information for land cover type identification, and RNNs, through their recurrent structure, deeply mine temporal features to model dynamic surface processes. This capability significantly improves the spatiotemporal consistency of classification results [27].

3.2.3. Generative Adversarial Networks (GAN)

Generative Adversarial Networks (GANs), based on the principle of adversarial training, have emerged as a powerful deep learning model with significant potential in the field of remote sensing image processing in recent years. A GAN consists of two components: a generator and a discriminator. Through adversarial training between these two, the generator learns to model the distribution of real data, enabling it to produce high-quality synthetic data [28]. GANs excel in scenarios with limited training data. For instance, Mahdianpari et al. integrated Sentinel-1/2 imagery with an improved AlexNet-GAN framework for wetland classification in Newfoundland. By synthesizing samples to mitigate data scarcity, they achieved a 92.3% overall accuracy, with F-1 scores for specific classes improving by up to 26% over the baseline. This underscores the efficacy of GANs for large-scale classification under data-constrained conditions [29].

3.2.4. The Vision Transformer (ViT)

The Transformer architecture introduces the concept of self-attention, which differentiates it from traditional RNNs or CNNs by allowing it to consider all positions in the input sequence simultaneously, rather than processing data sequentially [30]. Researchers have employed architectures such as 1D Convolutional Neural Networks (1D-CNN), Long Short-Term Memory networks (LSTM), and Transformers to significantly reduce memory consumption and processing time for sample data. These approaches maintain a high classification accuracy, achieving up to 99%, even when applied to large-scale remote sensing datasets [31]. Transformer architecture outperforms CNNs when dealing with noisy or augmented images, thanks to its self-attention mechanism, which allows information from the entire image to be accessed across all layers.

4. Conclusion

This paper provides a comprehensive review of the latest research advancements in forest land cover classification models based on remote sensing imagery. It systematically analyzes and discusses classification methods from three perspectives: classification methods based on units of classification, methods based on sample-based classification, and those based on feature space classification. The paper highlights the advantages,

disadvantages, and suitable applications of each approach. The analysis reveals that supervised classification models, known for their high accuracy and stability, hold a significant position in remote sensing image classification, while unsupervised models offer broader applicability due to their ability to operate without prior class knowledge. Additionally, machine learning and deep learning-based classification methods have shown strong potential and advantages in forest land cover classification.

Future research should transcend the conventional pursuit of model depth and instead explore "structurally intelligent" pathways for forest classification. First, to resolve the prevalent issue of blurred boundaries caused by forest fragmentation, researchers should integrate spatial-spectral attention mechanisms with edge-aware geometric constraint loss functions to enhance the precision of fine-scale mapping. Furthermore, the development of self-supervised pre-training and unsupervised domain adaptation is essential to leverage unlabelled remote sensing data for building foundation models. This approach effectively addresses the bottlenecks associated with the scarcity of ground-truth samples in remote regions and poor cross-regional generalization, ultimately establishing a next-generation forest monitoring framework characterized by high precision, low computational overhead, and robust performance.

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Digital Technology and Emerging Forms of Human Alienation: A Socio-Technical Analysis of Labor, Consumption, Interaction, and Cognition

Jingyu CUI, Liangliang WANG[1]
School of Marxism, Xi'an Shiyou University, Xi'an, P.R.China
ORCiD ID: Liangliang WANG https://orcid.org/0009-0005-9623-2766

Abstract. While the digital age reconstructs forms of social existence, it also reshapes human modes of being and value systems. Drawing on Economic and Philosophic Manuscripts of 1844 by Karl Marx, particularly the theory of alienated labor, this paper examines the existential crises generated by digital life. It argues that digital technology, driven by capital, is not a neutral tool but a new form of alienating force. This is reflected in the deskilling of labor, the symbolization of consumption, the instrumentalization of social interaction, and the fragmentation of cognition. These interconnected forms of 'digital alienation' foster utilitarianism, superficiality, and nihilism in value orientations. Grounded in the Marxist ideal of the free and all-round development of the individual, the paper further explores pathways to sublate alienation and reconstruct healthy value systems. It emphasizes integrating core socialist values into digital spaces through technological governance, educational innovation, and the cultivation of human subjectivity.

Keywords. digital age, existential dilemmas, value reconstruction, alienated labor, Technological Governance

1. Introduction

Social existence is increasingly embedded in digital technologies, making it necessary to revisit Marxist theoretical foundations in order to understand contemporary value transformation. In the Economic and Philosophic Manuscripts of 1844, Karl Marx develops the concept of alienation, identifying four interrelated dimensions under capitalist production: alienation from the product of labor, from the labor process, from species-being, and from other human beings [1]. Although formulated in the context of industrial capitalism, these categories provide a powerful analytical lens for interpreting the structural tensions of today's digital society.

In contemporary digital life, these forms of alienation are not only reproduced but also reconfigured through platform-based and data-driven systems [2-3]. Algorithmic management increasingly disciplines platform workers by embedding surveillance, performance evaluation, and behavioral nudging into everyday labor

[1] Corresponding Author: Liangliang Wang, wangliangliang@xsyu.edu.cn

processes. Social media platforms translate interpersonal interaction into quantifiable metrics such as likes, shares, and followers, thereby restructuring emotional expression into measurable digital labor. At the same time, data-driven consumption systems continuously shape and pre-structure individual preferences, subtly redefining desire through predictive analytics and recommendation algorithms. Personalized information environments, generated by algorithmic filtering, further intensify ideological segmentation and social polarization, fragmenting shared public experience.

These developments are often interpreted either through technological determinism or as neutral cultural evolution, both of which obscure their underlying structural determinants. From a Marxist perspective, however, social existence determines consciousness, and digital technology, as a key productive force, is never value-neutral [4]. Instead, it is embedded within and shaped by specific relations of production, particularly those associated with global capital accumulation. The emergence of platform capitalism demonstrates that technological systems are increasingly designed to optimize data extraction, behavioral prediction, and value capture, thereby extending the logic of capital into cognitive and affective domains.

Understanding value transformation in the digital era therefore requires moving beyond the surface of technological innovation to examine the deeper interaction between capital accumulation and rationalized digital systems. This paper conceptualizes this process as 'digital alienation', extending Marx's original framework to account for the systemic reorganization of labor, consumption, communication, and cognition under algorithmic governance. Within this framework, digital technologies function not merely as tools but as mediating structures that reshape human activity and social relations, producing new forms of value distortion characterized by utilitarian rationality, fragmentation of experience, and historical amnesia.

Building on Marx's humanist critique, this study analyzes how capital, mediated through advanced digital technologies, restructures everyday practices and subjective experience. It further explores how these processes generate new tensions between human subjectivity and technologically mediated systems of control. Rather than remaining at the level of critique alone, the paper also investigates possible pathways for transcending digital alienation under conditions of technological irreversibility. In particular, it emphasizes the reconstruction of value systems grounded in human subjectivity, collective agency, and normative orientation. Guided by core socialist values, such reconstruction is envisioned through coordinated efforts in technological governance, educational transformation, and cultural practice within digital space, aiming ultimately at the realization of more balanced and human-centered digital development.

2. Method

2.1 Research Design

This study adopts a qualitative socio-technical analytical framework to examine how digital technologies generate emerging forms of human alienation. Rather than developing an algorithmic or experimental model, the study investigates the interaction between technological systems and social relations through a structured theory-driven analysis.

2.2 Analytical Framework

The analysis is organized around four dimensions derived from Marxist alienation theory and contemporary digital society studies: labor alienation, consumption alienation, interaction alienation, cognitive alienation

2.3 Data Sources and Selection Criteria

The study relies on secondary sources including: peer-reviewed research on digital labor and platform economies, studies of algorithmic consumption and digital platforms, research on online interaction and social media behavior, literature on information overload and algorithmic cognition. Selection criteria included publication quality, relevance to digital technologies, and conceptual contribution to understanding human–technology relations.

2.4 Analytical Procedure

To investigate value shifts in the digital age, this study adopts Karl Marx's theory of alienated labor from Economic and Philosophic Manuscripts of 1844 as its core analytical framework. This perspective remains critically relevant, as it reveals how capital—mediated through big data and artificial intelligence (AI)system − systematically reshapes and distorts human existence in contemporary digital society.

The research employs a qualitative, theory-driven methodology. First, Marx's fourfold conception of alienation—alienation from the product, the labor process, species-being, and other human beings—is recontextualized within the digital era, identifying corresponding mechanisms in AI-driven platform labor, datafied consumption, algorithm-mediated interaction, and fragmented online cognition. Second, drawing on a critical hermeneutic approach, the study examines concrete digital phenomena—such as gig work under algorithmic management, consumption practices driven by data profiling, and information cocoons generated by personalized recommendation systems—as empirical manifestations of 'digital alienation.' It further analyzes how these practices give rise to specific distortions in value orientation, including utilitarianism, superficiality, and nihilism. Third, the analysis proceeds deductively across four interconnected lifeworld domains—labor, consumption, social interaction, and cognition—each corresponding to a dimension of Marx's original framework of alienation. This structured approach enables a systematic mapping between classical theory and contemporary digital conditions.

The study draws on secondary sources, including peer-reviewed academic literature, documented cases of digital platforms, and sociocultural trends reported in authoritative journals and policy documents. No primary empirical data are collected; instead, existing scholarship is critically synthesized through the lens of Marxist humanism. Particular emphasis is placed on the mediating role of big data analytics and AI algorithms in reshaping human practices and value systems.

By grounding its analysis in Marx's theoretical framework while extending it to digitally mediated contexts, this methodology ensures both analytical rigor and historical continuity, effectively bridging the insights of the 1844 Manuscripts with the value crises characteristic of contemporary algorithmic capitalism.

3. Results and Discussion

Applying the aforementioned methodology, this section presents empirical findings on digital alienation across key lifeworld domains, examines their underlying dynamics, and explores pathways for sublation—thereby moving from critical diagnosis to constructive engagement. The results are presented in Table 1.

Table 1. Analytical classification of digital alienation across labor, consumption, interaction, and cognition

Domain	Manifestations	Value Implications
Labor	Deskilling, quantified gig work	Utilitarianism, short-termism
Consumption	Symbolic consumption, desire guidance	Superficiality, hedonism
Interaction	Instrumental communication, quantified emotion	Indifference, utilitarian relations
Cognition	Information cocoons, fragmented cognition	Nihilism, historical apathy

As shown in the Table 1, the four domains—labor, consumption, interaction, and cognition—correspond to differentiated yet interconnected forms of digital alienation and value transformation. Recommendation algorithms may shape patterns of information exposure and attention allocation. Existing scholarship suggests that such mechanisms can potentially influence users' cognitive habits and engagement with broader social and historical contexts.

3.1 Multidimensional Manifestations of Digital Alienation

In the labor domain, under algorithmic management powered by big data and AI, complex work is atomized into quantifiable tasks. Ride-share drivers follow optimized routes; delivery riders are judged by minute-based metrics. This fosters a 'gig mentality': work as transient transaction rather than meaningful vocation. This reflects what Marx termed the 'alienation of labor activity itself': once a free, conscious, and creative confirmation of human essence, labor under digital capitalism becomes an external, coercive means of subsistence [5].This form of digital labor encompasses both paid labor by platform gig workers (e.g., ride-share drivers, content moderators)[6] and unpaid labor by ordinary internet users who post content on social media, produce behavioral data across apps, and even passively contribute their attention [7].Thus, we witness a huge rift between the 'peaceful and idealized life presented in social media feeds' and the overwhelming anxiety in real life, as well as the endless emergence of unscrupulous hype that seeks to gain online traffic at all costs, even challenging public order and good morals. This has resulted in the fact that 'while digital labor brings a certain degree of freedom and flexibility, it also gives rise to a deeper form of alienation'.

As Marx argues, free, conscious labor constitutes humans 'species-being'[8]. Digital alienation erodes professional pride and belonging, replacing them with utilitarian short-termism. In the consumption and daily life domain, digital platforms generate continuous desire via big-data profiling and AI recommendations, shifting consumption from use value to symbolic value (e.g., brand-collaboration sneakers, photo-oriented 'check-ins'). This 'symbolic consumption' ties happiness to external display— 'I am what I consume'. Instant gratification erodes frugality, producing alienated value systems such as the 'exquisitely poor'. In the cognitive and public

sphere domain, Personalized recommendation algorithms create 'information cocoons', reinforcing biases and sliding society toward post-truth conditions. Fragmented, decontextualized information weakens historical consciousness; grand narratives become memes (e.g., romanticizing the Republican era via filters), endangering national identity and cultural confidence.

3.2 Essential Critique: Life world Colonization and the Alienation of Values

The four dimensions identified above share a common underlying logic: driven by capital's imperative of value accumulation, technological systems increasingly colonize the lifeworld—the domain of communication, meaning-making, and value formation. In this process, algorithms commodify diverse aspects of human existence: labor is reduced to orders, consumption to symbols, communication to traffic, and cognition to polarized positioning.

Under conditions of digital capitalism, the internal criteria by which values are judged become both algorithmically structured and capital-driven. 'Good' is equated with traffic, 'kindness' with conversion, 'beauty' with attention, and 'ruth' with virality. Qualitative and intrinsic standards are thus displaced by quantitative metrics and instrumental calculations [9].

This transformation produces a systematic distortion of value orientation, manifesting in utilitarianism, fragmentation, and superficiality. These tendencies not only reshape individual perception and behavior but also erode the foundations of shared meaning and normative consensus, giving rise to widespread anxiety and a pervasive sense of value emptiness.

3.3 Path Exploration: Sublating Digital Alienation through Core Socialist Values

In the context of human development in the digital age, the central task is to reestablish the subjectivity of human beings under new technological conditions. Neither resistance to technology nor nostalgic attempts to restore a pre-digital past offer viable solutions. Instead, constructive responses require coordinated efforts across technological governance, education, and cultural development.

At the technological level, governance mechanisms must effectively regulate platform capital and data monopolies through antitrust enforcement, labor rights protection, and enhanced algorithmic accountability. At the same time, the development of non-profit and public-oriented digital platforms should be encouraged to rebalance the digital ecosystem. At the educational level, cultivating digital critical literacy is essential. This involves equipping individuals—especially students—with the capacity to decode technological systems, recognize algorithmic biases, and sustain rational judgment, reflective thinking, and historically grounded perspectives in digital environments [10]. At the cultural level, core socialist values should be organically embedded within the digital lifeworld. This requires leveraging emerging technologies such as big data, artificial intelligence, and VR/AR to create engaging and value-oriented cultural products, including immersive educational experiences and thematically rich digital media [11]. Supporting creators who promote constructive and socially beneficial content is also crucial for fostering a healthy digital culture [8]. Taken together, these pathways aim to transcend digital alienation while acknowledging the irreversibility of technological development. They ultimately point toward the Marxist ideal—articulated by Karl Marx—of the free and all-round

development of human beings as the normative horizon for value reconstruction in the digital age.

4. Conclusion

Value transformation in the digital age is not merely a cultural trend but a profound political-economic issue of human existence shaped by technological appearances. This study argues that Marx's theory of alienated labor in Economic and Philosophic Manuscripts of 1844 remains highly relevant, offering strong critical and explanatory power in the era of digital capitalism. The utilitarian, fragmented, and superficial tendencies of contemporary values stem from 'digital alienation', which arises from specific production relations and reflects a systemic distortion of human existence under digital technologies.

Marxism thus functions both as a 'weapon of criticism' and a 'criticism of weapons'. While capitalist applications of technology may intensify alienation and value disorder, socialist utilization can sublate alienation and promote individuals' free and comprehensive development. Accordingly, it is essential to strengthen technological governance, educational guidance, and cultural practice to ensure technology serves human flourishing, enabling core socialist values to thrive in the algorithmic age.

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Application Research of Portal Crane Intelligent Control System in Cargo Terminal of Huanghua Port

Xiaoyang LI[a], Jinsheng CHI[a], Zhenyuan HAN[a], Lijun DONG[a], Yunfei ZOU[b, 1], and Chaoyu SHEN[b]
[a] *Guoneng Huanghua Port Co., Ltd, Cangzhou 061000, China*
[b] *Waterborne Transportation Institute, Beijing 100088, China*

Abstract: Based on the actual operational process, this paper focuses on the research of technologies, such as grab shaking proof positioning, 3D laser scanning modeling, space anti-collision, visual recognition, and fully automatic operation. The technologies enabled the fully automated operation of portal cranes. These technologies have been successfully applied to the No. 6 portal crane of Huanghua Port Cargo Terminal. The portal crane has four fully automatic operating modes, including cabin-to-fixed point unloading, cabin-to-piece area unloading, fixed point grabbing and loading, and piece area grabbing and loading, thereby enabling intelligent control of portal crane operations.

Keywords: portal crane, grab shaking proof positioning, 3D laser scanning modeling, space anti-collision, fully automatic operation.

1. Introduction

With the growth of China's economy and global trade, Chinese ports have developed rapidly [1]. Portal cranes have the advantages of diverse types of work assignments, high work efficiency, and easy operation. Portal cranes have been widely used in terminal work areas and play a very important role in many lifting machinery in the port. The traditional mode of operation relies on the driver in the cab. It has the disadvantages of high operating skill requirements, a long period of driver training, and high labor intensity. The operating efficiency is unstable. There are greater safety risks. At present, crane automation technology is used in container operations in China. It has been widely used in ports such as Yangshan Port and Qingdao Port. However, the main lifting equipment at cargo terminals is rotary cranes, which has led to the absence of portal crane automation technology at these cargo terminals.

[1] Corresponding Author, Yunfei ZOU, Waterborne Transportation Institute, Beijing 100088, China; E-mail: zouyunfei@wti.ac.cn

2. Grab positioning and Anti-Shake Technology.

This paper adopts a closed-loop control system to achieve grab position control and anti-shake technology. Based on the coordinate positions of each mechanism to record the real-time spatial position of the grab and the kinematic model of the portal crane, the motion trajectories and speeds of each mechanism can be quickly and accurately calculated to realize anti-shake and positioning of the portal crane's grab [2-3].

2.1. Principle of anti-shake technology

Figure 1 shows the schematic diagram of the grab anti-shake system. The external variable used to estimate the shake angle is the equivalent rope length. Equation (1) gives the simple pendulum period formula. T is the single pendulum period, and the unit of T is seconds (s). L is the equivalent rope length, and the unit of L is meters (m). g is the acceleration of gravity.

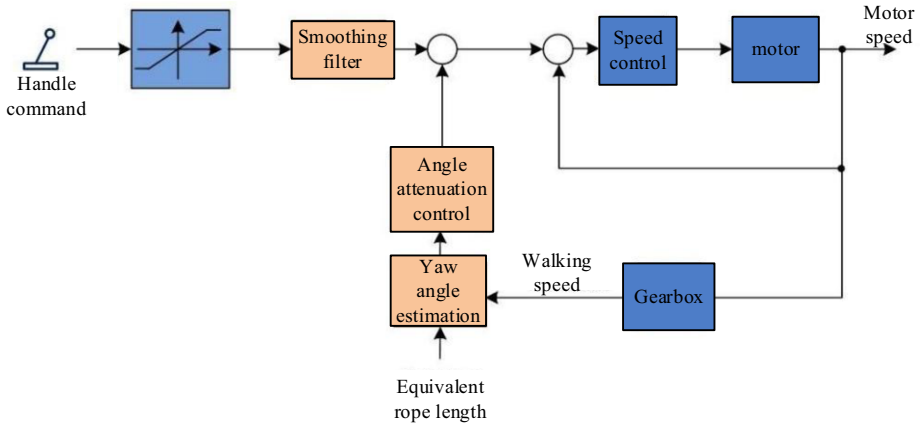


Figure 1. Diagram of grab positioning and anti-shake technology.

The equivalent rope length of the grab is determined by establishing a table of the oscillation period of the grab, and the deflection Angle of the grab is calculated by taking the walking speed and the equivalent rope as the external input variables. The motor speed is accurately regulated by the closed-loop vector control mode of the inverter, which realizes automatic hook operation [4].

$$T = 2\pi\sqrt{L/\mathrm{g}} \tag{1}$$

2.2. Grab positioning technology

After eliminating grab shaking, the spatial position of the grab can be determined from the positions of each mechanism of portal crane and the kinematics model of portal crane. The trajectory and speed of each mechanism are determined. The position of the grab is accurately located.

3. Material and Ship Type Modeling Technology.

This paper uses a laser scanner to scan the target area in 2D and adds Z-axis movement to generate 3D point cloud data [5]. Micro-nano filtering and non-local mean noise reduction algorithms are used to process the original data. Based on the viewing angle of the laser scanner, the spatial position of the target object is determined by an image feature recognition algorithm [6]. The rotation transformation algorithm is used to calculate the coordinate transformation matrix of the spatial coordinate system and the global coordinate system. The coordinate values of the hatches, ship's side decks, and material areas are determined in the global coordinate system.

3.1. Principal of coordinate transformation

Coordinate transformation describes the position of a physical object. Coordinate transformation generally includes three operations: translation, scaling, and rotation. For a given point, it is V_a in the A coordinate system. In the B coordinate system, its coordinate value V_b can be obtained by translation and rotation. The expression of T_{ab} is shown in Equation (2).

$$T_{ab} = \begin{bmatrix} R_{ab} & t_{ab} \\ 0 & 1 \end{bmatrix} \tag{2}$$

In Equation (2), R_{ab} is the rotation matrix and is t_{ab} the translation vector. Solving Equation (2) yields Equation (3).

$$V_a = T_{ab} * V_b \tag{3}$$

3.2. Modeling

3.2.1. Scanning calibration

The No. 6 portal crane is rotated to the direction where the boom is parallel to the coastline, and the boom points to the direction of the No. 5 portal crane. The scanner is activated in actual working conditions. The scene is 3D scanned. The point cloud map is obtained. The angle between the earth plane and the ideal horizontal plane is extracted. The predefined rotation zero position of the servo pan-tilt is corrected. The angle between the coastline and the crane's orientation is extracted. The rotation angle between the rotation coordinate system and the global coordinate system is corrected.

In addition to correcting the angle of the scanner, the offset of the gimbal base coordinate system relative to the portal crane rotation coordinate system should also be determined. According to the mechanical drawings of the portal crane and the point cloud data obtained by the scanner, a "point with the same name" can be found in the point cloud map to determine the offset between the two coordinate systems.

3.2.2. 3D scanning of the ship Type

After calibration is completed, the coordinate transformation chain between the scanner and the global coordinate system is determined. The coordinate system is defined as the X-axis parallel to the coastline, the Y-axis facing the sea, and the Z-axis vertically

upward. The origin is set as the vertical projection of the center on the dock surface. All coordinates of the portal crane are based on information from this coordinate system.

3.2.3. Hatch coordinate extraction

The hatch coordinate includes the hatch height and the four corner coordinates. First, the points in the world coordinate system are homogenized and denoised, and then the plane detection algorithm is used to determine the deck height. After that, the four corner coordinates of the hatch are determined using deck height and point cloud data.

3.2.4. Material extraction

To achieve fully automatic operation, the height of the material needs to be detected. The height of the grab drop can be controlled when grabbing the material. According to the operation process, the hatch range can be divided into checkerboard grids. Each cell represents a material capture process. According to the execution strategy, the automated operation process can be executed.

Based on the hatch range, the set safety margin, and the execution step size, the material area is divided into M × N checkerboard grids. The point height (Z direction) in each checkerboard is counted to determine the average height in the grid. The 3D modeling diagram of the material and ship type is shown in Figure 2. The center point of the grid and the average height (Z direction) are used as the target point for the actual portal crane. Based on the target point, the corresponding material grabbing operation is carried out.

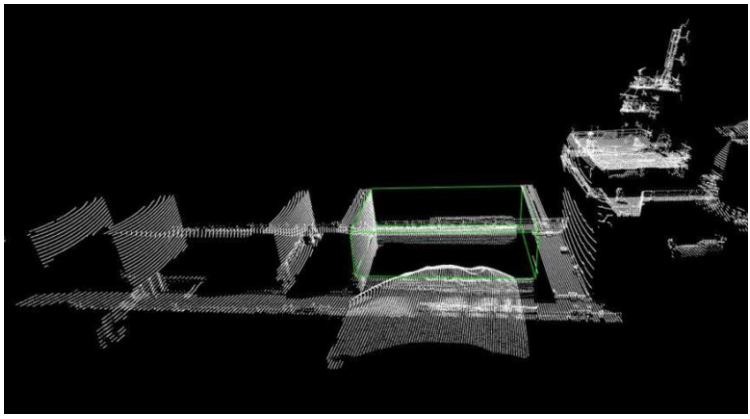


Figure 2. 3D modeling diagram of materials and ship type.

4. Safety Protection Technology.

4.1. Obstacle recognition technology

Obstacles on the driving route can be detected and avoided by obstacle recognition technology. To realize the dynamic protection during the fully automatic full-process operation [7], two laser scanners equipped with servo PTZ are installed on both sides of

the electric room of the portal crane, and a 16-line laser scanner (3D) is installed at the elephant trunk beam of the portal crane. Based on data from three laser scanners, the portal crane is equipped with the function of automatically identifying obstacles on the operating route [8]. It provides a safety guarantee for fully automatic operation.

4.1.1. Cab protection area

The schematic diagram of the cab protective area is shown in Figure 3. Based on the actual rotation speed of the portal crane, the point cloud data is obtained in the scanning range of the scanner. The amplitude and grab height of the portal crane boom are used as the defined area, and the number of point clouds in the area is counted. The conditions for setting the number of thresholds are as follows:

1) If the number of point clouds is less than the threshold number, it is considered that there are no obstacles in the protected area. The system is operating normally.

2) If the number of point clouds is greater than the threshold number, it is considered that there is an obstacle in the protective area. The command to stop rotation is generated and sent to the PLC, which controls the gantry crane to slow its rotation speed until it stops.

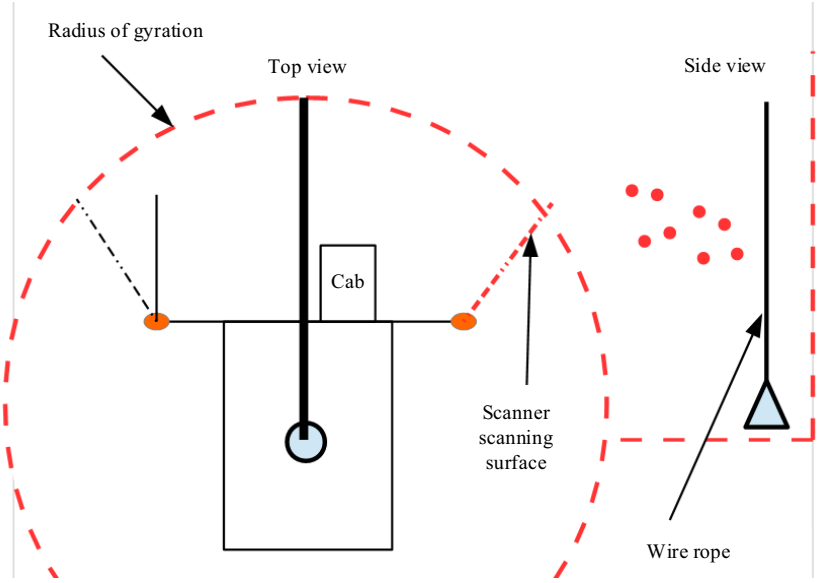


Figure 3. Diagram of the cab protection area.

4.1.2. Protective area at the elephant trunk beam

A schematic diagram of the protective area at the elephant trunk beam is shown in Figure 4. The 3D laser scanner is installed at the front of the elephant trunk beam. The scanner can scan in all directions horizontally. The vertical scanning angle is 30 degrees. During the fully automatic operation of the portal crane, the number of point clouds in the protective area can be counted. The obstacles in the protective area can be determined. The corresponding treatment measures can be taken. The working principle is the same as that of the protective area in the cab.

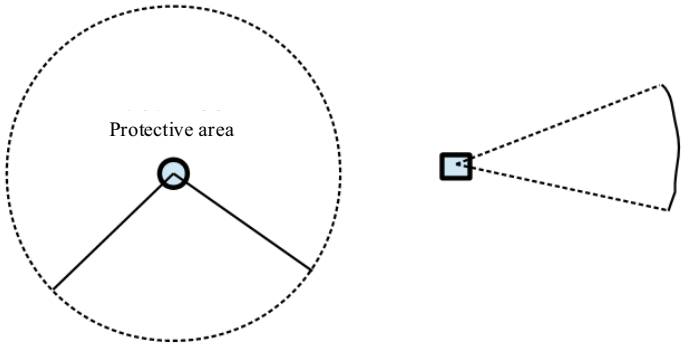
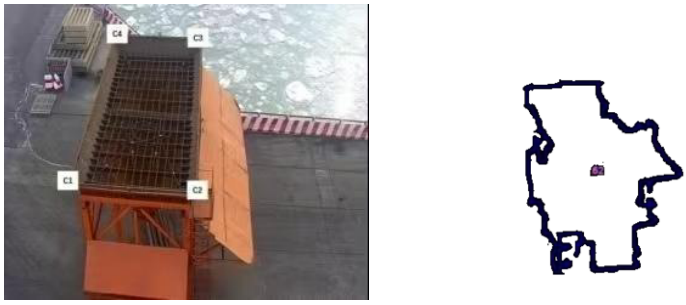


Figure 4. Diagram of the protective area at the elephant trunk beam.

4.2. Safety early warning technology

4.2.1. Internal parameter calibration and pixel coordinate acquisition

The calibration board and the open-source computer vision library (Open CV) are used to calibrate the internal parameters of the camera. The hopper image captured by the camera is converted from the RGB color space to the HSV space. The binary image is generated using image segmentation, morphological expansion, and corrosion. Based on deep learning, the image edge and contour extraction method is used to obtain the overall contour map [9]. Finally, the pixel coordinate values of the four corners are obtained through the linear transformation detection of vision. The schematic diagram of the corner points of the hopper is shown in Figure 5.



a) Three primary color space maps of hopper. b) Hopper outline diagram.

Figure 5. Diagram of the corner points of the hopper.

4.2.2. Calibration of external camera parameters

It is assumed that a certain edge of the hopper is parallel to the direction of travel of the portal crane. The target coordinate system is defined under this assumption. The direction of travel of the portal crane is defined as the X-axis. The Y-axis is perpendicular to the X-axis and parallel to the ground. The Z-axis is perpendicular to the ground. The origin is the ground projection of the hopper lower left corner.

It is assumed that the hopper is a square with a side length *W* and a height *H*. The coordinates of the four corners of the hopper in the world coordinate system can be defined as: (0, 0, *H*), (*W*, 0, *H*), (*W*, *W*, *H*), and (0, *W*, *H*). According to the coordinates of the four corners in the global coordinate system and the pixel coordinates in the image coordinate system, the external parameter matrix from the global coordinate system to the pixel coordinate system can be obtained.

4.2.3. Definition of warning areas

The warning area can be defined in the following two steps. The first step is to project the four corner points onto the ground, mark their coordinates as (0, 0), (*W*, *0*), (*W*, *W*), and (0, *W*), and extend these four projection points outward by *Ext* meter to obtain the coordinate values of the alert area in the global coordinate system; the second step is to determine the coordinate values of the alert area in the pixel coordinate system through the external parameter matrix obtained in Chapter 3.2.2. The schematic diagram of the hopper expansion area is shown in Figure 6.



Figure 6. Hopper expansion area Diagram.

4.2.4. Target detection

The field of view of people and cars can be determined using the image edge and contour extraction method. Safety accidents can be avoided. In practice, the target detection method based on background difference is prone to false alarms. The reason is that the harsh operating environment easily causes cloud shadows and dust. The safety warning system is extremely prone to false alarms. Therefore, a feature detection method is used to reduce the probability of false alarms.

4.2.5. Regional intrusion alarm

If an intrusion target appears in the area near the hopper, the safety warning system will be triggered. The location, size, and category of the intrusion target will be identified on the camera screen. According to the current operating actions of the portal crane, two safe disposal actions are designed: the first case is that when the grab is above the hopper and ready to open the hopper for unloading, if there is an invasion target in the area near the hopper, then stop opening the hopper operation; the second case is that

the portal crane is in the process of opening the hopper, if there is an invasion target in the area near the hopper, then urgently act of closing the hopper.

5. Fully Automatic Control Technology.

According to the control requirements, the system supports four control modes: unloading from the cabin to a fixed location, unloading from the cabin to the piece area, loading at a fixed point, and loading at a piece area. The operator manually completes one working cycle. The system automatically completes recording the coordinates and scanning the job points. A task schedule is created. Then start the operation command, and the system will automatically start the operation according to the above strategy. When the anti-collision system alarms, the operation is suspended immediately. After the alarm is eliminated, the operation can continue until the operation is stopped after the task of the operation planning table is completed. The automatic full-process operation flow is shown in Figure 7.

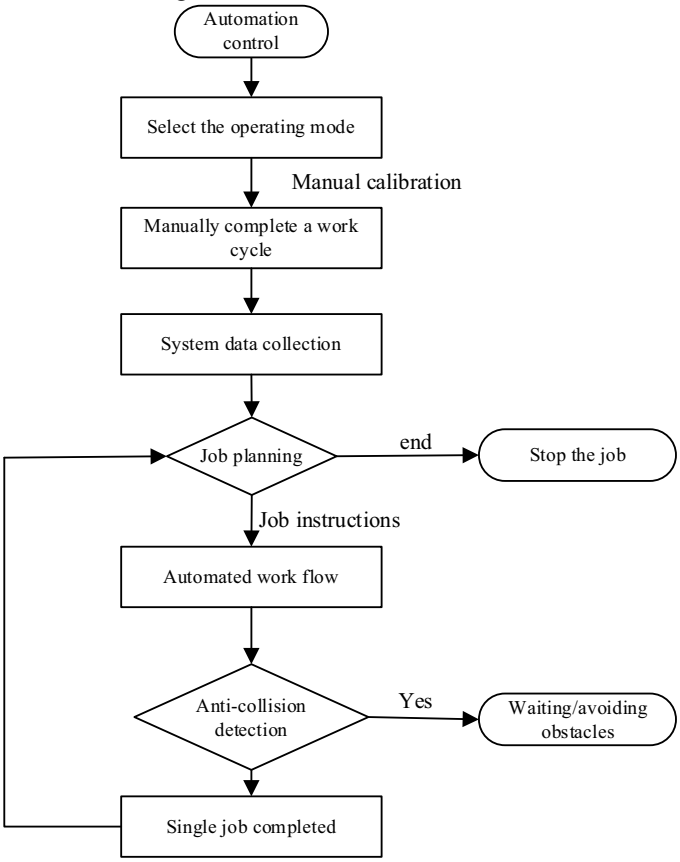


Figure 7. Automatic full-process operation flow.

6. Application of Portal Crane Intelligent Control System Technology.

The intelligent control system for portal cranes includes the grab anti-shake positioning system, the 3D laser scanning modeling system, the space anti-collision system, and the portal crane condition monitoring and management system. It has been successfully applied to the No. 6 portal crane of Huanghua Port Cargo Terminal.

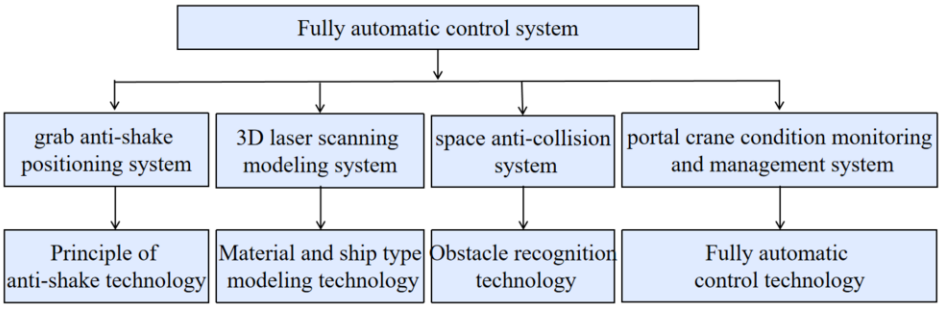


Figure 8. System composition and technical methods.

6.1. Grab the anti-shake positioning system

According to the operating characteristics of the No. 6 portal crane of the cargo terminal, the shaking proof positioning board and shaking proof positioning software are independently designed and developed. The data is collected in real time by the incremental encoders of each mechanism. It can realize the automatic shaking proof and positioning functions of the various mechanisms.

6.2. 3D laser scanning modeling system

Laser scanning equipment with a gimbal on the platform is installed outside the electrical room. The gimbal can dynamically control the laser to scan full coverage of the hatch and the operating location of the pitch angle range. The integrity of data collection for the identified target is guaranteed. Laser scanning equipment is used to identify the position of the hatch and the height of the ship's side. A 3D laser scanning modeling system for point cloud data processing is independently developed. The 3D laser scanning modeling system can process point cloud data and obtain information such as hatch positions and freeboard height of the ship.

6.3. Space anti-collision system

The multi-line laser scanner is installed on the bridge of the trunk. The laser scanner equipped with a servo gimbal is installed on both sides of the electrical room. By using the obstacle recognition module in the space anti-collision system, the dynamic protection of the portal crane during automatic operation can be realized. An alert camera is installed on the rotary platform, and the safety early warning module in the

space anti-collision system is used to realize the early warning of the safety area and ensure the automatic and safe operation of the portal crane.

6.4. Condition monitoring and management system

The condition monitoring and management system for the portal crane is installed in the automation control cabinet. The system provides real-time condition monitoring, fault collection, diagnosis and analysis, fault tracking, and maintenance. The system can record and save all monitoring values, and managers can check the current or historical working status of the portal crane at any time.

7. Conclusion.

This paper focuses on grab shaking proof positioning technology, 3D laser scanning modeling technology, space anti-collision technology, visual recognition technology, and fully automatic operation strategy technology. The intelligent control system has been installed on the No. 6 portal crane at Huanghua Port Cargo Terminal. The labor cost has been reduced by 20%. The safety level of portal crane operations has been fundamentally improved. The intelligent control system solves the problem of portal crane operation automation and marks a new stage in the development of the portal crane.

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Research on Building Material Screening Method Based on Deep Learning

Chuanjun Wang[a] and Mochao Zhou[a,1]
[a]*Nantong Institute of Technology, Nantong, China*
ORCiD ID: Mochao Zhou https://orcid.org/0009-0001-1482-5965

Abstract. To enhance the accuracy of building material sorting, a method based on deep learning is proposed. In this approach, building material images are used as inputs and undergo deep learning processing through two separate branch networks. One branch employs average pooling, while the other utilizes max pooling. During the convolution process, both 2D convolution and dilated convolution are utilized, and the SoftMax function is employed as the activation function. In the experimental process, the CNN method was selected as the reference approach for screening images of seven types of building materials. The experimental results demonstrate that our method significantly outperforms the CNN method in terms of both classification accuracy and convergence efficiency.

Keywords. Building materials, screening, deep learning, activation function

1. Introduction

Building material screening is a core aspect of the construction industry. It controls material quality from the source, ensures the safety and durability of building structures, and prevents safety accidents caused by material defects [1]. Intelligent screening breaks through the efficiency bottleneck and error limitations of manual sorting, achieves precise evaluation and classification of material properties, and can optimize material selection schemes through data analysis, helping the construction industry upgrade towards intelligence, efficiency, and sustainability [2-3]. Currently, the integrated development of image retrieval and deep learning is entering a stage of deep innovation. The iteration of deep learning technology has brought comprehensive changes to image retrieval, from feature extraction to semantic understanding [4-5]. At the level of feature extraction, Convolutional Neural Networks (CNNs) have become the core support of image retrieval due to their powerful ability to capture local features. Through multiple layers of convolution and pooling operations, CNNs can accurately extract low-level features such as texture and shape from images [6-7]. Vision Transformers (ViTs), with their global attention mechanisms, break the local vision limitations of CNNs, enabling efficient extraction of global semantic information from images and further improving retrieval accuracy [8-9]. In the dimension of semantic understanding, multimodal deep learning models have become a research hotspot. They can perform associative learning between images and multimodal information such as

[1] Corresponding Author: Mochao Zhou, Nantong Institute of Technology, Nantong, China; Email: zhoumochao2026@163.com.

text and audio, allowing image retrieval to break through pure visual matching and achieve accurate retrieval based on semantic content. In addition, the application of Generative Adversarial Networks (GANs) in image retrieval is gradually deepening. By generating diverse image samples, GANs enrich the data sources for retrieval and also provide possibilities for stylized image retrieval [10]. In this paper, a dual-branch deep learning network will be constructed to achieve image retrieval of building materials, thereby achieving the goal of intelligent screening of building materials.

2. The Proposed Method

2.1. Method Framework

To enhance the accuracy of building material screening, we employ a deep learning algorithm framework. Once the images of building materials are input into the deep learning network, they are processed through two separate branches for learning, and then merged to generate the screening results. The overall framework of this method is illustrated in Figure 1.

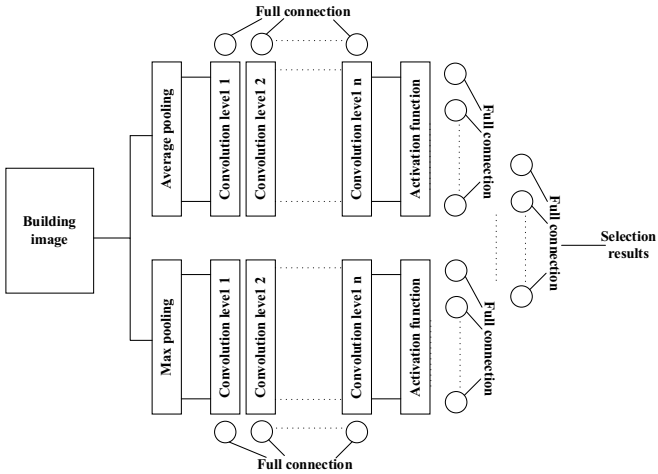


Figure 1. Deep learning framework for image filtering of building materials

As can be seen from Figure 1, after the architectural image is fed into the deep learning network, it undergoes processing through average pooling in the upper branch and maximum pooling in the lower branch. Subsequently, it goes through convolution, activation, and other treatments before being fused to generate the screening results. The merging of two different methods at two branches can increase the accuracy and reliability of building material screening.

2.2. 2D convolution and dilated convolution

There are many types of convolutional forms that can be adopted in the deep learning process, and 2D convolution is chosen in this paper. The mathematical operation performed by 2D convolution is shown in formula (1):

$$y^l(u,v) = \sum_{c=1}^{C}\sum_{i=1}^{I}\sum_{j=1}^{J} x^l(u-i, v-j)k^l(i,j) \tag{1}$$

Here, (x, y) is the pixel position, (u, v) is the convolution position, $k(i, j)$ is the kernel function, l is the number of layers, and C is the number of channels.

If the target area of building materials in the image is large enough, it is necessary to broaden the field of view to achieve more accurate observation and judgment. To expand the field of view in deep learning, dilated convolution can be further employed. So, the use of dilated convolution is equivalent to further supplementing and improving 2D convolution.

Compared to conventional convolution, the core advantage of dilated convolution lies in its ability to significantly expand the receptive field with the same number of parameters, without requiring additional parameters. At the same time, it can acquire global information without reducing the resolution of the feature map, avoiding the information loss problem that occurs when conventional convolution expands the receptive field through downsampling. Furthermore, it can flexibly capture multi-scale features by adjusting the dilation rate, performing better in tasks that require both details and global information, such as semantic segmentation and object detection.

The mathematical operation performed by dilated convolution is shown in formula (2):

$$y(p) = \sum_{i=1}^{I} x(p + r \cdot i)k(i) \tag{2}$$

Here, p is the current point, x is the input, y is the convolution result, $k(i)$ is the kernel function, and r is the number of holes.

2.3. Activation processing

After 2D convolution and dilated convolution, an activation function is further applied to enhance the nonlinear expression capability of the deep learning process. The ReLU activation function has become a common choice in the field of deep learning due to its multiple advantages. Its calculation logic is simple, requiring only the determination of the sign of the input and the selection of the maximum value, without complex exponential operations, which significantly improves the computational efficiency of the model.

The mathematical operation performed by the ReLU activation function is shown in formula (3):

$$\mathrm{Re}\,Lu(x) = \begin{cases} x & x > 0 \\ 0 & x \le 0 \end{cases} \tag{3}$$

As an improved version of ReLU, LReLU's core advantage lies in addressing the "neuron death" issue of ReLU. ReLU maps negative inputs directly to 0. If neurons receive negative inputs for a long time, the gradient will remain constant at 0, preventing weight updates and causing permanent deactivation. However, LReLU introduces a minimal slope (typically 0.01) in the negative range, allowing negative inputs to output small non-zero values. During backpropagation, the gradient is no longer 0, ensuring continuous neuron updates. At the same time, it retains the advantages of ReLU, such as efficient computation and stable gradients in the positive

range. In scenarios such as deep networks and data distribution shifts, LReLU offers superior model robustness and training stability.

The mathematical operation performed by the LReLU activation function is shown in formula (4):

$$L\,\mathrm{Re}\,Lu(x)=\begin{cases}x & x>0\\ ax & x\le 0\end{cases} \tag{4}$$

Here, x is the input, and a is the activation coefficient.

The SoftMax activation function differs from the LReLU activation function in its positioning, with its advantages primarily lying in its adaptability to multi-classification tasks. It can transform the model output into a probability distribution with a sum of 1, intuitively reflecting the confidence of samples belonging to various categories, which aligns with the probabilistic interpretation requirements of classification tasks. The mathematical operation performed by the SoftMax activation function is shown in formula (5):

$$SoftMax(a_i)=\frac{e^{a_i}}{\sum_j e^{a_j}} \tag{5}$$

Here, e is the deviation, a_i and a_j is the coefficient.

3. Experimental results and analysis

In previous research work, a method based on deep learning networks was proposed for the screening of building materials. To verify the effectiveness of this method, experimental research was conducted. During the experiment, a dataset of building material images was first constructed, with a total of 12,000 images selected. Some sample images are shown in Figure 2.



Figure 2. Sample images of building materials

As can be seen from Figure 2, the constructed image dataset includes images of various types of building materials, such as board materials, reinforcement materials, cage materials, sand and stone materials, and so on.

Next, we first verify the accuracy of the proposed deep learning method for image screening of building materials. Here, the CNN method is selected as the reference method. Both methods are applied to the classification screening of a self-built dataset, where the seven types of building materials are: 1-board materials, 2-reinforcement materials, 3-cage materials, 4-sand and stone materials, 5-powder materials, 6-block materials, and 7-pipe materials. The comparison of the accuracy of the two methods in classification screening is shown in Figure 3.

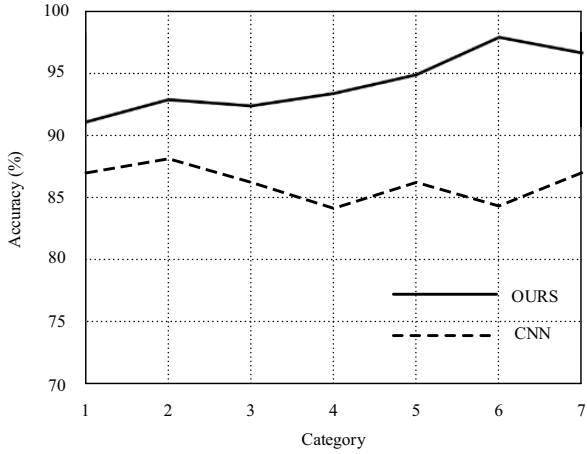


Figure 3. Comparison of accuracy rates for classification and screening using two methods

As can be seen from Figure 3, our proposed deep learning method achieved higher classification and screening accuracy for all seven different types of building materials. A comparison between the two sets of curves reveals that the CNN method generally achieves a screening accuracy of 85-90% for images of these seven types of building materials, whereas our method achieves a screening accuracy of over 90% for all types of building material images.

Further comparison of the convergence speed and iteration accuracy of the two methods is shown in Figure 4.

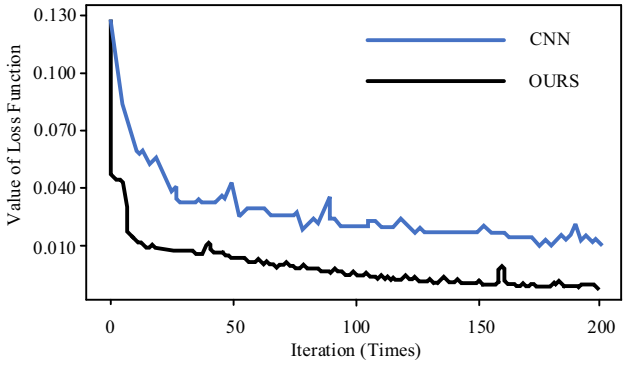


Figure 4. Comparison of iteration effects between two methods

As can be seen from Figure 4, our method exhibits a faster convergence speed and higher convergence accuracy in the process of filtering building material images. After 40 iterations, the value of our method's loss function has already dropped below 0.01 and continues to decrease. In contrast, the value of the loss function for the CNN method remains above 0.01 even after 200 iterations.

4. Conclusions

To effectively enhance the accuracy of building material sorting, this paper proposes an innovative deep learning scheme. This scheme utilizes building material images as the input carrier and constructs dual-branch parallel deep learning architecture. One branch introduces average pooling operations, focusing on extracting global feature information from the images; the other branch adopts max pooling strategies, concentrating on capturing local key features of the images. During the convolution operation stage, the scheme innovatively integrates 2D convolution and dilated convolution techniques. The former ensures the precise extraction of basic features, while the latter explores richer deep features by expanding the receptive field. Finally, the SoftMax activation function is utilized to complete classification mapping. In the experimental phase, traditional CNN methods are selected as the control group, and classification tests are conducted on seven different types of building material images. The results show that compared to traditional CNN methods, this approach achieves significant improvement in classification accuracy metrics, all reaching over 90%. At the same time, the convergence speed and stability of the model also demonstrate significant advantages, providing an efficient and feasible technical path for intelligent sorting of building materials.

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Improved Particle Swarm Optimization for Transient Electromagnetic Inversion

Zhao Le, Haitao Yan[1], Kaifeng Wu, Yonglong Yang, Hui Ye, Wentao Zhang and Shaobiao Liang

CCCC Second Highway Consultants Co., Ltd., Wuhan, Hubei, China

Abstract. Transient electromagnetic (TEM) method is a geophysical exploration technique characterized by high detection accuracy, significant depth penetration, and a wide range of applications, making it extensively utilized in engineering surveys. Current TEM inversion primarily relies on gradient-based linear inversion algorithms, which offer high inversion efficiency but are highly dependent on the initial model, prone to local optima, and the accuracy of the inversion results is heavily influenced by prior geological information. In contrast, stochastic evolution-based nonlinear inversion algorithms exhibit low dependence on the initial model and high inversion accuracy, but they are computationally intensive and suffer from low convergence efficiency, limiting their applicability in real-field data. This study presents an improved particle swarm optimization (IPSO) algorithm, building upon the conventional PSO framework. The improvement is achieved through two key modifications: dynamically reducing the swarm size during later iterations to enhance inversion efficiency, and substituting invalid particles with valid ones to improve the global search capability. In comparison with the standard PSO, the IPSO algorithm demonstrates less computation, higher convergence efficiency, and higher inversion accuracy. The effectiveness of the proposed algorithm, validated by both synthetic and field data examples, is expected to promote the broader application of nonlinear inversion methods in TEM inversion.

Keywords. Transient electromagnetic, Improved particle swarm optimization, Efficient nonlinear inversion, Independent of the initial model.

1. Introduction

The transient electromagnetic (TEM) method is based on the conductivity differences of underground media. The method involves transmitting a primary pulsed magnetic field into the ground and then analyzing and inferring the subsurface geoelectric structure by observing and recording the decay pattern of the induced secondary field. This method is widely used in geological surveys and engineering investigations due to its strong applicability, high efficiency, and high vertical resolution [1-3].

Efficiency, accuracy, and reduced dependence on prior information are key to the development of TEM inversion [4-5]. Currently, gradient-based local linear inversion methods generally have high inversion efficiency, but the accuracy of the inversion

[1] Corresponding author: Haitao Yan, E-mail: yanhaitao@msn.com

results heavily relies on prior geological information. When the initial model is inaccurately set, the inversion process is prone to falling into local extrema, and leading to inversion failure [6-8]. In contrast, global optimization algorithms based on random evolution typically have low dependence on initial models, are less likely to fall into local extrema, and offer higher inversion accuracy. However, they generally have large computation and low convergence efficiency, making them less applicable in field measurement data inversion [9-12].

Particle swarm optimization (PSO) is a typical swarm intelligence random evolution algorithm with widespread and mature applications in various fields [13-15]. It does not require setting an initial model, only needs to define a broad model search range, and has low dependence on prior geological information. It has a large swarm size, which makes it having a strong global optimal solution search capability and high convergence efficiency [16-18]. However, further improvements are still needed to enhance its inversion efficiency and broaden application.

This study proposes an improved particle swarm optimization (IPSO) algorithm basing on the traditional PSO algorithm. The population size in the middle and later stages is reduced to decrease the computation and improve inversion efficiency. The particle diversity is continuously maintained by substituting invalid particles with valid ones to enhance the global search capability [19-20]. This research conducted comparative studies of PSO and IPSO algorithms in theoretical examples, verifying the superiority of the algorithm. In real measurement data inversion, the inversion results showed high consistency with borehole data, validating the algorithm's applicability in field data.

2. Methodologies

Since the IPSO strategy has been described in detail by Yan (2024) [20], this paper briefly introduces its main steps as follows:

(1) Randomly generate M_1 initial particle positions (p).

Each particle corresponds to a model for TEM inversion, and the initial model generation rules are shown in Eqs. (1) and (2).

$$\rho_i = \rho_{\min} + r(\rho_{\max} - \rho_{\min}), \tag{1}$$

$$Thk_i = Thk_{\min} + r(Thk_{\max} - Thk_{\min}), \tag{2}$$

where ρ_i and Thk_i are resistivity and layer thickness of the i^{th} layer, respectively; $\rho_{\min}$ and $\rho_{\max}$ are the minimum and maximum resistivity values, set to 50 and 800 (Ω•m) in this paper, respectively; $Thk_{\min}$ and $Thk_{\max}$ are the minimum and maximum layer thickness, set to 10 and 100 (m) in this paper, respectively; r is a random number distributed uniformly in (0, 1).

(2) Calculate the particle parameters.

Calculate the particle objective function (Φ) based on the layer model corresponding to the particle, conduct TEM forward modeling to obtain theoretical induced voltage and

apparent resistivity, and the objective function is the root mean square error (RMSE) between measured values and theoretical values, as shown in Eq. (3).

$$\Phi = \sum \left\| \rho_{pre} - \rho_{obs} \right\|_2^2, \tag{3}$$

where Φ denotes the objective function; ρ_{pre} and ρ_{obs} are the predicted and observed apparent resistivity, respectively; the symbols $\| \ \|_2$ denotes the l_2-norm of a matrix.

Calculate the individual optimal position (*pbest*), swarm optimal position (*gbest*) position-increment (v), and update the particle position by Eqs. (4) and (5).

$$p_i^{k+1} = p_i^k + v_i^{k+1}, \tag{4}$$

$$v_i^{k+1} = \omega v_i^k + a_1 r_1 (pbest_i^k - p_i^k) + a_2 r_2 (gbest^k - p_i^k), \tag{5}$$

where i and k denote the particle serial number and the iteration number, respectively; p_i^k and v_i^k are the position and position-increment of the i^{th} particle at the k^{th} iteration, respectively; $pbest_i^k$ is the previous best position of the i^{th} particle at the k^{th} iteration; $gbest^k$ is the previous best position of the entire swarm at the k^{th} iteration; r_1 and r_2 represent the random numbers uniformly distributed in (0, 1); ω is the inertia weight, which is set to 0.729; a_1 and a_2 denote the local and global factors, respectively, which are set to 1.494 in this paper according to Clerc (2002) [21].

(3) Reduce population size.

Setting the population size as M_1 to iterate K_1 times, then changing the population size as M_2 to iterate K_2 times, and M_2 is less than M_1. This ensures that IPSO maintains a larger population in early iterations to enhance global search capability, while employing a smaller population in later iterations to improve inversion efficiency.

(4) Perform particle diversity maintenance.

Every N iterations, perform particle diversity maintenance by removing invalid particles and randomly adding new particles.

(5) Iteration termination.

The iteration terminates when the objective function is less than the preset value (Φ^T) or the number of iterations reaches the upper limit.

The parameters of IPSO algorithm used in this paper are listed in Table 1, and the flowchart of IPSO is shown in Figure 1.

Table 1. Parameters used in the IPSO inversion.

M_1	K_1	M_2	K_2	N	ω	a_1	a_2
128	20	64	80	20	0.729	1.494	1.494

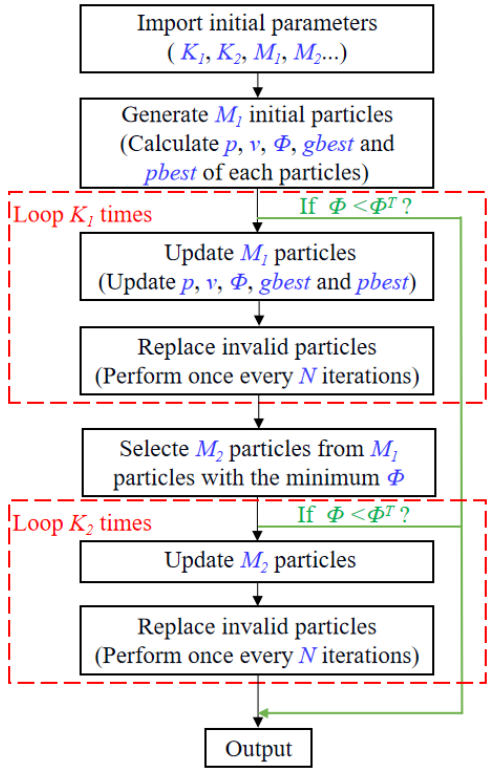


Figure 1. Flowchart of the IPSO inversion.

3. Synthetic examples

This paper sets up two layered geological models with alternating high and low resistivity, denoted as HKH and KHK, with their resistivity and thickness listed in Table 2. This study uses the forward-modeled apparent resistivity of HKH and KHK models as the measured data in synthetic examples.

This study conducts inversions using both PSO and IPSO, and their results are summarized as follows: the inverted model parameters are provided in Table 2; the comparisons of induced voltage, apparent resistivity, and the layered model are shown in Figures 2, 3, and 4, respectively; and the RMSE reduction curves are compared in Figure 5.

In previous studies, both induced voltage and apparent resistivity could be used as target parameters for TEM inversion. However, as can be seen from the comparison of Figures 2 and 3, the apparent resistivity exhibits greater differences than the induced voltage. This implies that performing apparent resistivity inversion offers higher sensitivity than induced voltage inversion. Therefore, this paper recommends adopting apparent resistivity inversion.

As shown in Figure 4, both PSO and IPSO inversion results are close to the true model, but the inversion results of IPSO are superior to those of PSO. As shown in Figure 5(a), the IPSO inversion converges within 38 generations, achieving a final RMSE of 0.0468; the PSO inversion converges after 60 iterations and yields a final RMSE of 0.0635. The

PSO inversion uses 128 particles (M) per generation, and converges at the 60th generation, which implies a total of 7,808 forward modeling operations (= 128 + 128 * 60). In contrast, the IPSO algorithm uses 128 particles (M_1 = 128) in the first 20 generations (K_1 = 20) and reduces to 64 particles (M_2 = 64) thereafter, resulting in a total of 3,840 forward modeling calculations (= 128 + 128 * 20 + 64 * (38 - 20)). In other words, the computational cost of IPSO at convergence (3,840) is only 49.2% of that for PSO (7,808), while the RMSE of IPSO (0.0468) is only 73.7% of that of PSO (0.0635).

The same trend is observed in Figure 5(b): the IPSO inversion converges within 42 generations, achieving a final RMSE of 0.0458; the PSO inversion converges after 66 generations, achieving a final RMSE of 0.0662. The computational cost of IPSO at convergence (128 + 128 * 20 + 64 *(42 - 20) = 4,096) is only 47.8% of that for PSO (128 + 128 * 66 = 8,576), while the RMSE of IPSO (0.0458) is only 69.2% of that for PSO (0.0662). Compared to the PSO algorithm, IPSO shows a substantial reduction in both computational cost and RMSE, demonstrating its superior convergence efficiency and inversion accuracy.

Table 2. Parameters of the geoelectric models in synthetic examples.

Layer No.	Model	Resistivity (Ω·m)	Thickness (m)	Model	Resistivity (Ω·m)	Thickness (m)
1		300	50		50	50
2		100	50		200	50
3	**HKH**	200	100	**KHK**	100	100
4		50	100		350	100
5		250	∞		250	∞
1		281	46		58	46
2	**HKH-PSO**	130	54	**KHK-PSO**	192	52
3		214	97		116	110
4		68	106		341	90
5		246	∞		245	∞
1		292	55		53	45
2	**HKH-IPSO**	106	59	**KHK-IPSO**	207	58
3		206	99		110	101
4		62	106		335	91
5		247	∞		252	∞

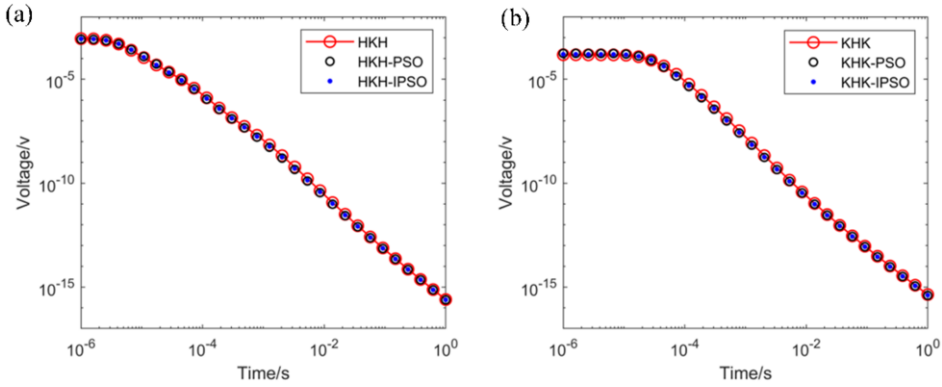


Figure 2. The induced voltage comparisons of the HKH and KHK model inversions. (a) is the induced voltage inverted by HKH model, and (b) is the induced voltage inverted by KHK model. The x-axis represents logarithmic time, the y-axis represents logarithmic induced voltage, the red lines and circles represent the true model, the black circles represent the model inverted by PSO algorithm, and the blue points represent the model inverted by IPSO algorithm.

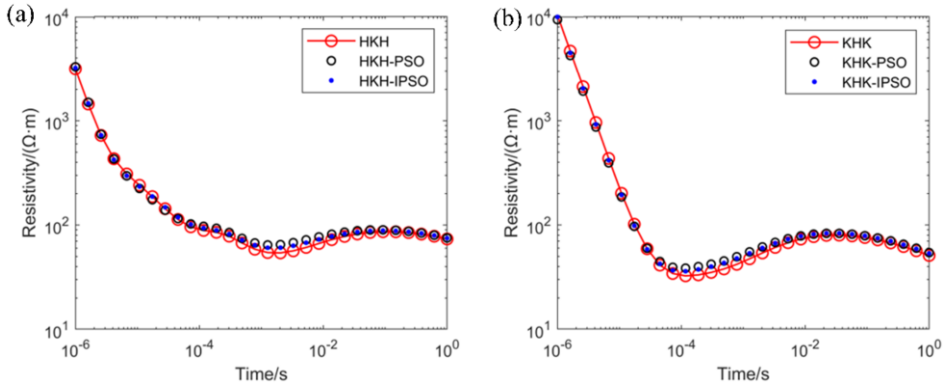


Figure 3. The resistivity comparisons of the HKH and KHK model inversions. (a) is the resistivity inverted by HKH model, and (b) is the resistivity inverted by KHK model. The x-axis represents logarithmic time, the y-axis represents logarithmic resistivity, the red lines and circles represent the true model, the black circles represent the model inverted by PSO algorithm, and the blue points represent the model inverted by IPSO algorithm.

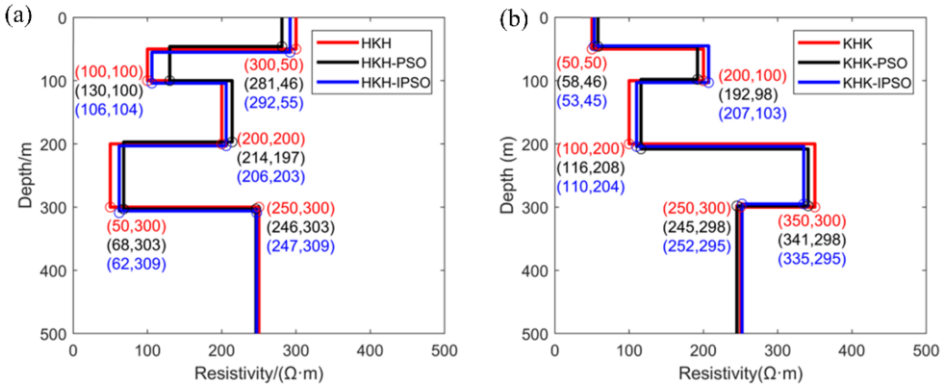


Figure 4. The geoelectric model comparisons of the HKH and KHK model inversions. (a) is the geoelectric model inverted by HKH model, and (b) is the geoelectric model inverted by KHK model. The x-axis represents resistivity, the y-axis represents depth, the red lines represent the true model, the black lines represent the model inverted by PSO algorithm, and the blue lines represent the model inverted by IPSO algorithm.

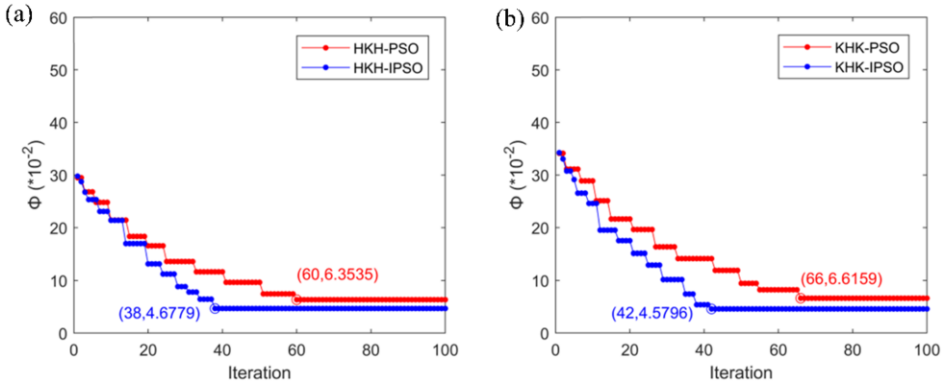


Figure 5. The RMSE comparisons of the HKH and KHK model inversions. (a) is the RMSE inverted by HKH model, and (b) is the RMSE inverted by KHK model. The x-axis represents iteration, the y-axis represents RMSE. The red and blue lines represent the RMSE from the PSO and IPSO inversions, respectively.

To further clarify why the IPSO algorithm achieves higher accuracy and efficiency despite its reduced population size, this paper introduces the concepts of model resistivity difference and calculated resistivity difference. The strata model is discretized at 1-m depth intervals up to 400 m, and the resistivity differences are calculated using Eq. (6). This paper obtains the calculated resistivity through forward modeling, and the calculated resistivity difference is derived using Eq. (7). If both the model resistivity difference and the calculated resistivity difference between two particles are low (<0.05), the particles are identified as similar particles. Such particles contribute similarly to the model update during iterations, and their presence significantly increases computational cost without correspondingly enhancing the ability to search for the optimal solution. Among similar particles, the one with a larger RMSE is referred to as an invalid particle and will be eliminated. During particle diversity maintenance, pairwise similarity evaluation is performed for all particles. After removing all invalid particles, the remaining particles are termed valid particles. If the number of valid particles falls below the predefined population size, new particles are randomly generated to replenish the swarm.

$$D_m = \sum_{i=1}^{H} [2 \frac{\rho_m(i) - \rho'_m(i)}{\rho_m(i) + \rho'_m(i)}]^2 \tag{6}$$

$$D_r = \sum_{j=1}^{T} [2 \frac{\rho_r(j) - \rho'_r(j)}{\rho_r(j) + \rho'_r(j)}]^2 \tag{7}$$

where D_m and D_r are the difference of the model and resistivity, respectively. H and T are the total number of the model depth points and logarithmic time points, respectively. ρ_m is the model resistivity, and ρ_r is the calculated apparent resistivity.

Figure 6 displays the particle distribution during the PSO inversion of the HKH model, where the vertical axis represents the RMSE of the apparent resistivity (Eq. 3), and the horizontal axis denotes the RMSE in resistivity between the trial model and true models (Eq. 8).

$$\Phi^m = (\sum_{i=1}^{H} (\rho_m(i) - \rho_{true}(i))^2 / H)^{1/2} \tag{8}$$

where Φ^m is the RMSE in resistivity between the trial model and true models; $\rho_m(i)$ and $\rho_{true}(i)$ represent the resistivity of the trial and true model at the i^{th} depth point, respectively.

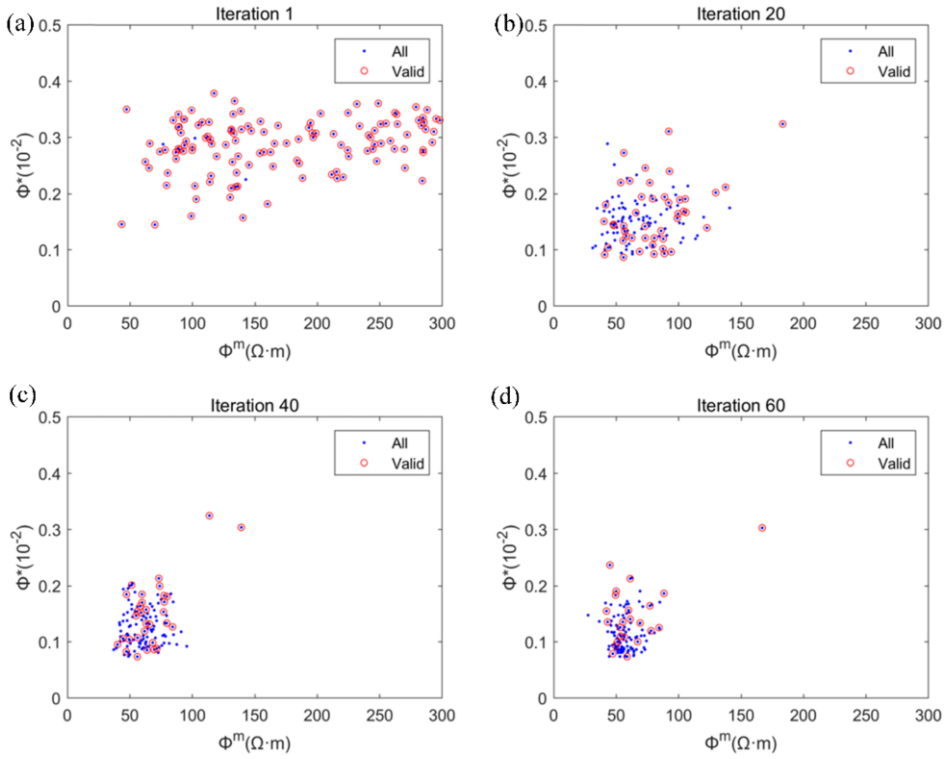


Figure 6. The particles distribution that changes with iteration during the PSO inversion of the HKH model. (a), (b), (c) and (d) denote the particle distributions of the 1st, 20th, 40th and 60th iterations. Blue points represent all 128 particles in the swarm. Red circles denote the valid particles, with counts of 125, 45, 32, and 23 across the respective iterations.

As can be seen from Figure 6, during the PSO inversion process, the number of valid particles gradually decreases as the number of iterations increases, which implies that a significant amount of ineffective computation is performed in the middle to later stages of the inversion. In contrast, the IPSO algorithm incorporates particle diversity maintenance every N iterations, with $N = 20$ in this study. Figure 7 presents a comparison of particle distributions before and after the maintenance. It can be seen that diversity maintenance significantly increases the number of valid particles, which enables the IPSO algorithm to possess a stronger ability to search for optimal solutions. This also results in the IPSO algorithm achieving higher convergence efficiency and more accurate inversion results, despite its lower computational cost.

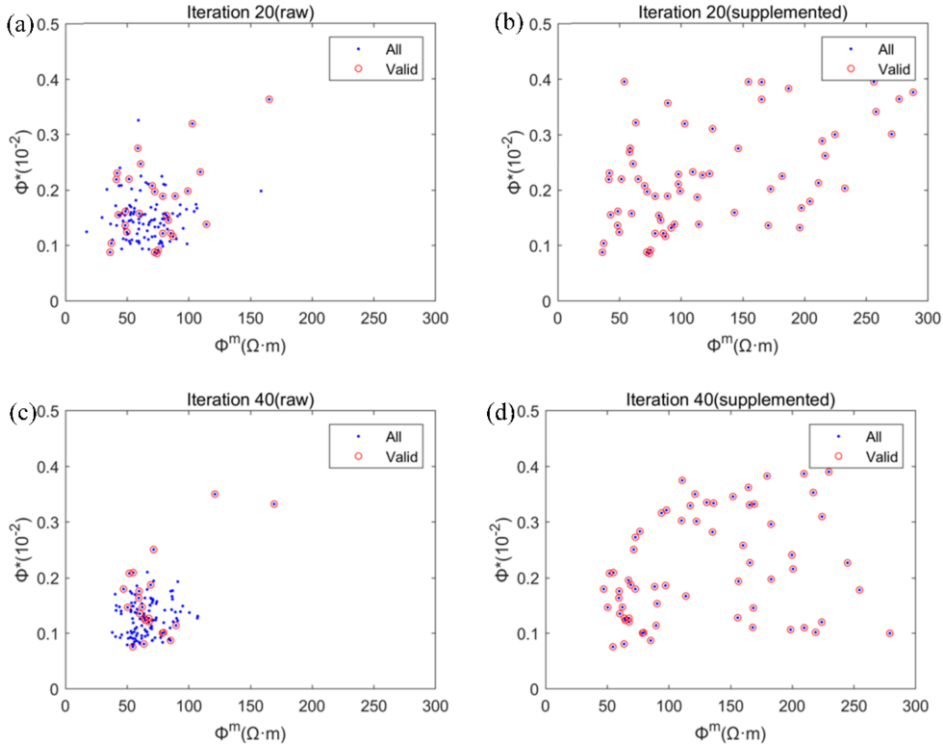


Figure 7. Comparison of particle distributions before and after particles supplementation during IPSO inversion of the HKH model. Subplots (a) and (c) show the distributions at the 20th and 40th iterations before particles supplementation, while (b) and (d) show the corresponding distributions afterward. Blue points represent all particles in the swarm (128 per iteration). Red circles highlight the valid particles, numbering 29, 64, 22, and 64 in (a) to (d), respectively.

4. Field data application

To validate the effectiveness and engineering applicability of the proposed method, we apply it to field-measured data for inversion analysis. The field data is collected in Zhangqiu District, Jinan City, Shandong Province. A 25Hz transmission base frequency is adopted, collecting data at 25 frequency points. A transmission coil of 100×100 m^2 and a reception coil of 10×10 m^2 are used, with a transmission current of 80 A. The obtained field-measured apparent resistivity curve of TEM is shown in Figure 8. In Figure 8(a), the blue points and lines are the field-measured data, this study applied a 3-point moving average filter to the data, resulting in the smoothed curve shown in red of the figure. The high accuracy of the IPSO inversion is demonstrated by the high consistency in apparent resistivity (Figure 8(b)) and its good agreement with borehole data (Figure 9).

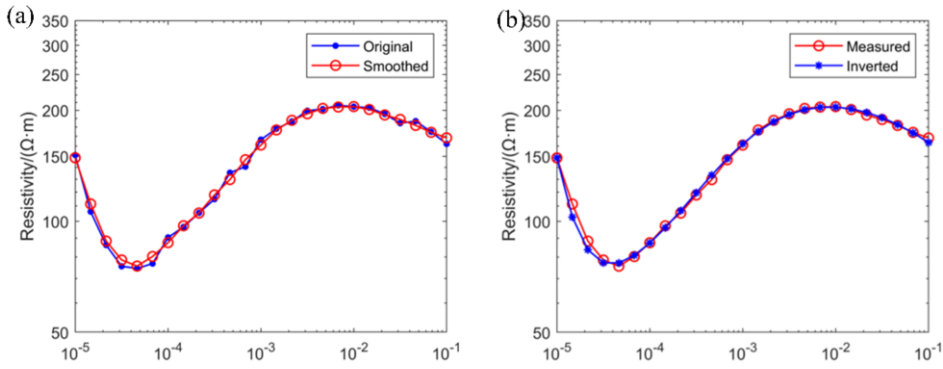


Figure 8. The resistivity comparisons of the field data inversion. (a) shows the comparison between the original and smoothed resistivity, where blue point and line represent the original data, and the red ones represent the smoothed data. (b) shows the comparison between the measured (smoothed data of (a)) and inverted resistivity, where the blue curve and points represent the measured data, and the red curve and points correspond to the inversion results.

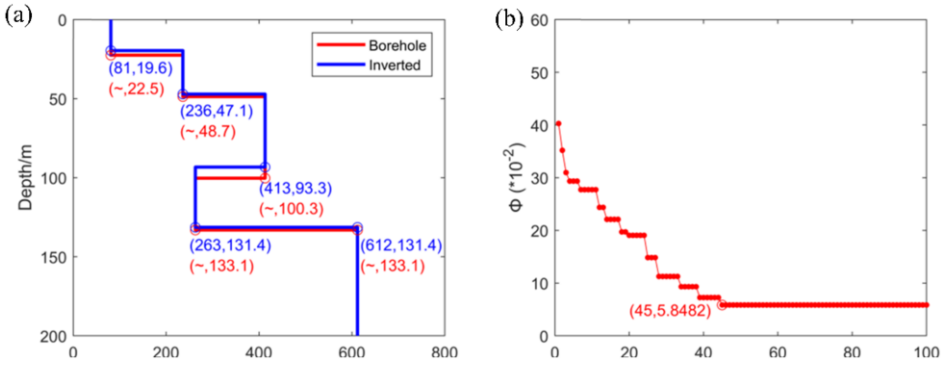


Figure 9. Model comparison and inversion error for the field data. (a) is the comparison between the borehole (red lines) and the inverted model (blue lines). (b) is the RMSE of the IPSO inversion.

5. Conclusions

The IPSO algorithm proposed in this study is well-suited for TEM inversion. Compared to traditional gradient-based local optimization algorithms, IPSO exhibits lower dependence on initial models and higher inversion accuracy. In synthetic examples, the IPSO algorithm demonstrates higher accuracy, stronger convergence, and lower computational cost compared to the PSO algorithm, indicating good application prospects. Subsequently, in field measured data, the IPSO inversion results show high consistency with the borehole, verifying the applicability of the IPSO algorithm in field data application. The IPSO algorithm does not require setting an initial model and has low dependence on prior geological information, resulting in higher inversion efficiency and good application prospects.

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Section 5

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The Impact of Family Care on Meaning in Life Among Middle School Students

Jie Cao[a], Xinyu Zhao[a] and Lanyan Qin[a, 1]
[a] *Faculty of Education and Law, Xiangnan University, China*

Abstract. Lack of meaning in life is a significant risk factor for adolescent mental health, closely associated with psychological distress such as depressive emotions. This study surveyed 1,014 middle school students to explore the relationship between family care and meaning in life. The results indicate that family care significantly and positively predicts meaning in life. Additionally, both family care and meaning in life show notable gender differences, while no significant differences were observed across grades. The findings confirm that family care can enhance adolescents' meaning in life, offering important practical value for preventing psychological distress and fostering the development of an internal meaning system among adolescents.

Keywords. adolescents, meaning in life, family care

1. Introduction

The sense of meaning in life is people's perception of life goal and existence value, which includes two dimensions: pursuing the meaning of life and having the meaning of life, reflecting the extent to which individuals perceive their pursuit of value and purpose, as well as whether they feel their lives are meaningful. [1]. Frankl first put forward the concept of life meaning in psychological research, pointing out that individuals need to establish and pursue their life goals and values through self-awareness, and then translate these aspirations into action [2]. Yu and Deng further proposed that meaning in life arises from the value recognition and self-identity individuals develop while exploring life's purpose [3]. This perception not only motivates individuals to pursue meaning but also enhances their awareness of their own value and life direction.

A lack or absence of meaning in life is often associated with psychological difficulties. In recent years, there has been a high incidence of depression among adolescents. According to the *Report on the Development of National Mental Health in China (2021–2022)*, 14.8% of adolescents were found to be at risk of depression, a rate significantly higher than that of adults (10.6%). The occurrence of depression is directly related to the lack of meaning in life. Lan and Wang found that the stronger one's meaning in life, the lower the level of depression [4]. This protective effect operates through two mechanisms: directly, by providing a sense of purpose and alleviating existential emptiness; and indirectly, by enhancing subjective well-being, which in turn reduces depressive symptoms. This is consistent with the research of Baquero-Tomás et

[1] Corresponding Author: Lanyan Qin, 3158342060@qq.com

al. [5], who surveyed 566 Spanish university students and identified a significant negative correlation between meaning in life and depressive symptoms. In other words, individuals with a stronger sense of life meaning tend to experience less severe depression, whereas those lacking such meaning face a considerably higher risk.

The lack of a sense of meaning in life has become a defining issue of our time, and the psychological distress it engenders extends far beyond depression and other diagnosed mental disorders. Implementing effective measures to enhance meaning in life is therefore essential for promoting the mental health development of adolescents. Based on this, it is an urgent problem for practitioners and academic circles in the fields of mental health, social work, and other youth services to explore a universally feasible intervention path from the perspective of enhancing meaning in life of teenagers. Accordingly, the scientific measurement of meaning in life and the clarification of its influencing factors have become essential prerequisites for effective intervention.

Previous studies have discussed the influencing factors of the sense of meaning in life from many aspects. Chen et al. collected data from 1,043 secondary vocational school students and found that campus exclusion threatens individuals' basic needs, thereby hindering the construction of meaning in life [6]. Yang and Xian reported that mobile phone dependence negatively affects both the seeking and possession dimensions of meaning in life [7]. Li et al. administered a questionnaire to 772 college students and revealed that parenting styles characterized by emotional warmth and understanding significantly promote the development of meaning in life in children. Such parenting conveys care, support, and love through daily interactions, enabling children to adopt a positive and optimistic attitude when facing setbacks, thereby enhancing their perception of meaning in life [8].

Family care reflects the functional operation of family system, which is closely related to individual mental health. According to Smilkstein, family care refers to the degree to which family members collaborate to complete various tasks, thereby strengthening mutual affection and supportive behaviors [9]. An individual's satisfaction with family care can be comprehensively assessed across five dimensions: adaptation, growth, emotional atmosphere, cooperation level and intimacy. Skinner et al. further argue that the fulfillment of basic family functions depends on members' ability to complete a series of tasks, and that by providing support to one another, families are better equipped to cope with crises and emergencies, thereby promoting the development of both the family and its individual members [10]. As an effective index to evaluate family function, family care can reflect individual's subjective satisfaction with their family operation.

Research on family care, both domestically and internationally, has primarily focused on its relationship with individuals' psychological states, social support, social anxiety, and related factors. Tang et al. focused on the elderly group, and analyzed the correlation among their sense of belonging, family care and alexithymia [11]. The results showed that family care could significantly predict alexithymia. Jing et al. paid attention to the current situation of family rearing patterns and family care of juvenile delinquents [12]. The research found that the family function level of juvenile delinquents was significantly lower than that of ordinary adolescent families, with more pronounced impairments across multiple functional dimensions. Moreover, a significant correlation was found between parental rearing styles and family care. The research results of Xia et al. showed that the family function of middle school students is negatively correlated with their social anxiety; that is, the higher the family function, the lower the individual's

social anxiety [13]. Zhang et al. found that better family functioning was linked to stronger feelings of hope in students [14].

Previous studies have shown that family care and sense of meaning in life have a significant relationship. Studies have shown that family intimacy can significantly and positively predict the individual's sense of meaning in life [15]. This is in line with the research of Zhou et al., who stated that good family care helps older adults maintain a positive mental state, enhance their sense of social connection, and improve their overall sense of meaning in life, thereby enabling them to achieve better psychological adaptation and quality of life when facing aging and health challenges [16]. The research by Cheng et al. further confirms that good family care helps higher vocational students to explore the meaning of life more effectively [17]. Therefore, this study will take teenagers as the investigation object, study the mechanism of family care on the sense of meaning of life, further reveal the influencing factors of sense of meaning of life, and provide a basis for improving teenagers' sense of meaning of life.

2. Research design

2.1 Research object

In this study, 27 classes were selected by cluster sampling, and a questionnaire survey was conducted. A total of 1244 questionnaires were collected, and 1014 valid questionnaires were obtained after screening, with an effective recovery rate of 81.5%.

2.2 Research tools

2.2.1 Family Care Index Questionnaire

In this study, a questionnaire compiled by Smilkstein was used, with 5 questions in total [9]. Using a three-level scoring system, the higher the score, the stronger the perceived family care.

2.2.2 Meaning in life scale

In this study, the meaning in life scale developed by Steger et al. was used as the measuring tool [1]. The scale contains 10 measurement items, with a 7-point scoring method. The score of the scale is positively correlated with the level of individual sense of life meaning.

3. Research results

3.1 Demographic information

After checking the missing and abnormal values, 130 data were deleted, and the remaining 1014 data were used for the final data analysis. Descriptive analysis mainly includes gender, grade and one child or more. Table 1 shows the basic information of the respondents. There are 510 men and 504 women in this survey, accounting for 50.3%

and 49.7% respectively. There are 325 students in grade seven, 362 students in grade eight and 327 students in grade nine, accounting for 32.1%, 35.7% and 32.2% respectively. There are 104 only children (10.3%) and 910 non-only children (89.7%).

Table 1 Demographic information

Variables	Items	Frequency	Percentage (%)
Gender	Man	510	50.3
	Woman	504	49.7
Grade	Grade 7	325	32.1
	Grade 8	362	35.7
	Grade 9	327	32.2
One child or more	One child	104	10.3
	More than one child	910	89.7
	Total	1014	100.0

3.2 Descriptive analysis

As can be seen from Table 2, the score of junior high school students' sense of meaning in life (M=4.93) is slightly higher than the theoretical median of 4 points (7 points), indicating that junior high school students' sense of meaning in life is at a medium level as a whole. The average score of family support is 2.07, which is slightly higher than the middle level of the questionnaire score (the questionnaire adopts 3-point scoring method and 2 is the middle score), indicating that the overall family support of junior high school students is at the middle level.

Table 2 Descriptive analysis result

	N	Min	Max	Mean	St. Deviation
MIL	1014	1	7	4.93	1.267
FC	1014	1	3	2.07	.546

Note: MIL: meaning in life, FC: family care

3.3 Analysis of Differences

Independent samples t-test and one-way ANOVA were employed to examine the differences in the sense of meaning in life among junior high school students across gender, only-child status, and grade level. Table 3 indicated that there was a significant difference in the sense of meaning in life between males and females. Males (5.05 ± 1.220) scored significantly higher than females (4.80 ± 1.302), with a statistical difference of $t = 3.258$, $p < .05$. However, no significant differences were observed for the variables of only-child status or grade level. Meanwhile, there was a significant gender difference in family support, with males (2.11 ± 0.554) scoring significantly higher than females (2.03 ± 0.537). The statistical difference was $t = 2.140$, $p < .05$. However, no significant difference in family care was found between only children and non-only children ($t = 1.238$, $p > .05$). Table 4 indicated no significant difference in family care across different grade levels ($p > .05$).

Table 3 Independent t-test results

Variables	Items	Mean	St. Deviation	Levene's Test for Equality of Variances		t-test for Equality of Means		
				F	Sig.	t	df	Sig. (two-tail)
MIL	Man	5.05	1.220	1.886	0.170	3.258	1012	0.001
	Woman	4.80	1.302					
	One child	5.04	1.207	0.641	0.424	0.990	1012	0.323
	More than one child	4.91	1.274					
FC	Man	2.11	0.554	1.613	0.204	2.140	1012	0.033
	Woman	2.03	0.537					
	One child	2.13	0.560	0.439	0.508	1.238	1012	0.216
	More than one child	2.06	0.545					

Note: MIL: meaning in life, FC: family care

Table 4 ANOVA

		Sum of squares	df	Mean square	F	Sig.
MIL	Between Groups	2.722	2	1.361	0.848	0.429
	Within Groups	1623.501	1011	1.606		
	Total	1626.223	1013			
FC	Between Groups	0.301	2	0.150	0.503	0.605
	Within Groups	302.232	1011	0.299		
	Total	302.533	1013			

Note: MIL: meaning in life, FC: family care

3.4 Correlation Analysis

This study employed Pearson correlation analysis to examine the strength and direction of the relationships between variables. As shown in Table 5, family care was significantly positively correlated with the sense of meaning in life ($r = .336$, $p < .01$).

Table 5 Correlation analysis result

	MIL	FC
MIL	1	.336**
FC	.336**	1

Note: MIL: meaning in life, FC: family care

3.5 Hypothesis Testing

As shown in Table 6, family care had a significantly positive effect on the sense of meaning in life ($\beta = 0.743$, $t = 5.245$, $p < 0.001$), supporting the proposed hypothesis.

Table 6 Hypothesis test result

	Beta	St.Deviation	T value	Sig.
FC	0.743	0.142	5.245	<.001

Dependent variable: MIL

4. Discussion

This study explores the influence of family care on the sense of meaning in life among junior high school students. It enriches research on the factors affecting the sense of meaning in life and offers policy recommendations for students, parents, schools, and relevant policymakers to promote the enhancement of students' sense of meaning in life.

The results indicate a significant gender difference in meaning in life, which is consistent with the findings of Li and Ye [18,19]. The higher meaning in life observed among male students may be related to differences in psychological traits between genders. For example, females tend to be more emotionally sensitive and susceptible to mood influences, while males are generally more outgoing and bolder, potentially making it easier for them to derive meaning from external experiences[20–22]. Additionally, this study found that male students reported significantly higher levels of family care than female students, aligning with S. Zhang but contrasting with Zhong [23,24]. The discrepancy in results may stem from the fact that females, being more attentive to details, are more likely to perceive subtle parental attitudes within the family. From a social gender perspective, males tend to adopt more external coping strategies and pay less attention to details, leading to differences in their perception of family care.

This study reveals that family care has a significantly positive impact on meaning in life, suggesting that higher levels of family care are associated with a stronger meaning in life among students. This finding aligns with Cheng [17]. Accordingly, positive communication, interaction, care, and support among family members can enhance students' satisfaction with family functioning, foster more positive emotions, and ultimately help students discover meaning in life.

From the perspectives of family care, this study further affirms the rationale behind "home-school-community collaborative education". It also offers practical insights for educators and practitioners working in related fields to intervene in the mental health services for adolescents and students. Specifically, the findings suggest that strengthening family care may serve as an effective pathway for enhancing students' meaning in life. This approach can contribute to the development of a collaborative education mechanism involving families, schools, and communities, thereby promoting the mental health and well-being of adolescents. Ultimately, such efforts may help students achieve self-identity, seek purpose in life, realize their potential in engaging with the world, and fulfill their life value.

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Analysis of the Impact of AI Education Applications on the Urban-Rural Digital Divide

Cizhen Zhang [a,b] and Leqiong Qian[a,1]
[a] *Xiangnan University, Hunan Province, 423000, China*
[b] *Hunan "14th Five-Year Plan" Key Cultivation Base for Educational Science Research, Xiangnan University Lifelong Education Research Base, Hunan Province, 423000, China*

Abstract: With the accelerated penetration of artificial intelligence (AI) technology in the field of education, AI education applications have provided the possibility for the cross-regional flow of high-quality educational resources and are regarded as an important tool to narrow the urban-rural digital divide. Starting with concept definition, this study explores the application differences of AI education between urban and rural areas and their impact mechanism on the digital divide, based on data from the 2025 Research Report on the Application of Artificial Intelligence among Primary and Secondary School Teachers. Using literature review, case study, and empirical analysis, this paper analyzes the potential mechanism of AI education applications in narrowing the urban-rural digital divide, discusses the possible positive effects and new inequality risks, and puts forward targeted policy and practical suggestions combined with cases, aiming to provide reference for promoting educational equity and high-quality development.

Keywords: Artificial Intelligence; Educational Application; Urban-Rural Digital Divide; Educational Equity

1. Introduction

The digital technology revolution has profoundly reshaped the global education system. As one of the core technologies, artificial intelligence (AI) is driving the transformation of education models towards personalization and intelligence. However, the problem of the urban-rural digital divide remains severe: according to the *Statistical Report on Internet Development in China* (2023), the internet penetration rate in rural areas (61.9%) is still lower than that in urban areas (83.1%), and the uneven distribution of high-quality educational resources has led to the continuous expansion of the digital skills gap between urban and rural students.[1] The issuance of a series of policy documents including the *Beijing Municipal Work Plan for Promoting Artificial Intelligence Education in Primary and Secondary Schools (2025–2027)* signifies that artificial intelligence education has evolved from the preliminary pilot stage to full-scale systematic implementation.

[1] Corresponding Author, Leqiong Qian. E-mail: 992864172@qq.com
Derived from the Teaching Reform Project of Xiangnan University: Exploration and Practice of Integrating Red Culture into University Teacher Education Courses Guided by the "Red Candle Spirit"

Theoretically, AI can break through the constraints of time and space, delivering high-quality teaching content to remote areas at low cost, thereby alleviating the traditional problem of uneven distribution of educational resources. In reality, however, there are significant differences between urban and rural areas in terms of hardware facilities, network coverage, teacher quality, and students' family digital access capabilities. The reality of unbalanced regional development has exposed AI education applications to the risk of "imbalanced technological empowerment": urban schools have built a full-scenario application ecosystem of "AI teaching assistants + intelligent learning partners + smart classrooms", while rural schools are generally plagued by basic problems such as lack of equipment, unstable networks, and insufficient teachers.[2]

2. Related Research

2.1 The Evolution of the Connotation of the Digital Divide

Research on the digital divide began in the 1990s, initially focusing on the "access gap"—the disparity in access to information technology among different groups. With the popularization of technology, scholars have gradually realized the multidimensional nature of the digital divide: Norris proposed a dichotomy of "access divide" and "use divide";[3] VanDijk further expanded it into four dimensions: "access, skills, usage, and outcomes".[4] Scholar van Dijk put forward the "use gap" and "capability gap", emphasizing the differentiated impact of digital skills.[5] The core of the urban-rural digital divide lies in the fairness of access to educational resources, and AI education applications may reshape this pattern by changing the way resources are allocated. In the field of education, the digital divide manifests systematic gaps between urban and rural learners in terms of access to digital infrastructure, digital literacy levels, and technological application effects, which can be specifically summarized into three core dimensions: access divide, literacy divide, and outcome divide.[6]

2.2 The Empowering Effect of AI Education Applications

AI education applications refer to systems and tools that provide intelligent support for teaching, learning, assessment, management, and other links based on technologies such as machine learning, natural language processing, and computer vision, such as intelligent question banks, personalized learning recommendations, voice interactive Q&A, and learning behavior analysis.

Existing research generally believes that AI education applications can promote educational equity through three aspects: (1) Resource Inclusiveness: AI course platforms break geographical restrictions, enabling rural students to access high-quality content; (2) Personalized Learning: Intelligent tutoring systems adapt to students' cognitive levels and compensate for teacher shortages in rural areas; (3) Teacher Burden Reduction: AI marking and lesson preparation tools free up teachers' time and improve teaching quality.

2.3 Controversies and Limitations

At this stage, the academic community has controversies about the potential of AI education applications to exacerbate inequality in several aspects: (1) Technological

Barriers: Rural teachers lack AI operation capabilities, leading to idle equipment; (2) Algorithmic Bias: AI recommended content tends to cater to the interests of urban students, ignoring the actual needs of rural areas; [7](3) Economic Threshold: The high cost of AI equipment and maintenance pose affordability challenges for rural schools to afford.

3. Research Methods

3.1 Literature Research Method

This paper systematically reviews the mainstream literature in the fields of the digital divide, artificial intelligence education, and educational equity both domestically and internationally, including policy documents, academic papers, and research reports, clarify the connotation of core concepts, the context of theoretical evolution, and the research status, and provide theoretical support for the construction of the research framework.

3.2 Case Study Method

Select two typical cases for in-depth analysis: one is Beijing (municipal-level coordinated model), representing the exploration of balanced AI education in economically developed areas; the other is Yuzhou City (county-level practice model), representing the implementation of AI education in central and western regions. Through collecting policy documents, practice reports, media coverage and other materials from the case areas, a stratified sampling method was employed to select 100 students and 20 teachers across urban-rural, school-stage, and subject dimensions. Questionnaires and semi-structured interviews on AI education application compiled by the researchers were used to carry out investigations and interviews. The demographic characteristics of the participants are detailed in Appendix 1. This study extracts the specific models, effects and problems of AI education applications and verifies the research hypotheses.

3.3 Comparative Research Method

Conduct a horizontal comparison of the current status of AI education applications in urban and rural areas from the dimensions of access, literacy, and outcomes, analyze the gaps and their causes; at the same time, conduct a vertical comparison of the cases of Beijing and Yuzhou, summarize the practical experience and applicable paths of regions with different development levels, and provide reference for the formulation of differentiated policies. In addition, based on the secondary data from the *2025 Research Report on Artificial Intelligence Application among Primary and Secondary School Teachers*, jointly issued by the Regional Education Professional Committee of the Chinese Society of Educational Development Strategy and Xuekewang, descriptive statistics were used to analyze the current situation of urban-rural application. Regression analysis was conducted based on 120 first-hand survey data to test the research hypotheses.

3.4 Research Framework

Based on the dialectical perspective of "technological empowerment - structural constraints", this study constructs a three-dimensional analytical framework (see Table 1).

Table 1: three-dimensional analytical framework

Access Dimension	Literacy Dimension	Literacy Dimension
(1) Urban-rural supply differences in hardware equipment required for AI education applications (2) Urban-rural supply differences in network infrastructure (3) Urban-rural supply differences in software resources AI	(1) Urban-rural gaps in teachers' and students' AI tool operation capabilities (2) Urban-rural gaps in teachers' and students' digital thinking (3) Urban-rural gaps in teachers' and students' ethical cognition	(1) Differentiated impacts of AI applications on the academic performance of urban and rural students (2) Differentiated impacts of AI applications on the comprehensive quality of urban and rural students (3) Differentiated impacts of AI applications on the development opportunities of urban and rural students

4. Research Results

4.1 Urban-Rural Differences of AI Education Applications

Against the backdrop of the accelerated integration of artificial intelligence into education and teaching, urban and rural schools exhibit significant uneven development in terms of technology supply, resource allocation, and application capabilities. This study conducts statistical analysis and comparison of the practical gaps in AI education applications between urban and rural areas from three key dimensions: hardware configuration, software resources, and teacher capacity, so as to reveal the prominent problems and constraints faced by rural areas in the implementation of AI education. (see Table 2).

Table 2: Urban-Rural Differences of AI Education Applications

Comparison Dimension	Urban Data	Rural Data	Results
Coverage Rate of Hardware Configuration	89.2%	47.5%	32% of AI equipment in rural areas is idle
Proportion of AI Courses	38%	12%	Urban areas focus on advanced skills; rural areas only cover basic content
Teachers' Skill Proficiency	65.3%	18.7%	Rural teachers have concerns about technological application

Note: Data in the table are secondary data sourced from the *2025 Research Report on Artificial Intelligence Application among Primary and Secondary School Teachers*. The 120 first-hand survey data were used for qualitative analysis and regression testing. Due to the limited sample size, they cannot support precise percentage conclusions for large samples.

(1) Significant Gap in Hardware Configuration: Low Coverage + High Idleness Rate, Coexistence of Resource Waste and Insufficient Supply

Data shows that the coverage rate of intelligent terminals (such as tablet computers and AI laboratories) in urban schools reaches 89.2%, while that in rural areas is only 47.5%; among rural schools, 32% of AI equipment is idle due to unstable networks or lack of maintenance. Urban students can carry out practical projects such as robot programming and image recognition through AI laboratories, while rural students' access to AI equipment is limited to "open class demonstrations", with almost no opportunities for independent operation in daily teaching. Urban students accumulate operational experience and innovative thinking through regular use of AI devices, while rural students only remain at a superficial cognitive level of “having heard of AI.” The technological literacy gap between the two groups begins to at the point of school entry.

(2) Structural Imbalance in Software Resources: Low Proportion + Disconnected Content, Curriculum Design Detached from Rural Teaching Reality

The proportion of AI courses in urban schools (38%) is much higher than that in rural areas (12%), and the content tends to focus on "advanced skills" such as programming and robotics, which are disconnected from rural students' life experiences. For example, the AI course in a rural primary school only involves "basics of speech recognition", while urban schools of the same type have launched "Introduction to Machine Learning". Urban students build programming and data analysis capabilities through advanced AI courses, gaining advantages in key admissions programs such as innovation bonus points in the high school entrance examination and university foundational disciplines enrollment plans; rural students only master basic skills, making it difficult for them to gain an advantage in future career competitions, which further solidifies the connection between education and social stratification.

(3) Prominent Shortcomings in Teachers' Capabilities: Weak Capabilities + Outdated Concepts, Technological Application Remains Superficial

Only 18.7% of rural teachers can proficiently use AI teaching tools, which is much lower than the 65.3% in urban areas. Interviews reveal that most rural teachers perceive AI as “operationally complex” and worry about being replaced, resulting in superficial technology use. Urban teachers skillfully use AI tools to design personalized assignments and analyze learning data for precision teaching; rural teachers, due to low proficiency, only use AI equipment as “video players”, leaving the core value of AI education—cultivating computational thinking and innovative capacity—completely unrealized.

4.2 The Impact Mechanism of AI Education Applications on the Digital Divide

(1) "Resource Balancing Effect": Narrowing the Gap in Content Access

Through surveys of teachers and students in two typical practice regions of AI education, case analysis shows that rural schools transmit real-time courses from famous urban schools to rural campuses through "AI synchronous classrooms", increasing the proportion of rural students accessing high-quality resources from 23% to 68%, and the average score of digital knowledge tests has increased by 15.2 points.

(2) "Capability Enhancement Effect": Strengthening Skill Acquisition

To further verify the capability enhancement effect of AI education applications, this study conducted a regression analysis to examine the heterogeneous impact of AI application level on digital skills between urban and rural students. The marginal benefit rural students is significantly higher than that for urban students *(see figure 1)*.

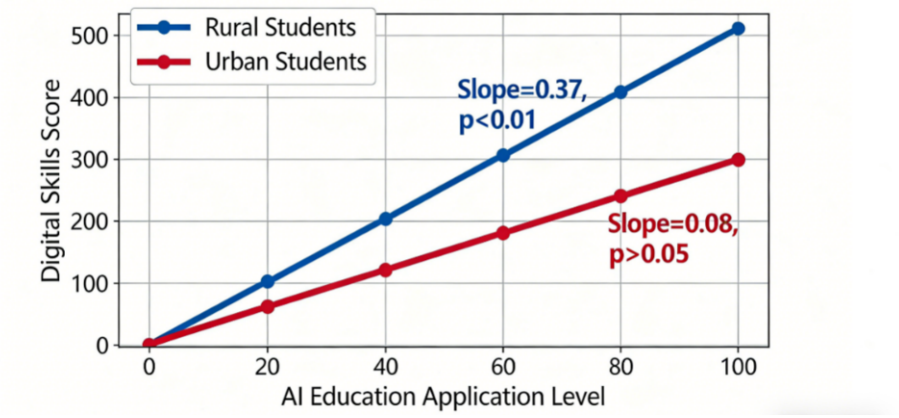


Figure 1: Digital Skills of Students in Different Regions

Table 3 Regression Results of AI Education Application on Students' Digital Skills

Variable	Coefficient	S.E.	t-value	p-value
AI_Level (Rural Group)	0.37	0.082	4.51	<0.01
AI_Level (Urban Group)	0.08	0.065	1.23	>0.05
Control Variables	Controlled	—	—	—
R^2	0.296	—	—	—
F-value	18.72	—	—	<0.01

Regression Equation: $DigitalSkill = \beta_0 + \beta_1 \times AI_Level + \beta_2 \times Urban + \beta_3 \times Control + \varepsilon$
Dependent Variable: DigitalSkill (Students' digital skills score)
Independent Variable: AI_Level (AI education application level)
Control Variables: Gender, school stage, family digital resources, parental education level

Data analysis indicates that for every one-unit increase in the level of AI education application, the digital skills score of rural students increases by 0.37 points ($p<0.01$), while there is no significant effect on urban students ($\beta=0.08$, $p>0.05$). The overall model fits well ($R^2=0.296$, $F=18.72$, $p<0.01$), confirming that AI yields stronger marginal empowerment for rural students and that the regression results are valid and reliable.

(3) "Technological Barrier Effect": Exacerbating the Risk of Marginalization

Some schools in Yuzhou City have seen AI equipment become "decorations" due to the lack of network support; the digital skills score of students from low-educated families (parents with junior high school education or below) is 22.5 points lower than that of students from high-educated families, reflecting the negative impact of "digital intergenerational transmission".

5. Discussion and Conclusion

5.1 Discussion

(1) The "Double-Edged Sword" Effect of AI Education Applications
AI is not a panacea: its poverty alleviation effect depends on technological adaptability and institutional guarantees. Ignoring the actual needs of rural areas (such as network infrastructure and teacher training) may lead to falling into the "technological utopian trap".
(2) The Root Cause of Urban-Rural Differences
The urban-rural digital divide is essentially structural inequality: the shortcomings of rural areas in infrastructure, human capital, and policy support make it difficult for AI technology to be converted into actual benefits. It is necessary to tilt resources through "compensatory policies" rather than simply relying on market logic.
(3) Enlightenment from International Experience
India's "Digital India" initiative has trained rural teachers through "AI teaching assistants", increasing the math scores of rural students by 20%;[8] Kenya has used low-cost SMS-based AI courses to cover remote areas, proving that a low-cost and localized technological path is more effective.

5.2 Conclusion

This study draws three core conclusions:
(1) There are three-dimensional gaps in "hardware - software - human resources" in AI education applications between urban and rural areas, with rural areas at a significant disadvantage;[9]
(2) AI narrows the digital divide through resource balancing and capability enhancement, but technological barriers may exacerbate the marginalization of vulnerable groups;[10]
(3) Policy interventions should focus on "capacity building" (such as teacher training) and "infrastructure" (such as network coverage), rather than simply pursuing technological accumulation.
In theory, AI education applications have the potential to bridge the urban-rural digital divide and promote educational equity, but their actual effects are constrained by multiple factors such as access conditions, digital literacy, algorithmic fairness, and implementation models. Without supporting policy support and technological optimization, they may not only fail to narrow the divide but also form new inequalities in terms of access and use. Therefore, promoting the application of AI in education, it is essential to adhere to the tripartite collaborative path of "technology – institution – humanity". focusing on quality and equity while expanding coverage, and truly realizing that the achievements of educational digitalization benefit every learner in urban and rural areas.

5.3 Policy Recommendations

(1) Strengthen Infrastructure Construction: Prioritize the deployment of 5G networks and AI laboratories in rural areas, and reduce equipment usage costs;
(2) Conduct Targeted Teacher Training: Develop "AI + local curriculum" training modules to improve teachers' technological application capabilities;

(3) Establish Supervision and Evaluation Mechanisms: Avoid AI algorithmic bias and regularly evaluate the educational equity effect of technological applications.

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Appendix 1 Brief Demographic Characteristics of Participants

Demographic Characteristics of Student Sample (n=100)

Variable	Category	Number	Percentage (%)
Gender	Male	53	53.0
	Female	47	47.0
School Type	Urban School	52	52.0
	Rural School	48	48.0
School Stage	Primary School	41	41.0
	Junior High School	37	37.0
	Senior High School	22	22.0
Number of Home Digital Devices	0	9	9.0
	1	28	28.0
	2	36	36.0
	3 or more	27	27.0
Highest Parental Education Level	Primary School or Below	18	18.0
	Junior High School	25	25.0
	Senior High School / Secondary Technical School	31	31.0
	Junior College or Above	26	26.0

Demographic Characteristics of Teacher Sample (n=20)

Variable	Category	Number	Percentage (%)
Gender	Male	8	40.0
	Female	12	60.0

Teaching Experience	Less than 5 years	6	30.0
	5–10 years	7	35.0
	10–20 years	5	25.0
	More than 20 years	2	10.0
Subject Taught	Chinese	5	25.0
	Mathematics	5	25.0
	English	4	20.0
	Science / Information Technology	3	15.0
	Others	3	15.0
School Type	Urban School	11	55.0
	Rural School	9	45.0
AI Education Training Experience	Attended	7	35.0
	Not Attended	13	65.0

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Research on the Reading Promotion of Excellent Traditional Culture in University Libraries Through Digital and Intelligent Enabling Technologies

Lina Li[a] and Zhen Liu[b1]
[a] *Xiangnan Preschool Education College, China*
[b] *The First People's Hospital of Chenzhou, 423000, China*

Abstract. The deep development of digital and intelligent technologies provides technical support for the innovation of reading services in university libraries, and the inheritance and dissemination of excellent traditional culture have ushered in an opportunity for digital development. Digital and intelligent technologies can optimize the work system of libraries in aspects such as resource construction, service models, and dissemination channels, and to a certain extent alleviate the practical problems such as scattered resources, monotonous forms, and insufficient interactivity in the promotion of traditional culture reading. This paper adopts the methods of literature research, argumentation, and policy analysis, taking university libraries as the research subject, defining core concepts such as digital empowerment, excellent traditional culture, and reading promotion, sorting out the current development status of traditional culture reading promotion in university libraries, analyzing the internal logic and practical value of the application of digital technologies, and constructing an optimization path from four dimensions: resource construction, service innovation, dissemination channels, and guarantee system. Combined with the current operation status of universities, the priority and implementation constraints for implementation are clarified. The research finds that at present, university libraries in the process of intelligent transformation have problems such as generalized application of concepts, insufficient technical adaptation, weak privacy ethics, and low degree of resource integration. Based on this, optimization suggestions are proposed in aspects such as resource integration, technical adaptation, risk control management, and talent development, with the aim of providing theoretical references for the digital transformation of traditional culture reading promotion in university libraries.

Keywords. Digital and Intelligent Empowerment; University Libraries; Traditional Culture; Reading Promotion; Intelligent Services

1. Introduction

The national cultural digitalization strategy clearly states the promotion of the digitalization and activation of cultural resources, and the establishment of a sound public cultural service system based on intelligent technologies. University libraries, as the core venues for campus culture construction, literature resource preservation, and

[1] Corresponding Author, Zhen Liu, The First People's Hospital of Chenzhou, China; Email: 274215322@qq.com

student reading cultivation, undertake important functions of inheriting excellent traditional culture and enhancing students' humanistic literacy. In the context of digitalization and intelligence development, the promotion models of traditional manual services and paper resource displays have become difficult to meet the contemporary college students' fragmented, diversified, and individualized reading needs. Intelligent algorithms, big data, artificial intelligence and other technologies have gradually integrated into the operation processes of libraries, providing technical support for the integration of library collections, precise reading services, and cultural scene construction. [1] Promoting the deep integration of culture and technology, integrating the application of advanced and applicable technologies, and enhancing the dissemination power, appeal and influence of culture. Under this background, exploring the optimization path of traditional culture reading promotion in university libraries from the perspective of digitalization empowerment has practical research value.

This paper mainly employs the following three research methods: First, the literature research method. By searching for relevant literature on library intelligence and traditional culture dissemination both domestically and internationally, and sorting out the existing research results, a theoretical foundation is established; Second, the dialectical method. By combining the characteristics of digital and intelligent technologies with the operation logic of university libraries, the mechanism of technology empowerment is analyzed; Third, the policy analysis method. Based on the national policies on cultural digitalization and university cultural construction, the industry development orientation is clarified.

This article is based on the development trend of digitalization, focuses on the specialized field of traditional culture reading in universities, combines emerging technologies such as big data and artificial intelligence, and aligns with the cutting-edge of industry. At the same time, considering the practical constraints such as limited university funds, slow technological iteration, and insufficient professional competence of personnel, it divides and optimizes the implementation priority of measures, and differs from general countermeasure research, possessing strong adaptability.

2. Core Concepts and Related Theoretical Foundations

2.1 Definition of Core Concepts

2.1.1 Digital Intelligence Empowerment

Digital intelligence empowerment is an enabling model that uses digital intelligence technologies such as big data, artificial intelligence, and cloud computing as its core. It relies on the entire process of data collection, storage, analysis, and application to optimize and restructure the original business processes, resource structures, and service models of the industry. Unlike the application of a single digital tool, digital intelligence empowerment places greater emphasis on the deep integration of technology and business. Under the premise of compliance, it explores data value and achieves refined services, intelligent management, and resource-intensive development. [2]

2.1.2 Reading Promotion in University Libraries

University library reading promotion is a public service activity based on the library's collection of literature resources, aimed at guiding reading, spreading culture, and cultivating literacy among students and faculty. Its core objective is to activate the library's resources, enhance readers' reading intentions, and improve the reading experience. Unlike public libraries, it places greater emphasis on aligning with the educational goals of universities and focusing on the coordinated development of academic and humanistic literacy.

2.1.3 Excellent Traditional Culture

Chinese excellent traditional culture is a collection of ideological concepts, humanistic spirit, and moral norms accumulated and formed by the Chinese nation during its long-term development. It encompasses contents such as literary classics, traditional arts, folk culture, and intangible cultural heritage. In the reading scenarios of universities, mainly ancient books, cultural works, and traditional art books are used as the main dissemination carriers.

2.2 Relevant Theoretical Foundations

2.2.1 Reader Service Theory

Reader service theory serves as the fundamental theory for library operations, emphasizing the core of meeting readers' needs, optimizing resource provision, service processes, and service environment. In the context of digital and intelligent empowerment, this theory requires libraries to leverage intelligent technologies to identify readers' reading preferences, match personalized cultural resources, and enhance the adaptability of traditional cultural reading services.

2.2.2 Resource Integration Theory

The resource integration theory emphasizes the aggregation, screening, reorganization and optimization of scattered and fragmented resources to maximize the efficiency of resource utilization. The traditional cultural resources of university libraries are scattered and have various formats. By leveraging digital and intelligent technologies, diverse resources such as printed ancient books, electronic documents, and digital cultural products can be integrated to build an integrated resource database.

2.2.3 Immersive Communication Theory

Based on multimedia, virtual reality and other technologies, the immersive communication theory breaks through the limitations of time and space, builds immersive experience scenarios, and enhances the audience's perception ability. This theory is applicable to the dissemination of traditional culture and can be implemented through intelligent scene construction to weaken the boring and obscure reading stereotypes of traditional culture. [3]

3. Problems in Promoting Traditional Culture Reading in University Libraries from the Perspective of Digital Intelligence

3.1 Insufficient Integration of Digital Resources and Obvious Shortcomings in the Supply System

Currently, most university libraries are still at the initial stage of digitalizing traditional culture resources. The resources are scattered, standards are inconsistent, and integration is not deep enough, which makes it difficult to meet the actual needs of digital intelligence-based reading promotion. On one hand, there is a lack of effective connection between physical ancient books, special collection resources, and digital resources in the library collections. The self-built databases and commercial databases are independent and not interconnected, and users need to switch between different platforms repeatedly to obtain the required resources, resulting in poor user experience [4]. On the other hand, the types of resources are relatively single, mainly consisting of textual classics, and the proportion of audio-visual, multimedia, and interactive resources that adapt to the reading habits of young students is relatively low, making it difficult to stimulate students' reading interest [5].

In addition, the metadata indexing of traditional culture resources is relatively superficial, lacking unified indexing standards and systematic knowledge connections, and failing to build a complete knowledge network, resulting in low resource retrieval efficiency and low utilization rate [6]. At the same time, most libraries have insufficient digitalization efforts for local and school-specific cultural resources, and the resource supply is highly homogeneous, lacking distinctive high-quality resources that have their own characteristics, making it difficult to meet the individualized reading needs of young students [7].

3.2 The application of digital and intelligent technologies is at a relatively shallow level, and the enabling effect has not been fully realized.

Although most university libraries have introduced digital and intelligent technologies to carry out traditional culture reading promotion work, the technology application mostly remains at the basic level of resource digitization and online exhibitions, lacking depth and breadth, and failing to fully realize the core enabling value of digital and intelligent technologies. For instance, the application of core technologies such as big data analysis, user profiling, and intelligent recommendation is insufficient. Most libraries still cannot achieve personalized and precise push of traditional culture resources, and the promotion work still has the phenomenon of "massive dissemination" [8].

In terms of the application of cutting-edge technologies, the application of VR/AR, AIGC, and the metaverse is relatively scarce. There are no immersive and interactive reading experience scenarios, which are difficult to stimulate the enthusiasm of young students [9]. Some libraries also have a cognitive bias of "emphasizing technology but neglecting content", investing a large amount of funds in technology procurement and platform construction, but ignoring the exploration, sorting, and innovation of traditional culture content, resulting in a serious disconnection between technology and content, forming a "two-layered" phenomenon, and the cumulative effect of digital and intelligent technologies has not been effectively demonstrated [10].

3.3 The service model is still relatively traditional, and the collaborative promotion mechanism has not yet been established.

Currently, the service model for promoting traditional cultural reading in university libraries remains rather conventional. It mainly relies on traditional forms such as offline lectures, book exhibitions, and essay competitions. There is a serious disconnection between online and offline services, and a fully integrated digital and intelligent service loop has not been established [11]. From the perspective of the promotion entities, the reading promotion work in most libraries is mainly undertaken by a single department of the library, failing to effectively collaborate with relevant departments such as the student affairs department, the ideological and political department, the academic affairs department, and the network information center within the university, nor strengthening cooperation with cultural institutions such as cultural centers and museums outside the university. The promotion strength is relatively weak, making it difficult to form a working synergy [12].

At the same time, the cross-border collaboration, resource sharing, and value creation promotion mechanism has not yet been established. There is a lack of effective communication, collaboration, and resource integration between libraries and relevant departments within the university, as well as with cultural institutions outside the university. This leads to insufficient professionalism of the promotion content, weak technical support, and limited dissemination scope, making it difficult to achieve large-scale and high-quality development of traditional cultural reading promotion [13].

3.4 Shortage of Composite Talents, and the Guarantee System Needs Improvement

In the context of digitalization, the implementation of excellent traditional culture reading promotion work in university libraries requires a team of professionals who possess comprehensive capabilities in library science, traditional culture, information technology, and new media operation. However, from the current situation, the staff teams in university libraries generally face problems such as outdated knowledge structures and insufficient digitalization skills. Most librarians lack professional capabilities in ancient book collation, digital technology application, and new media content creation, making it difficult for them to meet the actual demands of digitalization-based reading promotion work [10].

Furthermore, some universities do not attach sufficient importance to the promotion of excellent traditional culture reading, lacking dedicated funding support, and facing difficulties in promoting the digital transformation of resources, purchasing technical equipment, platform operation, and event organization [7]. In terms of assessment and evaluation, most universities still adopt traditional evaluation models, focusing on superficial indicators such as the number of activities and the number of participants, which leads to the problem of "emphasizing form over effect". They have not established an evaluation system centered on the effectiveness of cultural education, making it difficult to comprehensively measure the actual effectiveness of reading promotion work and hindering the sustainable development of digitalization-enabled reading promotion work [14].

3.5 The privacy risk control system is not complete, and the ethical awareness is weak

Some university intelligent systems have problems with ambiguous data collection boundaries, and there is a potential risk of excessive collection of users' reading records, browsing trajectories and other private information. At the same time, there is a lack of data anonymization, permission control, and algorithm supervision mechanisms, which leads to security risks such as data leakage and algorithm bias.

4. The Internal Logic of Digital Intelligence Empowering the Promotion of Traditional Culture Reading in University Libraries

4.1 Technological Logic: Utilizing Intelligent Technologies to Optimize Business Processes

The university library's collection of outstanding traditional culture resources is extremely rich. However, due to technical limitations in the past, most of the collection resources were in a static preservation state, and the phenomenon of "emphasizing collection but neglecting utilization" was quite common. A large number of precious resources were left unused, making it difficult for students to access and deeply understand them, resulting in the failure to fully leverage the dissemination value of traditional culture resources.

Big data and artificial intelligence technologies can categorize, label, and digitize the collection resources, simplifying the processes of resource retrieval, organization, and storage; cloud computing ensures stable storage of massive cultural resources and reduces hardware operation costs; virtual reality technology builds immersive cultural scenarios, optimizing the reading experience. Technological empowerment can simplify manual operation processes and make up for the shortcomings of the traditional operation model's low efficiency.

By leveraging big data and cloud computing technologies, libraries can achieve efficient storage, standardized classification, and rapid retrieval of massive traditional cultural resources, completely changing the previous problems of cumbersome searching and low utilization efficiency. This enables users to obtain the required resources conveniently and accurately [14]. Relying on cutting-edge technologies such as VR/AR/MR and digital twins, ancient academies' scenes, historical life scenes, and the operation processes of intangible cultural heritage can be precisely restored. The abstract cultural connotations can be transformed into concrete contents that are visual, audible, and experiential, effectively enhancing young students' perception and identification of traditional culture [15]. The application of OCR and AI intelligent recognition technologies can realize the automatic recognition, punctuation, translation, and conversion between simplified and traditional Chinese characters of ancient books, significantly reducing the threshold for reading ancient books and making the long-dormant ancient books truly "come alive" and enter the study lives of young students [16].

4.2 Resource Logic: Achieving Intensive Management of Multicultural Resources

Digital and intelligent technologies can break through the storage barriers of paper, electronic, and audio-visual resources, integrate traditional cultural resources both

within and outside the school, and build a unified search platform. Through resource screening, classification annotation, and elimination of invalid and redundant information, the resource structure is optimized, providing high-quality and systematic traditional culture reading resources for teachers and students.

One of the core missions of university libraries is to guide young students to appreciate the charm of Chinese excellent traditional culture, absorb cultural wisdom, and strengthen cultural confidence through high-quality cultural services and cultural dissemination. The application of digital and intelligent technologies has provided a new carrier for the deep integration of traditional culture, ideological and political education, and general education, further enriching the connotation and form of cultural education, and strengthening the unique position of libraries in the cultural inheritance and education system.

By leveraging digital technology, libraries can transform traditional cultural contents such as poetry, songs, rituals, and intangible cultural heritages into forms that young students enjoy, such as short videos, H5 pages, and interactive games. This effectively shortens the distance between traditional culture and young students, enhancing the affinity and penetration of cultural dissemination [12]. This innovative dissemination method not only expands the cultural service functions of libraries but also enables young students to deeply understand the contemporary value of Chinese excellent traditional culture in a convenient and interesting reading experience, inherit the Chinese cultural heritage, cultivate cultural literacy, and thereby strengthen cultural confidence and grow into new era individuals who are capable of taking on the responsibility of national rejuvenation.

4.3 Service Logic: Optimizing Service Model to Meet User Needs

The traditional reading promotion work often adopts a "one-size-fits-all" mass-oriented push model, which neglects the differentiated reading needs of young students with different majors and interests. As a result, the promotion work lacks targetedness and effectiveness. One of the core advantages of digital intelligence empowerment is to promote the reading promotion work to shift from a "supply-oriented" approach to a "demand-oriented" one. By precisely aligning with user needs, the attractiveness and effectiveness of the promotion work can be enhanced.

By leveraging big data technology, libraries can comprehensively collect various dimensions of data such as users' borrowing records, search behaviors, interest preferences, and interaction feedback. Through data mining and analysis, they can construct precise user cultural reading profiles, clearly understanding the explicit and potential needs of users [8]. On this basis, intelligent algorithms are used to carry out personalized resource recommendations, thematic content push, and related reading guidance, achieving "precise irrigation" of traditional cultural resources and enabling students of different majors and interests to find resources that meet their own needs [9]. At the same time, digital and intelligent technologies have further expanded the service scenarios of reading promotion, establishing an online and offline integrated and all-media covered service system. Through functions such as intelligent recommendations, voice guidance, and interactive question answering, they provide students with round-the-clock and personalized cultural services, effectively enhancing the appeal and practical effect of the promotion of excellent traditional culture reading [10].

5. The Optimization Path for Promoting Traditional Culture Reading in University Libraries under Digital Intelligence

5.1 Building a Digitalized and Systematic Traditional Culture Resource System

5.1.1 Digital Collection and Integration of Comprehensive Resources

University libraries should first conduct a comprehensive survey of their outstanding traditional culture resources, understand the quantity and current status of various resources, and use advanced technologies such as high-definition scanning, 3D modeling, and audio-video recording to complete the digital conversion of all resources in a standardized manner, ensuring the quality and completeness of the digital resources [16]. At the same time, strengthen the integration of purchased databases and open traditional culture resources from the internet, break down resource barriers, and achieve interconnection, co-construction, and sharing of various resources [4]. Establish a collaborative construction mechanism between universities and local cultural institutions, jointly carry out the collection and digitalization of characteristic traditional culture resources such as local customs, intangible cultural heritage skills, and oral history, and build a distributed digital resource alliance to achieve complementary advantages and resource sharing [6].

5.1.2 Knowledge Graph-driven Deep Organization of Resources

Through the construction of a knowledge graph, multi-dimensional correlation retrieval of traditional cultural resources is achieved, helping users quickly understand the development context of culture and grasp the relationships between resources, significantly improving the efficiency of resource retrieval and utilization [14].Through the construction of a knowledge graph, multi-dimensional correlation retrieval of traditional cultural resources is achieved, helping users quickly understand the development context of culture and grasp the relationships between resources, significantly improving the efficiency of resource retrieval and utilization [14]. A unified metadata indexing standard is formulated, and various digital resources are deeply indexed, classified, and organized to build an expandable, interrelated, and retrievable knowledge resource library, laying a solid foundation for precise services and personalized recommendations [9]. A unified metadata indexing standard is formulated, and various digital resources are deeply indexed, classified, and organized to build an expandable, interrelated, and retrievable knowledge resource library, laying a solid foundation for precise services and personalized recommendations [9].

5.1.3 Construction of Stratified and Classified Specialized Resource Library Groups

Build targeted thematic resource libraries to enhance the precision of resource supply [5]. In combination with regional cultural characteristics, deeply explore local outstanding traditional cultural resources and construct traditional cultural resource libraries with regional characteristics, creating distinctive brands for resource promotion [7]. According to the reading needs of students from different disciplines and different educational stages, build interdisciplinary traditional cultural resource libraries to achieve precise and distinctive supply of traditional cultural resources and meet the individualized needs of different groups [13].

5.2 Deep application of digital and intelligent technologies, innovation of traditional culture reading experience

5.2.1 Personalized services driven by big data and AI

Build a data warehouse for users' cultural reading behaviors, comprehensively collecting information such as users' reading history, search preferences, interaction feedback, and participation records of activities, and using big data analysis techniques to draw precise user reading profiles, deeply understanding users' reading needs and interest preferences [8]. Based on the user profiles, using intelligent algorithms to carry out personalized resource recommendations, thematic content push, and related reading guidance, ensuring that the pushed content is highly matched with users' needs, achieving "precise irrigation" of traditional culture resources [9]. Develop AI intelligent question-answering robots for traditional culture and voice search systems, integrating core contents such as classic literature knowledge, cultural allusions, and intangible cultural heritage skills, providing users with 7×24-hour intelligent consultation and search services, further enhancing the convenience of resource acquisition [16].

5.2.2 Construction of Immersive and Interactive Experience Scenarios

Actively introduce cutting-edge technologies such as VR/AR/MR, combined with traditional cultural characteristics, to develop interactive applications such as "Virtual Courtyard Tour", "Intrusive Immersive Experience of Intangible Cultural Heritage Skills", and "Reconstruction of Ancient Historical Scenarios", allowing users to experience the charm of traditional culture in a realistic manner and enhancing the interest and immersion of the reading experience [15]. Make full use of AIGC technology, combined with traditional cultural content, to automatically generate diverse content such as traditional poems, cultural stories, audio books, and short videos, enriching the expression forms of traditional culture and adapting to the reading habits of young students [9]. Design game modules such as knowledge challenges, online check-ins, and interactive quizzes, integrating traditional culture learning into interesting and interactive activities, effectively enhancing students' participation, sense of achievement, and retention [12].

5.2.3 Integrated Multi-platform and Multi-channel Communication Matrix

Based on the communication habits and acceptance characteristics of young students, a multi-platform and multi-channel communication matrix consisting of "library official website + WeChat official account + video account + Douyin/Bilibili + mini-program" is constructed. Short videos, animations, live broadcasts, audio books and other lightweight and fragmented traditional culture content are produced to achieve precise dissemination and wide coverage of traditional culture [10]. A one-stop mini-program/APP is developed, integrating core functions such as resource search, online reading, event registration, interactive community and intelligent recommendation, to create a convenient and efficient mobile service entrance, enabling students to access traditional culture resources and related services anytime and anywhere [8]. Promote the deep integration of online and offline services, and set up QR codes, interactive large screens and other facilities in offline reading spaces to achieve a service loop of

"offline experience + online extension", enhancing the continuity and completeness of services [14].

5.3 Innovative Digitalization Service Model, Expanding Cultural Education Scenarios

5.3.1 Creating an Intelligent Traditional Culture Reading Space

Carry out digitalization renovations on the existing reading spaces in libraries, creating an intelligent traditional culture reading space that integrates resource display, immersive experience, discussion and exchange, and learning and research [13]. Reasonably configure intelligent search terminals, VR experience equipment, interactive touch screens, e-book walls, etc., and set up functional areas such as ancient book digital reading area, intangible cultural heritage experience area, and cultural discussion area to meet the diverse reading and experience needs of students [15]. Utilize digital twin technology to build an online virtual reading space mirror image, achieving interconnection of online and offline spaces and seamless service connection, further expanding the service boundaries of the reading space [14].

5.3.2 Establish a brand and series-based promotion activity system

In line with campus culture construction and the needs of young students, plan influential brand promotion activities such as "Chinese Classic Digital Reading Festival" and "AI Traditional Culture Lecture Hall", to create distinctive and rich in content reading promotion brands [10]. Integrate the promotion of excellent traditional culture reading with course ideological education, general education, and campus cultural festivals, promoting traditional culture to be integrated into the entire process of education and teaching, achieving the organic combination of cultural education and knowledge transmission. Establish a long-term operation mechanism for the activities, regularly carry out regular and series-based promotion activities, and promote the reading promotion work to transform from "periodic activities" to "regular services", continuously enhancing the influence of traditional culture dissemination [12].

5.3.3 Establish a value co-creation mechanism involving multiple stakeholders

Establish a collaborative promotion alliance, clearly define the responsibilities and divisions of each entity, unite the working forces, and promote the high-quality development of traditional culture reading promotion work [13]. Invite domain experts to serve as advisors to enhance the professionalism and authority of the promotion work [16]; collaborate with the school's information technology department to provide technical support to ensure the smooth progress of digital and intelligent promotion work [14]; encourage student clubs to participate in activity planning, content dissemination, and operation management to enhance the targeting and appeal of the activities [12]. Strengthen cross-border cooperation with off-campus cultural institutions such as local cultural centers, museums, and heritage protection centers, jointly hold online exhibitions, academic discussions, practical research and other activities to achieve resource sharing, complementary advantages, and value co-creation [7].

5.4 Improve the guarantee system and promote long-term development of the work

5.4.1 Build a composite digital and intelligent talent team

Establish a regular training mechanism and organize librarians to conduct specialized training on digital and intelligent technologies, traditional culture, new media operation, resource indexing, etc. on a regular basis, continuously enhancing the professional capabilities and comprehensive qualities of the existing librarians [10]. Increase the intensity of talent recruitment, focusing on attracting professionals in fields such as humanities and history, computer science, and new media, optimizing the knowledge structure and professional structure of the librarian team [8]. Form a cross-departmental working team composed of librarians, ideological and political teachers, technical experts, and student leaders, clearly defining responsibilities and working collaboratively to provide talent support for digital and intelligent reading promotion work [13].

5.4.2 Improve the funding, management and security guarantee mechanisms

Actively seek support from the school's special funds, incorporate the promotion of digitalized reading into the library's annual budget, and prioritize the smooth progress of tasks such as resource digitalization conversion, technology equipment procurement, platform operation, event organization, and personnel training [7]. Incorporate the promotion of traditional culture reading into the library's annual work plan and assessment system, clearly define responsibility divisions, and establish a sound management system to ensure the standardized and regular implementation of the work [4].

Strictly follow relevant data security laws and regulations, establish a complete data security and content review mechanism, adhere to the principle of minimal data collection, only collect necessary de-identified reading data, and prohibit excessive user profiling. Establish technical measures such as data encryption, permission control, and content review to prevent user information leakage; optimize algorithm logic to avoid algorithm bias and ensure the fairness and diversity of cultural resource promotion. Ensure the political nature, ideological content and security of resources [17].

5.4.3 Establish an evaluation system centered on educational effectiveness

Abandon the traditional evaluation model that "emphasizes hardware but neglects actual results" and "focuses on form but neglects content" and establish an evaluation system centered on the actuality of cultural inheritance, user satisfaction, resource utilization rate, and educational value [12]. The evaluation indicators should cover multiple dimensions such as the quality of resource construction, technical application level, activity participation rate, user satisfaction, and the enhancement of students' cultural identity, to comprehensively measure the actual effectiveness of reading promotion work [9]. Use various methods such as big data analysis, questionnaire surveys, in-depth interviews, and case analysis to conduct systematic evaluation, forming an "evaluation - feedback - optimization" closed-loop mechanism. Based on the evaluation results, continuously optimize the promotion strategies and service

models, and promote the digital and intelligent empowerment of reading promotion work to continuously improve [10].

6. Conclusion and Future Work

Digital and intelligent technologies have provided new opportunities for the promotion of traditional culture reading in university libraries. They can improve the shortcomings of the traditional promotion model in terms of resource integration, service optimization, and channel expansion. Currently, there are still problems such as scattered resources, rigid forms, insufficient accuracy, and weak risk control systems in the promotion of traditional culture reading in university libraries in China. To adapt to the current development status of universities, libraries should adhere to the principle of gradual optimization, prioritize the improvement of basic digital resource construction, and standardize data privacy management; in the medium term, optimize intelligent push services and expand communication channels; in the long term, combine with financial conditions to build immersive cultural scenarios. Through multi-dimensional optimization of resources, services, risk control, and talents, promote the high-quality development of traditional culture reading promotion and contribute to the construction of humanistic education in universities.

As the cultural digitalization strategy continues to advance, intelligent technologies will deeply integrate into the entire process of library operations. In the future, university libraries should continuously deepen technological integration, taking into account both the quality of cultural dissemination and data security, and balancing the development of intelligence with the warmth of humanistic services. Subsequently, based on on-site research data, comparisons can be made between the construction differences of universities in different regions and at different levels, and the plans can be further refined and optimized. At the same time, social cultural institutions can be linked up to build a collaborative dissemination system both inside and outside the campus and continuously explore the contemporary educational value of excellent traditional culture.

This article is a theoretical qualitative study. No empirical work such as field research or questionnaire interviews has been conducted yet, and there is no quantitative data to support the research conclusions. Moreover, due to the limitation of the research scope, the resource differences among different levels and regions of universities have not been distinguished, and the universality of the research results is somewhat limited. In the future, combined with the field research data, the optimization plans for different types of universities can be further refined.

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Design of an AIGC-Powered Immersive English Oral Communication Scenario System

Danyan Xiao and Chuyi Zou [1]
Guangdong University of Foreign Studies, Guangzhou, China.

Abstract. In the context of educational digital transformation, traditional English oral teaching still faces challenges such as insufficient authentic contexts, limited interaction, and inadequate personalized support. To address these issues, this paper proposes an immersive English oral communication system based on Artificial Intelligence Generated Content (AIGC) and Virtual Reality (VR) technologies for CEFR A1–C2 learners, and designs a three-stage teaching model covering pre-class, in-class, and post-class learning processes. The framework aims to reduce the authenticity gap and psychological burden in oral English learning. Based on situated cognition theory, the system integrates AIGC-driven content generation, multi-turn dialogue interaction, learner modeling, dynamic scenario matching, and a four-dimensional evaluation mechanism to achieve personalized oral training and continuous feedback. The evaluation model assesses learners in terms of linguistic accuracy, expression fluency, communicative appropriateness, and learning initiative. Simulation-based analysis results show that the proposed system achieves balanced improvements across all four dimensions compared with traditional teaching approaches, with particularly significant gains in learning initiative and expression fluency. However, the long-term effectiveness of real classroom deployment and the quality control of AIGC-generated content still require further exploration. Overall, the proposed closed-loop mechanism of "Learner Modeling–Scenario Matching–Dialogue Generation–Evaluation Feedback" provides a scalable framework for intelligent and personalized language learning systems.

Keywords. Immersive Oral Teaching; AIGC; Situated Cognition; Personalized Learning; Dynamic Adaptive Language Learning Model; AI-based Language Learning Model

1. Introduction

Traditional English oral teaching is still largely characterized by teacher-centered and standardized instructional models, which often fail to address learners' individual communication needs and cognitive differences. Although students spend substantial time participating in formal language courses, many still struggle to apply English effectively in authentic communicative situations. This mismatch between language learning and practical application can be regarded as a form of "language learning waste",

[1] Corresponding Author: Chuyi Zou, School of English Education, Guangdong University of Foreign Studies, China; Email: chuyi_1228@qq.com.
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highlighting the need for more immersive, adaptive, and learner-centered instructional frameworks. The construction of the AIGC-powered immersive English oral communication scenario system is based on AIGC and VR technologies. Its purpose is to create an English oral interaction environment that integrates multiple thematic scenarios to address current issues in oral teaching, such as an over-emphasis on formal training, insufficient cultivation of cross-cultural communication skills, and a singular pedagogical evaluation system. By using AI to generate dialogue contexts that closely mirror real-life situations—covering themes such as daily communication, cross-cultural exchange, and academic discussion—the system enables students to naturally integrate language use with cross-cultural practice during highly realistic interactions. This facilitates the transformation of language learning from passive knowledge acquisition toward authentic communicative competence and learner-centered interaction.

2. Current Research Status

The application of artificial intelligence (AI) in the field of language teaching continues to deepen. Hua and Wang (2023) pointed out that the application of virtual reality (VR) technology in language learning is showing a continuous growth trend and has significant effects on improving learning immersion and communicative competence [1]. Moreno Giménez et al. (2025) further integrated AI with VR to build a real-time interactive language learning environment, achieving immersive dialogue training [2]. Research by Lou (2025) indicates that VR environments can effectively enhance learners' linguistic expression and communicative abilities [3]. Ali Karakas (2023) explored how AI supports cross-cultural communication and language teaching, transforms teaching methods, and improves cross-cultural competence, while elaborating on its core advantages such as personalized feedback, adaptive learning, and connecting language users [4]. Microsoft's (2023) VALL-E possesses powerful in-context learning capabilities, enabling zero-shot, highly natural speech synthesis that retains the speaker's emotion and acoustic environment [5]. OpenAI (2022) noted that InstructGPT, fine-tuned based on human feedback, can achieve efficient alignment between language models and user intent, resulting in more authentic and controllable output [6]. OpenAI (2020) demonstrated that GPT-3 achieved powerful few-shot learning capabilities by expanding model scale, completing oral-related tasks such as translation, Q&A, and real-time reasoning without fine-tuning [7]. MetaGPT encodes human Standard Operating Procedures (SOPs) into prompt sequences, assigning differentiated roles to agents in a pipeline mode to decompose complex tasks and achieve collaborative verification, which significantly improves the coherence and reliability of multi-agent collaboration [8]. Therefore, this study introduces a multidimensional evaluation and feedback mechanism into the immersive oral teaching framework to promote the coordinated evolution of learner modeling, scenario adaptation, and dialogue interaction.

3. Design Framework

Addressing the issues of monotonous scenarios, insufficient interaction, and one-sided evaluation in traditional English oral teaching, this paper constructs a generative immersive English oral teaching system framework based on AIGC and virtual reality technology. Supported by situated cognition theory, the framework emphasizes that

language learning must be achieved through interaction within authentic contexts, thereby realizing the transformation of linguistic knowledge into practical communicative competence.

In terms of system design, relying on the content generation capabilities of AIGC and the immersive environment construction of VR/AR, the system builds oral scenarios covering diverse themes such as daily exchange, workplace communication, and cross-cultural interaction, allowing learners to conduct language practice in settings close to the real environment. Meanwhile, based on the CEFR language proficiency standards, the system performs dynamic adaptation for learners of different levels. Specifically: the A1-A2 stages focus on daily communication and campus life; the B1-B2 stages introduce workplace communication and problem-solving tasks; the C1-C2 stages focus on cross-cultural and academic contexts, strengthening pragmatic competence and critical expression. By dynamically adapting to different learner levels, a progressive advancement from basic communication to complex communicative tasks is achieved.

Regarding the instructional workflow, the system constructs a "pre-class, in-class, and post-class" three-stage teaching model. In the pre-class stage, the system conducts learning analytics based on the learner's proficiency level and historical data to generate personalized preview content, including vocabulary warm-ups, scenario imports, and task previews, achieving differentiated adaptation at the learning starting point ; in the in-class stage, learners enter immersive virtual scenarios and engage in multi-turn dialogue interactions with system-generated characters; the system dynamically adjusts dialogue difficulty based on the learners' real-time performance and introduces teacher intervention when necessary, thereby enhancing the authenticity and targeting of the interaction ; in the post-class stage, the system generates learning feedback based on interaction process data and provides targeted review and reinforcement training to promote the consolidation and transfer of learning outcomes. Furthermore, post-class feedback data are continuously fed back into the scenario resource library and language knowledge base, enabling dynamic updating and optimization of future interaction tasks and learning resources. In this way, the framework forms a sustainable closed-loop improvement mechanism for personalized oral English teaching. This feedback-driven updating process allows the system to continuously refine scenario difficulty, interaction strategies, and language resource allocation, thereby supporting sustainable instructional improvement and adaptive learning optimization.

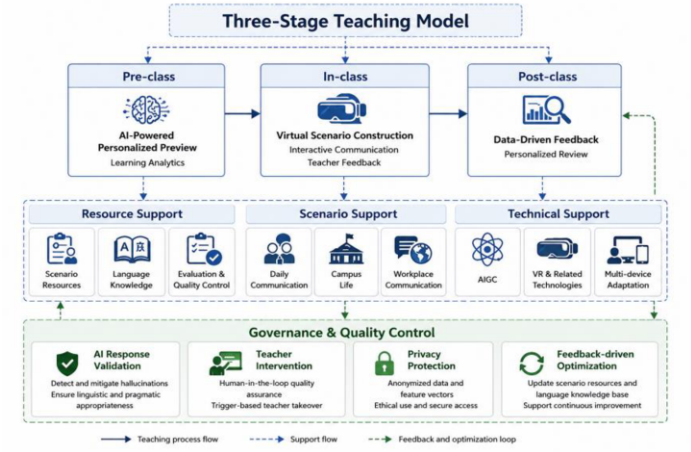


Figure 1. Three-Stage Generative Immersive Oral Teaching System Architecture

This figure presents the overall architecture of the generative immersive English oral teaching system, which adopts a "top-bottom" dual-layer structural design: the upper layer is the "pre-class, in-class, and post-class" three-stage teaching workflow, while the lower layer is a three-tier guarantee system comprising "resource support, scenario support, and technical support"; the two together constitute a complete teaching closed loop. To enhance the reliability and scalability of the framework, a governance and quality control layer is further incorporated, including AI response validation, teacher intervention, privacy protection, and feedback-driven optimization. Through continuous evaluation and resource updating, the framework forms a closed-loop improvement mechanism that supports sustainable instructional optimization and personalized learning.

In summary, the proposed framework not only enhances the authenticity and interactivity of oral English learning through immersive scenario construction and dynamic interaction, but also strengthens instructional reliability and continuous optimization through governance and quality control mechanisms, providing a scalable implementation path for intelligent and personalized language teaching.

4. AIGC-based Oral Interaction &Evaluation Model

This paper further constructs an English oral interaction and evaluation model based on generative artificial intelligence to achieve dynamic matching and optimization between learners, scenarios, and interaction processes. The model is embedded in the "pre-class, in-class, and post-class" three-stage teaching workflow. Through the synergistic effects of learner feature modeling, scenario matching mechanisms, dialogue generation mechanisms, and multidimensional evaluation mechanisms, it realizes intelligent support for immersive oral training.

In the pre-class stage, the system first constructs a Learner Model (LM) to characterize the learner's language proficiency level, interest preferences, and historical learning behaviors. To facilitate subsequent calculation and matching, learner features are represented in the form of multidimensional vectors:

$$LM = \{l_1, l_2, \dots, l_n\} \tag{1}$$

Specifically, each dimension corresponds to feature information such as the learner's vocabulary level, grammar mastery, phonetic performance, and communicative ability. Through the continuous updating of learning behavior data, the system achieves dynamic adjustment of the learner model and provides a basis for subsequent scenario recommendations. The system continuously updates this vector based on learning behavior data, thereby forming an iteratively optimized learner profile. To address data governance and privacy concerns, learner feature vectors and interaction records are anonymized and used only for adaptive learning analysis and dynamic scenario matching.

The system also introduces a Scenario Matching Model (SM) to achieve adaptive matching between the learner and oral interaction scenarios. Specifically, scenario features are also represented in vector form $S = \{s_1, s_2, \dots, s_n\}$, and the training scenario most suitable for the current learning state is selected by calculating the similarity between the learner feature vector and the scenario feature vector. This paper utilizes cosine similarity for measurement:

$$\mathrm{Sim}(\mathrm{LM}, \mathrm{S}) = \frac{\sum_{i=1}^{n} l_i s_i}{\sqrt{\sum_{i=1}^{n} l_i^2} \cdot \sqrt{\sum_{i=1}^{n} s_i^2}} \quad (2)$$

When the similarity reaches the set threshold, the system prioritizes recommending corresponding scenarios, achieving personalized preview and dynamic generation of classroom tasks.

The system constructs a four-dimensional Evaluation Model (EM), taking "evaluation as learning" as its core concept, to assess learners' oral communicative competence from multiple perspectives across four core dimensions. This evaluation is integrated throughout three stages: pre-class diagnosis, in-class real-time feedback, and post-class comprehensive evaluation, forming a complete evaluation closed loop. The evaluation model can be expressed as:

$$EM = \{Accuracy, Fluency, Appropriateness, Initiative\} \quad (3)$$

Within this model, $Accuracy$ assesses the learner's degree of normativity and precision in pronunciation, grammar, and vocabulary usage. The evaluation of pronunciation accuracy focuses on phonemic standards, correct stress, and natural intonation. The assessment of grammatical normativity emphasizes sentence structures that adhere to rules and the correct use of tense and voice. For vocabulary richness, the focus is on appropriateness of usage, variety of choice, and alignment with CEFR level requirements. Expression $Fluency$ evaluates the coherence, smoothness, and naturalness of the learner's oral delivery. Speech rate assessment focuses on whether the syllable output rate falls within a normal range. Pause characteristics are evaluated based on the rationality of pause frequency, the naturalness of pause locations, and the distinction between cognitive pauses and expressive barriers. Coherence focuses on the natural flow of discourse and the appropriate use of cohesive devices. $Appropriateness$ evaluates the decency, fitness, and effectiveness of language use in specific contexts. This includes whether the language style is adjusted according to the interlocutor and occasion, and whether appropriate politeness strategies are employed. It also assesses whether linguistic behavior in specific scenarios conforms to target-language socio-cultural norms, avoids pragmatic failures, and demonstrates intercultural awareness. Task completion focuses on whether communicative goals are successfully met, whether problems in the scenario are effectively resolved, and whether preset communicative functions are achieved. Finally, $Initiative$ e is used to assess the learner's proactivity and self-regulation during the learning process. The focus includes the preference for familiar versus challenging scenarios, the diversity of scenario distribution, and the active exploration of uncharted communicative domains.

The pre-class diagnostic stage positions the learner's CEFR level through initial four-dimensional level testing, establishing a competency baseline and outputting an initial capability profile along with personalized learning path suggestions. The in-class real-time feedback stage dynamically monitors four-dimensional performance during situational interaction, providing immediate error prompts and improvement suggestions to support learners in making real-time adjustments through visualization. The post-class comprehensive evaluation stage provides a four-dimensional comprehensive score for unit learning outcomes and analyzes progress trajectories, outputting periodic competency development reports and subsequent learning suggestions through problem attribution and reflection on learning behavior. The multidimensional evaluation results

are further utilized to update learner profiles, optimize scenario recommendation strategies, and dynamically adjust subsequent interaction tasks, thereby supporting continuous adaptive improvement throughout the instructional process.

Finally, by constructing a closed-loop mechanism of "Learner Model—Scenario Matching—Dialogue Generation—Evaluation Feedback," the model's operation is integrated throughout the entire process of pre-class diagnosis, in-class interaction, and post-class optimization. When evaluation results fall below the preset standards, the system automatically adjusts subsequent training tasks; conversely, it progressively increases task complexity, thereby achieving an adaptive evolution of the learning path.

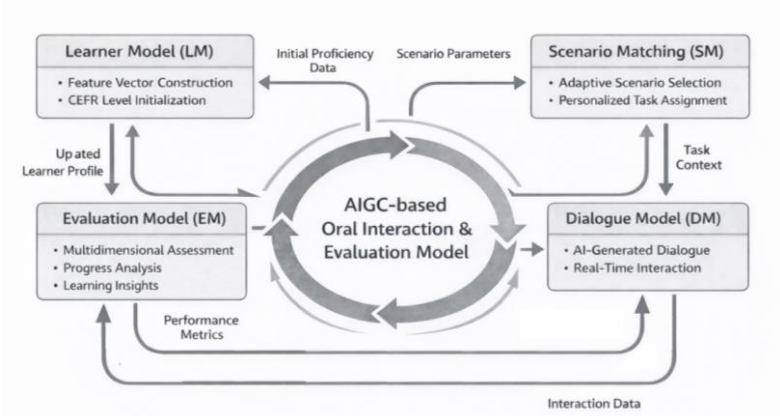


Figure 2. Interaction Mechanism of the AIGC-based Oral Interaction and Evaluation Model

As shown in the figure 2, each model achieves collaborative linkage through data flow. Behavioral data generated by learners during the pre-class, in-class, and post-class stages are continuously fed back into the Learner Model to update its feature representation. Meanwhile, evaluation results act back upon the scenario matching and dialogue generation modules to dynamically adjust subsequent task difficulty and interaction strategies. This forms a closed-loop mechanism of "data collection—model update—task optimization," enabling the adaptive evolution of the learning path.

In summary, the English oral interaction model constructed in this paper does not operate in isolation; rather, it is deeply embedded within the three-stage teaching framework. Through multi-model collaboration and dynamic feedback mechanisms, it achieves the organic integration of instructional workflows and intelligent algorithms.

5. Experimental results

To verify the effectiveness of the constructed generative immersive English oral teaching system, this paper analyzes its performance in enhancing oral proficiency by combining system design with typical application scenarios. In this study, a scenario-based simulation analysis was conducted to preliminarily evaluate the effectiveness of the proposed AIGC-driven immersive oral teaching framework. The simulation process focused on comparing traditional oral teaching methods and the proposed immersive interaction framework under comparable communicative tasks. The experimental setting included 30 simulation cycles across representative oral communication scenarios, including daily communication, workplace interaction, and cross-cultural dialogue tasks. Learner proficiency levels were initialized according to CEFR classifications ranging

from A1 to C2. During the simulation process, dialogue complexity and interaction difficulty were dynamically adjusted based on learners'performance and interaction feedback. The simulation analysis mainly relied on the proposed four-dimensional evaluation framework, including Accuracy, Fluency, Appropriateness, and Initiative. The interaction logic and scenario configuration process were implemented using Python-based simulation modules.

6. Conclusion

By combining Generative AI, Large Language Models (LLMs), and relevant intelligent interaction technologies, the teaching model proposed in this paper achieves dynamic expansion and continuous optimization upon traditional pedagogical frameworks. Through the introduction of multidimensional evaluation and feedback mechanisms, the system can constantly adjust training content and difficulty based on learner performance, progressively constructing personalized learning paths for different learners to more effectively meet diverse learning needs. Meanwhile, the integration of immersive scenarios and intelligent interaction helps reduce the psychological burden on learners during oral expression, boosting their learning confidence and improving overall learning outcomes. For educational practitioners and administrators, the proposed framework provides a potential reference for establishing standardized human-AI collaborative teaching workflows and intervention protocols for managing AIGC-generated instructional content. Future research may further explore the long-term cognitive impact of AIGC-assisted language learning, the scalability of the framework in multilingual learning environments, and more robust governance mechanisms for learner data privacy, fairness, and adaptive recommendation.

Overall, the proposed framework not only extends the application boundaries of AIGC and immersive technologies in oral English teaching, but also provides a scalable and continuously optimizable implementation path for the digital transformation of language education, offering a measurable roadmap toward intelligent and personalized language learning systems aligned with global language competency standards.

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Investigating the Role of the ADDIE Model in Enhancing Innovative Competence and Self-Directed Learning Skills in a Blended Learning Environment

Wenxia HE, Jialing HUANG, Xiaoran QIU, Haiyan DENG and Ze LIU[1]
School of Nursing, Xiangnan University, Chenzhou 423000, Hunan, China
ORCiD ID: Wenxia HE https://orcid.org/0000-0002-6251-8222

Abstract. Objective: The evolving landscape of science and technology imposes greater complexity on clinical nursing, making it imperative to develop innovative nursing professionals. Aligned with this national educational priority in China, our research aims to evaluate how the ADDIE model, when implemented in a blended online-offline teaching context, can improve the innovative competence of nursing students. Methods: The study recruited 225 undergraduate nursing students from the 2023 intake. The ADDIE model was applied to structure the course content and delivery for clinical nursing innovation skills. Pre- and post-implementation evaluations were conducted to measure changes in students' innovative ability, self-directed learning ability, and overall satisfaction with the teaching approach. Data were analyzed using paired t-tests and descriptive statistics. Results: The intervention yielded significant improvements in students' innovative ability and self-directed learning ability, with the differences being statistically significant ($P < 0.05$). The teaching model also achieved a 91% satisfaction rate among students. Conclusion: The integration of the ADDIE model into a blended learning environment successfully promotes the development of innovation skills and self-directed learning capabilities in nursing education. The high level of student satisfaction underscores the model's practicality and potential for wider adaptation across other academic domains.

Keywords. ADDIE model, Blended online and offline teaching, Innovative ability, Self-directed learning ability, Nursing students

1. Introduction

On January 31, 2024, during the 11th group study session of the 20th Central Politburo, General Secretary Xi Jinping emphasized that developing new, high-quality productive forces is an inherent requirement and a key focus for promoting high-quality development [1]. New quality productive forces are innovation-led, with innovative ability serving as the fundamental support and core element for their development [2]. Culti-

[1] Corresponding Author: Ze LIU, Xiangnan University, Chenzhou, Hunan, China; Email: liuze0113@xnu.edu.cn
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vating innovative ability necessitates fully leveraging the foundational role of higher education in talent development to enhance the quality of talent cultivation [3]. The National Nursing Development Plan (2021-2025) emphasizes the need to adhere to reform, innovation, and development to adapt to the new situations and requirements facing the development of the nursing profession. It points out that the demand from all sectors of society for nursing talents extends beyond clinically competent professionals to innovative nursing talents possessing innovative ability [4]. With the rapid advancement of the healthcare industry and increasing public health expectations, clinical scenarios have become more complex, posing new challenges to nursing practice. Consequently, cultivating high-quality nursing professionals with the ability to innovate has become a key objective of nursing education in China [5]. Innovation ability refers to an individual's capacity to use existing knowledge and experience, and through divergent and critical thinking, generate novel, unique, and valuable ideas or solutions. It plays a vital role in promoting technological progress and social development [6]. However, the current innovative ability of undergraduate nursing students is only at a moderate level [7]. Enhancing the innovative ability of nursing students represents a further societal demand for nursing talent cultivation in the context of new quality, productive forces.

The ADDIE model comprises five stages: analysis, design, development, implementation, and evaluation [8]. These stages are closely interconnected and aim to achieve specific behavioral changes and learning outcomes. The entire process emphasizes the design of educational programs, centers on student-centered learning, prompts course designers to establish more systematic and effective educational systems, and provides a framework for continuous improvement [9]. Ultimately, this places the entire educational endeavor within a "continuous improvement cycle." Di Hengdan et al. [10] applied the ADDIE model to the training of nurses' scientific research capabilities. Their results demonstrated that the model enhanced training satisfaction, improved research competence, and stimulated innovative engagement among nurses. Zhang Juan et al. [11] employed the ADDIE model combined with a flipped classroom approach to train neurology resident physicians, leading to an improvement in their self-directed learning ability. Supporting this finding, research by Shi Xiaoyan [12] demonstrates that the ADDIE model improves engagement, proactiveness, and clinical thinking among junior nurses during on-the-job training. This evidence further confirms the model's efficacy in enhancing students' innovation capabilities. The Surgical Nursing course at our institution is a provincial-level online-offline hybrid first-class undergraduate course in Hunan Province, providing the prerequisite conditions for implementing the ADDIE teaching model. This study investigates the introduction of the ADDIE teaching model into the Surgical Nursing course instruction, involving the restructuring of teaching content, to explore its impact on the innovative ability and self-directed learning ability of undergraduate nursing students. The details are reported as follows.

2. Subjects and Methods

2.1 General Information

This study employed convenience sampling and recruited five classes of undergraduate nursing students enrolled in 2023 as participants. Among them, 178 were female

(79.1%), and 47 were male (20.9%). The age range was 18 to 21 years, with a mean age of 19.64 ± 0.81 years.

2.2 Methods

A self-controlled study design was employed to analyze changes in students' innovative ability and self-directed learning ability before and after the course. The ADDIE model was implemented based on the Superstar Online Learning Platform, utilizing a blended teaching approach. The specific implementation process is described as follows.

2.2.1 Analysis Phase

During the analysis phase, the focus regarding students was on their current status of innovative ability and self-directed learning ability to establish a baseline. All enrolled students belonged to the "post-00 generation" and exhibited strong curiosity about new things and technologies. Utilizing common materials from daily life to create innovative nursing tools could satisfy their desire for new knowledge and techniques while reducing apprehension about enhancing their innovative ability. The blended learning approach could also alleviate issues such as the heavy course load of specialized subjects and limited in-class learning time.

2.2.2 Design Phase

To cultivate students' innovative ability and self-directed learning ability, instructors needed to integrate teaching content based on typical clinical cases, practical clinical nursing innovation tips, and cutting-edge disciplinary knowledge into their instructional design to enhance learning initiative. A teaching team comprising seven members was formed, including one Professor, two Associate Professors, one Associate Chief Nurse, two Lecturers, and one Nurse-in-Charge. Taking the chapter on nursing care for patients with musculoskeletal disorders as an example, the teaching content was designed by constructing innovative knowledge points based on real clinical cases. The teaching team was divided into a clinical subgroup and a teaching subgroup. The clinical subgroup collected innovative knowledge points based on problems identified in clinical practice. The teaching subgroup integrated these clinical problems into classroom teaching in the form of cases, aiming to open students' thinking and guide them in establishing an innovative mindset for problem-solving.

2.2.3 Development Phase

Within the nursing care for patients with musculoskeletal disorders, fractures at various sites are common clinical conditions. Fracture patients often experience swelling due to soft tissue injury. Ice application is a common early management strategy, but clinical ice application faces issues such as poor fixation due to displacement. Seizing this problem as an opportunity, an innovative ice pack fixation method was proposed and published on the Superstar Learning Platform, guiding students to propose solutions to this problem.

2.2.4 Implementation Phase

The ADDIE instructional design model was applied through the Superstar Online Learning Platform to structure a teaching activity centered on clinical innovation. A practical issue—the ineffective fixation of traditional ice packs in fracture patients—was selected as the instructional case.

(1) Prior to the class, a learning task was assigned via the platform, outlining the shortcomings of conventional cryotherapy fixation methods. Students were directed to examine provided literature and patent documents on the platform and to propose preliminary solutions. This pre-class phase also served to assess the students' baseline capacity for innovative thinking.

(2) During the course implementation, instructional strategies were informed by pre-class surveys measuring students' innovation competence and self-directed learning ability. Within the theoretical instruction segment, an ice pack constructed from common clinical materials—such as tarpaulin, buttons, and elastic bands—was introduced as a case example. This improvised device demonstrated both improved fit to the injured area and enhanced patient comfort. Through this case, students were guided to recognize that refining everyday clinical tools constitutes a viable form of innovation. The discussion also included the possibility of patent application for such improvements, aiming to mitigate student apprehension regarding the innovation process.

(3) Following the class, in addition to completing conventional theoretical assignments, students were required to review cutting-edge disciplinary literature—for instance, on the application of 3D printing technology in fracture internal fixation—and propose further clinically applicable cases leveraging relevant technical advances.

2.2.5 Evaluation Phase

Students' innovative ability, self-directed learning ability, and satisfaction with this teaching model were assessed before and after the course implementation. Innovative Ability: Evaluated using the scale developed by Wang Huixin [13]. This scale consists of 17 items across four dimensions: imagination, critical thinking ability, knowledge application ability, and problem-solving ability. It employs a 4-point Likert scale (1 = Completely Disagree, 2 = Somewhat Disagree, 3 = Somewhat Agree, 4 = Completely Agree), with a total score ranging from 17 to 68. Higher scores indicate stronger innovative learning ability. The Cronbach's α coefficient for this scale was 0.731, and the KMO value was 0.861. Self-Directed Learning Ability: Evaluated using the scale developed by Lin Yi [14]. This scale comprises 28 items across three dimensions: self-management ability (10 items), information acquisition ability (11 items), and learning collaboration ability (7 items). It employs a 5-point Likert scale (1 = Completely Disagree to 5 = Completely Agree), with a total score ranging from 28 to 140. Higher scores indicate stronger self-directed learning ability. The Cronbach's α coefficient for this scale was 0.86, the split-half reliability was 0.77, and the correlation coefficients between each dimension and the total scale ranged from 0.799 to 0.857. Teaching Model Satisfaction: Assessed using a 4-point rating scale: 4 = "Very Satisfied", 3 = "Satisfied", 2 = "Dissatisfied", 1 = "Very Dissatisfied".

2.3 Statistical Analysis

Statistical analysis was performed using SPSS 22.0 software. Measurement data that met or approximated a normal distribution were presented as mean ± standard deviation ($\bar{x} \pm s$). Comparisons of measurement data between groups were conducted using the t-test. A P-value < 0.05 was considered statistically significant.

3. Results

3.1 Student Satisfaction with the Course

A total of 225 students were surveyed. Among them, 150 students (66.7%) were very satisfied with this teaching model, 55 students (24.4%) were satisfied, and 20 students (8.9%) were dissatisfied (including those who were very dissatisfied). The primary reason cited was that this teaching model occupied excessive after-class time.

3.2 Comparison of Students' Innovative Ability Before and After Course Implementation

According to the results of the paired samples t-test, students' total innovative ability score (47.55 ± 8.15), critical thinking ability score (13.79 ± 2.81), and problem-solving ability score (11.60 ± 2.16) showed improvement after the intervention, with statistically significant differences ($p < 0.05$). No statistically significant differences were found in the scores for imagination and knowledge application ability ($p > 0.05$). See Table 1.

Table 1 Comparison of Students' Innovative Ability Before and After Intervention (n=225)

Variable	Group	Mean ± SD	t	p
Total Innovative Ability	Pre-test	45.55 ± 7.08	2.84	0.005
	Post-test	47.55 ± 8.15		
Imagination	Pre-test	13.10 ± 2.45	1.92	0.056
	Post-test	13.54 ± 2.46		
Critical Thinking Ability	Pre-test	13.08 ± 2.47	2.92	0.004
	Post-test	13.79 ± 2.81		
Knowledge Application Ability	Pre-test	8.35 ± 1.55	1.74	0.083
	Post-test	8.62 ± 1.82		
Problem-Solving Ability	Pre-test	11.02 ± 1.84	3.05	0.003
	Post-test	11.60 ± 2.16		

3.3 Comparison of Students' Self-Directed Learning Ability Before and After Course Implementation

According to the results of the paired samples t-test, students' total self-directed learning ability score (90.41 ± 11.07), learning collaboration ability score (22.40 ± 3.23), information acquisition ability score (36.07 ± 5.55), and self-management ability score

(31.94 ± 5.10) all showed improvement after the intervention, with statistically significant differences ($p < 0.05$). See Table 2.

Table 2 Comparison of Students' Self-Directed Learning Ability Before and After Intervention (n=225)

Variable	Group	Mean ± SD	t	p
Total Self-Directed Learning Ability	Pre-test	87.78 ± 10.87	2.55	0.011
	Post-test	90.41 ± 11.07		
Learning Collaboration Ability	Pre-test	21.78 ± 3.19	1.99	0.048
	Post-test	22.40 ± 3.23		
Information Acquisition Ability	Pre-test	34.91 ± 3.55	2.36	0.019
	Post-test	36.07 ± 5.55		
Self-Management Ability	Pre-test	31.08 ± 4.00	2.32	0.021
	Post-test	31.94 ± 5.10		

4. Discussion

The ADDIE model, as a classical training framework, has been preliminarily applied in the field of nursing in China and has achieved favorable outcomes [15]. The application of the ADDIE model can improve the quality and efficiency of curriculum development, enhance students' innovative ability and self-directed learning ability, promote educational development, and elevate teaching quality [16-19].

4.1 The ADDIE Teaching Model Can Enhance Students' Innovative Ability

The results of this study indicate that after implementing the ADDIE teaching model, nursing students' total innovative ability score, critical thinking ability score, and problem-solving ability score improved significantly. However, no significant improvement was observed in imagination and knowledge application ability scores, consistent with the findings of Xiang Qiu et al. [20]. The reason may be that integrating practical clinical nursing innovation skills into solving common clinical nursing problems during this course enhanced students' critical thinking and problem-solving abilities. These innovative techniques could be implemented using common materials from daily life, and developing such innovative nursing tools could lead to applications for utility model patents, thereby boosting students' innovative ability. The limited improvement in students' imagination and knowledge application may be attributed to their lack of clinical practice experience. Since their learning is primarily based on teacher-provided clinical cases without real-world exposure, they often struggle to establish meaningful connections between theoretical knowledge and actual clinical practice. To address this, future courses could incorporate real clinical nursing tools into the classroom, enhancing students' contextual understanding and thereby fostering their imaginative and applicative abilities.

4.2 The ADDIE Teaching Model Can Enhance Students' Self-Directed Learning Ability

Self-directed learning ability is a crucial competency that nursing students must acquire during their undergraduate studies, and its level has become an important criterion for evaluating the quality of higher medical education [21-22]. Traditional teaching models often result in low student engagement. In this study, the scores for all dimensions of self-directed learning ability and the total score were significantly higher after the ADDIE teaching model intervention compared to before (all $P<0.05$), aligning with the results of studies by Shi Xiaoyan [12] and Li Xiaomang [23]. Integrating the ADDIE model into blended (online-offline hybrid) learning in this course, restructuring teaching content, and incorporating clinical nursing innovation techniques required students to consult relevant literature and patent application information during their learning process. Consequently, their information acquisition ability improved. Furthermore, the process of reviewing cutting-edge disciplinary literature involved teamwork among students and effective management of extracurricular time for self-study, leading to enhancements in their learning, collaboration, and self-management abilities.

4.3 Most Students Were Satisfied with the ADDIE Teaching Model

The results of this study show that 91.0% of students were satisfied with the integration of the ADDIE teaching model into the blended Surgical Nursing course. This high satisfaction rate may be related to the model's emphasis during the analysis phase on understanding students' learning situations, enabling targeted teaching implementation. Additionally, the clinical nursing innovation skills integrated into the course were easily comprehensible teaching content, contributing to high student acceptance.

5. Research Limitations

This study is subject to several limitations. First, it adopted a quantitative research design without incorporating qualitative methods. Consequently, the findings lack triangulation through mixed-method data, which could have provided deeper insights into the underlying reasons for the improvement in students' innovation capabilities. Furthermore, in the teaching implementation process, to ensure instructional consistency and facilitate sampling, all students in the grade were selected for intervention, without designating a specific class as the intervention group. Although the sample size met statistical requirements, this sampling approach may affect the generalization of the results.

6. Conclusion

In conclusion, implementing the ADDIE teaching model based on the Superstar Online Learning Platform and integrating clinical nursing innovation skills into classroom teaching can enhance nursing students' innovative ability and self-directed learning ability. Students reported high satisfaction with this teaching model. This approach could be promoted in other nursing professional courses in the future. Future work

should explore its transferability to other medical specialties, assessing its influence on critical thinking and career competence to determine its long-term effectiveness.

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Research on the Educational Communication Path of Intangible Cultural Heritage 'Internet Celebrities' - Taking the Operation of Li Ziqi's Account as an Example

Huiai DENG[1] and Yiqi YANG
School of Literature and Journalism, Xiangnan University, No. 889, Chenzhou Avenue, Chenzhou 423000, China

Abstract. This study takes Li Ziqi's dissemination of intangible cultural heritage as a case. By analyzing A longitudinal analysis of Li Ziqi's cross-platform data (Douyin, Weibo, YouTube; 2016–2025) demonstrates that she embeds intangible cultural heritage into the temporal rhythms of daily life through process transparency and systematic life-oriented narration. This approach constructs an educational communication model characterized by emotional resonance and cognitive depth, effectively promoting a shift in the audience from viewing to understanding, and from recognition to identification. The model offers significant insights for the living heritage of intangible cultural heritage in the digital age. Consequently, this research provides a paradigmatic case for integrating intangible cultural heritage into modern digital life, offering critical implications for future heritage communication practices.

Keywords. Intangible Cultural Heritage, Li Ziqi, Educational Function, Full process presentation, Life oriented narrative

1. Introduction

In the era of new media communication, traffic has become an important indicator for measuring the effectiveness of cultural content dissemination. How to effectively guide traffic attention and create new development opportunities for intangible cultural heritage (hereinafter referred to as "intangible cultural heritage") through its dissemination power is one of the important issues facing the inheritance of intangible cultural heritage at present [1]. In 2021, the General Office of the Communist Party of China Central Committee and the General Office of the State Council issued the "Opinions on Further Strengthening the Protection of Intangible Cultural Heritage", which clearly stated the need to "adapt to the trend of deep media integration" and that

[1] Huiai DENG, School of Literature and Journalism, Xiangnan University, No. 889, Chenzhou Avenue, Chenzhou 423000, China; E-mail: 67176374@qq.com.

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"the content of intangible cultural heritage runs through the entire process of national education", pointing out the direction for contemporary dissemination of intangible cultural heritage. Exploring how intangible cultural heritage content can shift from simple "traffic attraction" to sustainable "educational empowerment" has important theoretical value and practical significance [2].

Among numerous intangible cultural heritage dissemination practices, Li Ziqi's account operation provides a case worthy of in-depth analysis [3]. After the revision, its content not only attracted widespread attention domestically, but also demonstrated strong cultural influence on international platforms, reflecting the transformation from "traffic harvesting" to "value cultivation". This article focuses on exploring how intangible cultural heritage accounts can fulfill users' deep needs, tap into traditional cultural values, achieve educational functions and live inheritance, and explore sustainable content development paths [4].

2. The data performance and educational potential of Li Ziqi's account operation

2.1. Research Methods and Data

To ensure methodological rigor and transparency, this study adopted a systematic procedure for data acquisition and analysis. Publicly accessible data were collected and synthesized via official application programming interfaces (APIs) or validated third-party analytics platforms—exemplified by Social Blade—encompassing both TikTok (Douyin) and YouTube. For TikTok, the dataset spans from January 1, 2023, to May 31, 2025, with analytical emphasis placed on two delineated phases: the pre-return interval (extending up to November 2024) and the post-return interval (May 2025). YouTube data have been continuously monitored since the channel's establishment in August 2017, and a focused examination was conducted on the temporal window immediately preceding and following the comeback event in November 2024. This temporal segmentation enables a comparative assessment of audience response patterns across distinct stages of the creator's online presence, thereby enhancing the interpretability of engagement trends.

The investigation was anchored in a predefined set of key performance indicators (KPIs): for TikTok, these encompass followers (cumulative total), total likes, number of published works (videos), and the arithmetic mean of average likes, comments, and shares per video; for YouTube, the KPIs comprise subscribers (cumulative total), subscriber growth rate (computed as the net increase during specified periods), and total views (cumulative channel aggregate). By grounding empirical findings in verifiable, temporally bounded, and platform-specific evidence, this structured framework supports robust analyses of audience engagement patterns and dissemination dynamics, ensuring that observed variations in metrics can be reliably attributed to the examined temporal and contextual factors.

2.2. Comparative analysis of data from domestic and foreign platforms

Taking the TikTok platform as an example, take the number of fans, likes, works, average likes, average comments, and average sharing as the horizontal axis, and take the two time periods before and after the return (as of November 2024) and after the

return (as of May 2025) as the vertical axis, establish a table for data analysis, as shown in Table 1 and Figure 1.

Table 1. Comparison of Key Engagement Metrics on TikTok Before and After Li Ziqi's Return

Indicator	Number of Fans	Number of Likes Received	Number of Works Average	Number of Likes per Video Average	Number of Comments per Video Average	Number of Shares per Video
Before Return (as of November 2024)	53 million +	230 million +	127	1.8million per video	60.000 per video	150,000 per video
After Return (as of May 2025)	60 million +	260 million +	130	2.05 million per video	70.000 per video	160,000 per video

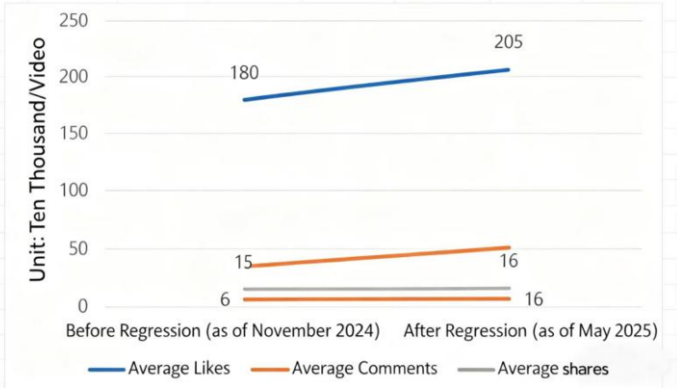


Figure 1. Trends in Average Engagement Metrics on Li Ziqi's TikTok Account Before and After Her Return

It can be seen from Table 1 and Figure 1 that after the return of Li Ziqi's account, the number of fans on the TikTok platform has increased by nearly 7 million, the number of likes has increased by nearly 30 million, the number of works has been updated by 3, the average number of likes has increased by 250000/video, the average number of comments has increased by 10000/video, and the average number of shares has increased by 10000/video. In general, the data shows an upward trend, and the continuous improvement of various indicators shows a very high popularity curve. Moreover, according to the traffic forecast of the TikTok platform, the data of Li Ziqi's account will continue to grow after May 2025.

Taking the YouTube platform as an example, with subscription volume, subscription growth rate, and total views as the horizontal axis, and before regression (as of November 2024) and after regression (as of May 2025) as the vertical axis, a table is established for data analysis, as shown in Table 2.

Table 2. Subscriber and View Metrics: Pre- and Post-Return Analysis

Time Period	Subscription Volume	Subscription Growth Rate	Total Play Volume
Before Return (as of November 2024)	19 million +	The channel released its first video in August 2017 and had over 11.4 million subscribers by July 2020. The subscriber count rose to 14.1 million by February 2021 and further increased to 17.7 million by October 2023.	Reached 1.345 billion times
After Return (as of May 2025)	20 million +	The channel released its first video in August 2017. By July 2020—within three years—it had surpassed 11.4 million subscribers. The subscriber count grew to 14.1 million by February 2021 and further increased to 17.7 million by October 2023. During this period, the	The three return videos after the comeback had over 500 million plays within three

	channel accumulated over 1.345 billion total views. Following a hiatus, the creator returned in November 2024. Within just three days of the comeback, the channel gained 200,000 new subscribers, with a single-day peak increase of 750,000. As of May 2025, the total number of subscribers exceeded 20 million.	days, and the first video Ziqi Donglai exceeded 100 million plays alone.

According to Table 2, after the return of Li Ziqi's account, the subscription volume on the YouTube platform increased by over 1 million people, with a considerable growth rate in subscription volume, and the total playback volume set a new record.

Li Ziqi's account operation has a huge fan base on both domestic and international platforms, and various data shows an upward trend, with traffic potential still to be explored. Especially after her return, her account has clearly been favored by more groups, and the interaction volume has continued to grow, constantly attracting public attention and discussion. Compared to before her return, there may be more development opportunities now.

It should be noted that the data in this study is time limited as of May 2025, and any subsequent changes in account operation data may affect the applicability of the conclusions.

With the evolution of user aesthetic preferences, if Li Ziqi's video creation content continues to adhere to the existing narrative framework over the long term, it may trigger "aesthetic fatigue" among netizens. Moreover, if the demonstration of intangible cultural heritage craftsmanship fails to continuously expand innovative dimensions, it is prone to falling into the predicament of "content homogenization"—for instance, repeatedly presenting similar life scenes and craftsmanship processes. It is necessary to be vigilant against potential challenges such as a slowdown in traffic growth and the loss of young users. This reserves room for reflection and optimization to ensure the long-term operation of the intellectual property and the sustainability of intangible cultural heritage dissemination.

2.3. The Educational Value Behind the Traffic

High mutual momentum reflects users' active willingness to learn about intangible cultural heritage content. Li Ziqi has returned to TikTok for three years, and the video comment area of his comeback is full of fans' welcome and expectation. From the perspective of user profiles, Generation Z (born between 1995 and 2010) accounts for over 60%. They grew up in the digital age and have a high acceptance of short videos. They actively interact in the comment section and often cut video clips for creative remixing and cultural interpretation. This has led to content such as intangible cultural heritage technology popularization and traditional life aesthetic insights, demonstrating their active exploration desire for intangible cultural heritage content [5].

International communication data proves that cultural education can break through geographical barriers. Most of the videos on Li Ziqi's account have no dialogue and rely on human movements and environmental sounds (such as bird songs and water currents) to convey information, breaking down language barriers; Explore cultural resonance points at home and abroad, focus on "common human emotions" (such as family love, reverence for nature, etc.), and enable audiences from different cultural backgrounds to perceive the logic of skills and cultural emotions; And avoid sensitive international topics, enter the international market in a peaceful and inclusive manner, and promote positive dissemination.

3. The path to realizing the educational function of intangible cultural heritage "internet celebrities"

3.1. The core dimensions of educational function

Table 3. Distribution of Core Educational Dimensions in Intangible Cultural Heritage Communication

Three Dimensions	Explanation	Proportion
Emotional Resonance	Give back to intangible cultural heritage protection through commercial transformation and establish emotional connection	35.8%
Knowledge Transmission	Visual narrative of the whole process	32.2%
Behavioral Guidance	The philosophy of slow life triggers cultural identity	32.0%

The data shown in Table 3 is derived from online surveys and the integration of average values, presenting the proportion of core dimensions of educational functions: emotional resonance (35.8%), using commercial feedback to protect intangible cultural heritage, triggering emotional connections; Knowledge transmission (32.2%) relies on visualizing technical processes and outputting intangible cultural heritage knowledge; Behavioral guidance (32.0%) promotes cultural identity practice through the philosophy of slow living.

3.2. Transparent presentation of the entire process, achieving skill recognition

Li Ziqi used the "full process immersive presentation" strategy to systematically showcase the complete chain of intangible cultural heritage techniques from raw material collection, processing to final products, and constructed a highly educational "process as education" model. She does not shy away from the complexity and time-consuming nature of her skills, and truthfully records the entire process of lacquer picking, tire making, lacquer carving, gold pasting, and even repeated remaking due to mistakes, concretizing the "slow" and "refined" aspects of traditional handicrafts. In terms of video structure, she adopts a "stepped time allocation" approach, giving longer presentation time to key technical difficulties and deep cultural connotations (such as lacquer modulation and hidden flower carving), guiding the audience to focus on core skills; At the same time, through "micro close ups", details such as paint texture and silk thread threading are displayed, supplemented by "overall scenes" to restore the production environment and process rhythm, forming a multi-level visual cognitive system. This narrative style of "fully transparent process" breaks the public's stereotype of intangible cultural heritage as "mysterious and unattainable", transforming abstract and static knowledge into dynamic and traceable practical processes. The audience not only "sees" the craftsmanship, but also "understands" the process logic and craftsmanship spirit behind it, achieving a transformation from passive observation to active cognition [6].

This path has completed the visual encoding and emotional transmission of intangible cultural heritage knowledge through authentic, complete, and detailed practical records, effectively promoting the cognitive popularization and value recognition of traditional skills at the public level, and providing a replicable immersive practice model for intangible cultural heritage education.

3.3. Life oriented narrative system, constructing cultural identity

Li Ziqi's dissemination of intangible cultural heritage goes beyond the display level of a single skill, and constructs a complete "intangible cultural heritage ecological education system" through "life oriented systematic narrative", achieving a deep transformation from skill transmission to cultural identity generation. She organically integrates intangible cultural heritage projects into the overall picture of traditional rural life in China, using the cycle of the four seasons and the 24 solar terms as the timeline, systematically linking daily work scenes such as spring plowing and sowing, summer sericulture, autumn harvest and wine making, and winter clothing and food making. In this narrative framework, Shu brocade is not only a textile technique, but also a life integration from planting mulberry and sericulture, silk dyeing to pattern design; The production of ink, brush, paper, and inkstone no longer exists in isolation, but is closely linked to the cultural traditions of farming, reading, family transmission, and literati writing. Every intangible cultural heritage technique has become a natural link in the traditional life chain, presenting a harmonious coexistence of "technique" and "Dao", "object" and "ritual", and "human" and "nature".

This narrative logic of "life as education" breaks the academic and fragmented mode of knowledge transmission, and restores cultural inheritance to a tangible, touchable, and participatory life practice. In the soothing rhythm and poetic imagery, the audience not only learns specific techniques, but also subtly understands the wisdom of seasonal changes, the philosophy of making the best use of things, the ethics of respecting heaven and cherishing things, and the artistic conception of traditional aesthetics. This contextualized and emotional expression has stimulated cultural resonance and identity recognition among the audience, prompting them to shift from passive observation to actively exploring the deep meanings behind seasonal culture, traditional customs, and even handicrafts. As a result, intangible cultural heritage is no longer just a "heritage" for viewing, but has become a sustainable way of life and spiritual belonging, truly achieving the essential goal of dynamic inheritance.

4. Conclusion

The contemporary dissemination of intangible cultural heritage should not stop at the accumulation of traffic, but should strive for educational empowerment and deep exploration of cultural values. Li Ziqi's account practice has shown that through the complementary paths of "full process transparent presentation" and "life oriented systematic narrative", the systematic transformation of intangible cultural heritage education functions can be effectively achieved. The former breaks down public cognitive barriers through authentic and complete technical processes, completing the visualization and embodiment of knowledge transmission; The latter restores skills to the traditional context of life, constructing a cultural ecosystem that covers solar terms, ethics, and aesthetics, and stimulating emotional resonance and identity recognition among the audience. This dissemination model is from "technique" to "way", from "observation" to "practice". In the future, the dissemination of intangible cultural heritage should draw on such practices, pay attention to the systematic, authentic, and contextualized expression of content, and promote the true living inheritance and global resonance of traditional culture in the digital age.

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Empowering Vocational Education Reform with Digital Intelligence: A CBE-Based Approach to the "Five Gold Standards"

Huiqi ZHONG[a,1] and Jingxiao HUANG[a]
[a] *School of Management, Guangdong Polytechnic of Science and Trade, Guangzhou, China*

Abstract. The construction of the "Five Gold Standards" (also termed the "Five Pillars of Excellence") — encompassing Gold Majors, Gold Courses, Gold Teachers, Gold Bases, Gold Materials,is a crucial measure to promote the comprehensive reform of vocational education, while digital intelligence empowerment is the core force driving the modernization of vocational education. Currently, higher vocational colleges are exploring practices in Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative actively but still face many challenges. By constructing a logical chain of "theoretical guidance — technological empowerment — practical application," this paper clarifies the core connotation of CBE (Competency-Based Education) theory, identifies the construction core and implementation keys of the "Five Gold Standards" based on this theory, proposes a collaborative upgrade path for the "Five Gold Standards" with digital intelligence as the technological enabler.Taking Guangdong Polytechnic of Science and Trade as an example, this paper elaborates on the practical measures taken to empower the "Five Gold Standards" initiative through digital intelligence, along with their implementation outcomes.

Keywords. "Five Gold Standards" Construction, Digital Intelligence Empowerment, CBE Theory.

1. Introduction

Vocational education in China is positioned as an independent type of education with "equal importance" to general education, having transformed from a "supporting role" in the education system to a mainstay supporting national innovation and industrial upgrading. "The 'Five Gold Standards' " is a specific Chinese policy framework initiated by the Ministry of Education. It is also termed the "Five Pillars of Excellence". In July 2023, Vice Minister of Education Wu Yan stated that for vocational education to become the "mainstay" in building a powerful education system, the key lies in systematically advancing the new infrastructure of the "Five Gold Standards"—namely, forging Gold Majors, Gold Courses, Gold Teachers, Gold Bases, and Gold Materials—first formally proposing the concept of the "Five Gold Standards" [1]. Furthermore, China's "Plan for Building High-Level Vocational Colleges and Majors with Chinese Characteristics (2025–2029)" institutionalizes the requirements for "Five

[1] Corresponding Author, Zhong Huiqi, School of Management, Guangdong Polytechnic of Science and Trade, Qingcheng District, Qingyuan City, Guangdong Province, China; Email: huiqi1203@126.com.

Gold Standards". It proposes that schools and enterprises "jointly forge the Five Gold Standards," marking its transition from concept to full-scale implementation. The "Five Gold Standards" construction is not merely a simple upgrade of internal elements within vocational education but represents a measure to comprehensively drive vocational education reform and achieve deep-seated transformation and upgrading of the education system through the holistic enhancement of key elements spanning the teaching system.

Vocational education originated from large-scale industrial production and has continuously developed alongside the process of industrialization. From a historical perspective, the rise of each industrial revolution has profoundly propelled the transformation and upgrading of vocational education. Currently, the trend of "digital intelligence" has been fully integrated into all areas of the economy and society, rapidly reshaping human production, services, and lifestyles. At this critical historical stage, the digital transformation of vocational education has become an inevitable trend, with digital intelligence also becoming the main force driving this transformation.

Digital intelligence can be understood as the integration of digital intelligence and intelligent digitalization, aiming to establish a deep dialogue and mutual deep learning between humans and machines. That is, with intelligence as the bond, a new ecosystem of human-machine integration, intelligent collaboration, and virtual-real co-construction is formed [2]. Digital intelligence empowerment refers to the deep integration of data elements with intelligent technology, enabling data to generate a powerful "fusion" effect based on intelligent technology, releasing the enormous value of data, and by reconstructing specific system elements and structures, driving the system to achieve human-AI collaborative value creation [3]. Compared with informatization and digitalization, digital intelligence, using digital technologies and artificial intelligence as tools and driven by deep learning and decision optimization, places greater emphasis on the intelligent analysis, processing and application of data, and stresses the application value of data in promoting social and economic development, optimizing industrial structure and reshaping development models [4]. Digital intelligence empowerment not only provides new educational tools and resources for the education system, optimizing classroom teaching [5-6], and promoting new teaching methods and educational governance, thereby realizing teaching model innovation and injecting new momentum into the education system [7-8]; but also brings opportunities for reshaping educational concepts and transforming talent cultivation methods, reshaping the talent cultivation paradigm to achieve a fundamental shift from "knowledge instillation" to "ability generation," and from "uniform cultivation" to "personalized support" [9], promoting the cultivation of new-quality talents [3-4], forming a future education form with higher quality, greater openness, and more flexibility.

Scholars have explored how digital intelligence empowers teaching management, classroom teaching reform, major construction, campus construction, and talent cultivation. However, research from a holistic perspective exploring practical pathways for Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative is still relatively scarce.This paper will construct a logical chain of "theoretical guidance—technological empowerment—practical application," guided by CBE theory, with digital intelligence as the technological enabler, to develop a collaborative upgrade path and practical research for the "Five Gold Standards" construction.

2. Meaning and Core Connotation of CBE Theory

2.1 The Meaning of CBE Theory

CBE, short for "Competency-Based Education," is an educational system and philosophy that organizes teaching around the comprehensive competencies required for occupational positions [10]. Specifically, it designs curriculum forms targeting the knowledge, skills, and attitudes needed for a specific occupation or group of occupations, starting from a comprehensive analysis of occupational role activities, based on the principle of providing the competencies required by industry and society for trainees to perform job duties. It emphasizes the dominant role of students in the learning process, with its core being how to equip learners with the practical abilities essential for engaging in a specific occupation [11]. The key to this theory lies in centering industry and job talent demands throughout the entire educational process. Its essence is an educational theoretical system that closely integrates market talent demands with cultivation models.

CBE theory is a globally recognized vocational education concept. It emerged after World War II in Western countries experiencing rapid economic and technological development, leading to a surging demand for a workforce with occupational competencies, while traditional education, detached from industry realities, failed to meet job requirements. CBE can be said to be a product of industrialized society's pursuit of efficiency and effectiveness. Since its introduction to China, CBE theory has been applied to vocational education through localization. In 1984, a monograph specifically discussing "Competency-Based Vocational Education" was published in Taiwan, China [12]. In 1995, Deng Zemin published "CBE Theory and Its Practice in China's Vocational Education," and CBE theory gradually gained practical application in educational institutions within China's vocational education. Nowadays, vocational education has a clear positioning with its unique talent cultivation orientation. Vocational education and teaching have shifted from a knowledge-based to a competency-based approach. CBE theory has become a theoretical cornerstone supporting China's vocational education field.

2.2 The Core Connotation of CBE Theory

Under the impact of globalization, the information technology revolution, and the concept of lifelong learning, CBE theory has also continued to evolve. Mainly in terms of competency cultivation, it has shifted from "job-specific skills" to "comprehensive skills" and "core competencies," with changes in the emphasis and scope of competency requirements to adapt to digital technology reforms and industrial development. However, CBE theory still maintains its core connotation, which can be systematically summarized into the following three points:

2.2.1 Supporting Personalized and Student-Centered Learning

CBE breaks away from the traditional educational philosophy based on credit hours or disciplinary knowledge, instead focusing more on achieving specific, predictable, or measurable competency objectives as the standard. In competency-based education, different students can have different course content and learning paces. It supports a student-centered educational philosophy, allowing students to learn at their own pace

[13], fostering an inclusive learning culture and a flexible, personalized, and transparent learning environment [14]. The teaching process based on CBE theory encompasses job demand analysis, quantification of competency objectives, personalized instructional design, and other stages. Consequently, it emphasizes student-centered learning more, and the teacher's role transforms from a knowledge transmitter to a learning architect.

2.2.2 Emphasizing Practical Work Skills and Real Scenarios

The starting point of CBE is a comprehensive analysis of occupational role activities, with cultivation goals centered on students acquiring the actual job competencies required for future specific occupations. This requires that "learning content equals work content." To achieve this goal, CBE typically employs the DACUM (Developing A Curriculum) course development method, following a process where excellent industry personnel, rather than solely academic experts, describe and define the competencies required for occupational positions. Teaching also emphasizes realization in authentic or simulated work scenarios. CBE focuses on achieving organized outcomes within a competency framework, using authentic teaching strategies, workplace-based assessments, and high-quality feedback [15]. The development of the teaching process is no longer merely "task decomposition," but flexibly combines with practical application through "creating authentic learning tasks" and "designing complete work processes."

2.2.3 Focusing on Quantified and Process-Oriented Assessment

CBE requires the quantification of vocational competencies, presenting course objectives as clearly measurable competency tasks and expected outcomes, emphasizing transparency in teaching implementation effectiveness assessment. Its implementation key involves competency-based quantified assessment with shared feedback from both teachers and students [16]. Simultaneously, teaching assessment focuses not only on the final competency outcomes but also values the process, providing feedback during the process for continuous teaching adjustment.

3. Trends and Challenges in Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative

Digitally empowering education involves deeply integrating digital intelligence technology into the education field, driving educational transformation through technological innovation to achieve personalized, intelligent, and efficient education. It is not merely a simple application of technology in education but a shift in educational philosophy, emphasizing student-centeredness, competency cultivation orientation, and focusing on students' personalized development and innovation capability cultivation [9]. From the top-level design for building a powerful education system at the national level to educational reform practices in various vocational colleges, Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative in vocational education is emphasized.

Many colleges are actively conducting digital intelligence exploration and practice in the "Five Gold Standards" field. In specific practices, many colleges

commonly adopt a series of reform measures, However, many challenges remain in the process of Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative: digital intelligence Initiative has not been systematically promoted, cannot be fully integrated into the overall development strategy of colleges, and lacks long-term promotion mechanisms. Training bases still lag behind real enterprise scenarios in areas such as data processing, process simulation, and digital technology application. Due to the teachers' lack of ability in integrating and applying, and because they merely regarded the digitalization of teaching resources as a task for assessment and evaluation rather than starting from the perspective of "solving actual teaching problems", they simply made the teaching resources available online and considered this as the digitalization of teaching. The online teaching resources were merely one-way transmissions for students to watch, such as "documents or videos", and failed to achieve a deep integration with the curriculum system and teaching process, effectively activating and guiding students' two-way interaction. As a result, the digital resources ended up being merely piles of materials, and students' personalized learning and ability advancement training were hindered. A normalized school-enterprise cooperation mechanism has not been formed, making it difficult to keep pace with the rapid iteration of industrial technology under the digital economy. Teachers lack motivation to improve digital literacy capabilities, merely staying at simple applications of classroom information technology. Full-process data-based assessment of teaching and student competencies has not been achieved.

4. The Practice of Digital Intelligence Empowerment of the 'Five Gold Standards' Initiative based on CBE Theory

The proposal of the "Five Gold Standards" construction is the most systematic practical embodiment of CBE theory in the vocational education field [17]. CBE theory provides the implementation goals and requirements for the "Five Gold Standards" construction, while digital intelligence empowerment is the key force enabling the realization of these goals and requirements.

4.1 Construction Core and Implementation Keys of the "Five Gold Standards"

The key to successful CBE theory implementation lies in concretizing the abstract "competency" content through rigorous analysis, setting standards, reconstructing resources, and scientific assessment, establishing specific objectives and decomposing implementation keys, implementing them in every practical aspect of vocational education, enabling precise matching between educational and industry job requirements.

Based on CBE theory, the talent cultivation objectives of vocational education need to fully embody the competency-based educational philosophy, focusing on cultivating students' occupational competencies and comprehensive qualities required by actual industry demands and jobs. This also dictates that the educational practice process needs to break through disciplinary theoretical frameworks and focus on cultivating students' comprehensive abilities for future positions. Based on the core connotations of the CBE theory, such as "supporting personalized and student-centered learning", "emphasizing practical work skills and real scenarios", and "focusing on quantified and process-oriented assessment", this paper determines the core of the

"hardware" construction and, on this basis, clarifies the key contents to be implemented. Details are shown in Table 1.

Table 1. Construction Core and Implementation Keys of the "Five Gold Standards" based on CBE Theory.

"Five Gold Standards"	Construction Core based on CBE Theory	Implementation Keys
Gold Majors	The basis for major establishment and adjustment is not disciplinary logic but the competency requirements of occupational position groups.	Dynamically identify changes in skill competencies of market occupational groups; achieve precise alignment between competency standards and job demands.
Gold Courses	Break the disciplinary system course structure; build a modular competency-based curriculum system.	Courses present observable, measurable competency performance standards and assessment methods.
Gold Teachers	The teacher's role shifts from "knowledge transmitter" to "learning guide, skills coach, and competency assessor."	Teachers themselves must deeply understand industry standards, master practical skills, and be proficient in competency-based instructional design and assessment methods.
Gold Bases	The practical teaching environment must be an authentic or highly simulated work environment.	Maximally replicate enterprise production and service scenarios.
Gold Materials	The form of teaching materials shifts from "disciplinary knowledge carriers" to guidance materials organized around typical work tasks, projects, or cases as the main thread.	Material content synchronizes with industrial technology iteration and emphasizes student-centeredness, supporting students' autonomous training and self-checking.

4.2 The Practical Pathway for Digital Intelligence Empowerment of the "Five Gold Standards" Initiative

Based on CBE theory, vocational education emphasizes the high alignment between the skills students learn and dynamic industry job requirements, and values the scientific decomposition and systematic assessment of the entire competency cultivation process. Taking Guangdong Polytechnic of Science and Trade as an example, Digital intelligence empowerment provides crucial technological support and key power for this. How to conduct digital intelligence empowerment for the "Five Gold Standards" construction is the practical pathway to unlocking the construction core and implementation keys of the "Five Gold Standards," and also the key path to achieving the transformation and upgrading of the education system.

4.2.1 Digital Intelligence Empowerment of the "Gold Major" Initiative

Majors are the foundation and soil for education system development; "Gold Majors" are the general guiding principle of the "Five Gold Standards" new infrastructure system. Building "Gold Majors" requires focusing on current industrial transformation and upgrading needs, corresponding to industry chain development trends, scientifically planning majors, and establishing a digital intelligence supply-demand matching mechanism. The core logic of major upgrading and transformation needs to shift from the internal logic of "providing skills" to the external logic of "oriented towards future industries." Specific practical measures include: (1) Phasing out outdated majors, actively conducting digital intelligence upgrades and transformations of existing traditional major (clusters), comprehensively infusing "AI+" elements. For example, a certain higher vocational college transformed its Electronic Information Engineering Technology major cluster towards the new generation of artificial intelligence technology field, with the Electronic Information major developing towards embedded AI, the Automotive Electronics major towards autonomous driving, and the Mobile Internet major towards the Internet of Everything. Some colleges gradually transform traditional majors, forming majors like Digital Trade, Smart Health

Management, Intelligent Manufacturing, Smart Logistics, Digital Culture and Tourism, etc. (2) Adding new majors or micro-majors that align with digital intelligence and help foster new quality productive forces. Oriented towards the embedded AI, Internet of Everything, digital integration, and cross-border integration trends of future industries, empower major (cluster) construction with digital intelligence and add related majors. For instance, currently, some higher vocational colleges, according to digital industry development, have added major clusters like Intelligent Manufacturing, Artificial Intelligence, etc., and majors in big data, AI technology, IoT, industrial software design, integrated circuits, intelligent connected vehicles, and other digital fields, offering micro-majors like "AI Smart Inspection for Rail Transit" and "UAV Civil Engineering Inspection." (3) Dynamically monitoring industry job changes, establishing a synchronous adjustment mechanism between major construction and industrial development job demands. Fully utilizing digital technology, collaborating with industry enterprise experts and industry research institutions, using big data analysis technology to investigate regional industrial development dynamics, enterprise talent demands, and cutting-edge technological developments, precisely identifying emerging positions, skill gaps, and talent demand changes. For example, a vocational college in Guangdong maps a "mapping diagram" of majors connecting to industries, researches and develops a "degree of fit" model for major-to-industry connections, using "degree of fit" analysis as an important basis for synchronous adjustment between major clusters and industrial development.

4.2.2 Digital Intelligence Empowerment of the "Gold Course" Initiative

Courses are the key channels for teaching implementation; "Gold Courses" are the specific carriers of the "Five Gold Standards" new infrastructure system. Vocational education courses must highlight competency-based orientation, emphasize the realization of student competencies, and undergo dynamic evaluation and adjustment. "Gold Courses" require that the curriculum system and content closely follow the cultivation objectives under the digital economy. Practical measures unfold from two dimensions: curriculum construction and classroom reform, specifically including: (1) Reconstructing the curriculum system based on changes in industrial job demands due to digital intelligence. On one hand, schools and enterprises jointly build and share course resources, update the curriculum system based on real work processes infused with digital intelligence, and innovate assessment methods. Organize school-enterprise experts to map competency profiles, incorporate enterprise typical job operation procedures into course standards, design teaching modules based on real enterprise projects, and develop new courses. Schools and enterprises jointly promote assessment method reform, with students completing enterprise projects by module, achieving measurable outcomes and competencies. On the other hand, upgrading and transforming traditional course content, adding learning content like AI applications, machine learning, and data analysis to professional courses. For example, upgrading Construction Technology to Intelligent Construction Technology; adding consumer profiling and precision marketing based on data analysis to Marketing courses; adding fintech content to Financial Product Marketing Practice. (2) Utilizing digital intelligence to innovate classroom teaching. Introducing new-generation information technologies like cloud computing, big data, IoT, VR/AR, AI, and robotics into the classroom. Implementing project-based teaching methods and information-based teaching method reforms. Establishing new teacher-student relationships, innovating

classroom evaluation methods, guiding students in autonomous learning, collaborative learning, and participatory learning. For example, an automotive engineering vocational university, supported by information technology, supplements and upgrades traditional courses, subdivides each course content into modules that can be randomly combined, develops supporting digital learning resources, and creates a modular curriculum system with intelligent, precise push capabilities.

4.2.3 Digital Intelligence Empowerment of the "Gold Teacher" Initiative

Teachers are the key executors of teaching reform; Gold Teachers are the most dynamic and core element within the "Five Gold Standards" new infrastructure system. To cope with industrial digital intelligence transformation, it is necessary to form structured teaching innovation teams proficient in both professional teaching and possessing digital literacy and interdisciplinary integration capabilities. Specific measures include: (1) Constructing hierarchical and categorized training plans for digital intelligence teaching. Develop teacher training plans at different progressive levels: literacy popularization, skill enhancement, and innovative application. While popularizing digital literacy among all professional teachers, enhance the industry-education integration capabilities of backbone teachers, and select teachers with teaching innovation potential to collaborate with enterprises on real industry project R&D, cultivating a group of teaching innovation leaders capable of solving complex project problems, adapting to the AI era, possessing innovation capabilities, and high skill levels.Utilize the training program to enhance teachers' ability in integrating teaching. Teachers fully leverage the advantages of digital capabilities, starting from the teaching problems of the courses, and utilize features such as hyperlinks, simulations, and data interaction to restructure and optimize the course content and structure. Integrate digital resources deeply with course teaching to solve the problem of digital resources becoming merely a collection of materials. (2) Constructing a school-enterprise teacher co-cultivation and sharing mechanism. Implement teacher co-cultivation, collaborate with high-quality industry enterprises to jointly formulate new standards for "dual-qualified" teachers covering professional ethics, digital literacy, technical skills, and engineering practice abilities, using these as standards for teacher recruitment, cultivation, and selection. Jointly create teacher cultivation practice bases integrating practical teaching, technological R&D, and social services with digital intelligence industry enterprises. Establish a long-term school-enterprise talent sharing mechanism, introducing excellent enterprise mentors to deeply participate in course development and practical teaching, and encouraging teachers to participate in real enterprise projects. (3) Constructing a teaching innovation-oriented evaluation and incentive system. Incorporate digital intelligence teaching achievements into teacher evaluation indicators, encourage teachers to introduce digital technology to change classroom teaching methods, and engage in innovative practices such as teaching following real industry projects under digital intelligence reforms.

4.2.4 Digital Intelligence Empowerment of the "Gold Base" Initiative

Practical teaching bases are the foundational support for educational activities; "Gold Bases" are important pillars of the "Five Gold Standards" new infrastructure system, supporting the transformation of theoretical teaching into actionable practical abilities. In practice base construction, it is necessary to closely follow changes in the AI era, providing students with the most realistic work scenario simulations to improve

practical teaching effectiveness. Match practical requirements with competency requirements in real work scenarios to better quantify teaching outcomes. Specific measures include: (1) Creating on-campus digital intelligence practical teaching bases and industry-education integration training bases. Vigorously construct virtual simulation training centers and digital twin factories synchronized with industrial scenes. Collaborate with leading enterprises and industry frontrunners to build a number of high-level industry-education integration training bases that share resources, integrating practical teaching, real enterprise production, social technical services, etc. For example, a higher vocational college in Guangdong, relying on communication technology, computer network technology, and IoT technology, cooperated with companies like Huawei, Red Hat, and 360 to build on-campus and off-campus practical teaching bases, developing a series of productive practical projects. (2) Promoting school-enterprise joint construction of digital intelligence platforms and applied technology innovation centers to facilitate data interoperability and resource sharing. Timely update software and hardware facilities and equipment in industry-education integration bases, achieving seamless connection between teaching/training bases, internship bases, practice bases, and enterprise talent and technical requirements. (3) Establishing a normalized innovation mechanism for school-enterprise cooperation. Explore sustainable development mechanisms for school-enterprise joint construction and sharing, innovating cooperation methods, operational models, and cost-sharing mechanisms. For example, a higher vocational college, through joint school-enterprise establishment of R&D centers, forms a "risk-sharing, benefit-sharing" technology consortium to conduct technological output.

4.2.5 Digital Intelligence Empowerment of the "Gold Material" Initiative

Teaching materials are the knowledge carriers for teaching implementation; "Gold Materials" are important media within the "Five Gold Standards" new infrastructure system. The comprehensive vocational competencies under the digital economy should be embedded into material content, and new-form materials should be actively developed. Specific measures include: (1) Conducting "AI+" upgrades and transformations of material content. AI represents a profound transformation in the work paradigm for all, encompassing guiding principles, working methods, core competencies, and work habits that reach consensus, not just technological upgrades. This requires that when integrating digital technology and AI into material content, it's not merely about adding technical content, but should focus on enhancing students' future adaptability through projects simulating real scenarios. Collaborate with enterprises to incorporate new technologies, processes, and standards into corresponding courses. Systematically process real work processes and their digital intelligence transformation, incorporating dimensions like data thinking and intelligent tool application. Through induction and generalization, extract typical work tasks and key skill points suitable for human-machine collaboration and data-driven environments, ensuring these are representative, operable, and reflect the impact and reshaping of work processes, job competencies, and decision-making methods by digital intelligence technology. (2) Developing digital materials, loose-leaf materials, work manual-style materials, and other diverse formats. Based on professional digital resources, develop vivid, interactive digital materials, and compile loose-leaf or work manual-style materials tailored to vocational education characteristics. Digital materials can fully embody intelligent evaluation, intelligent learning guidance, and intelligent

learning assistance, support open structures and dynamic resource updates, and adapt to students' online and blended learning. Loose-leaf and work manual-style materials can highlight task authenticity, free combinability, and dynamic updates.

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Study on the Factors Affecting the Teaching Effectiveness of Integrating the Great Anti-Epidemic Spirit into University Ideological and Political Courses Based on the SEM Model

Chunhui ZHANG[1]
Department of Marxism, Wuhan University of Science and Technology, China

Abstract. To explore the influencing factors and mechanisms of integrating the great anti-epidemic spirit into ideological and political education in universities, this study clarifies the differentiated impact paths of six major factors—campus cultural environment, education subjects and resources, curriculum and textbook system, educational processes, technologies, tools, social context, and regional differences—on students' cognition, emotions, and behavioral intentions. A questionnaire survey was conducted among 612 college students from six universities in Hubei Province, and empirical analysis was performed using structural equation modeling (SEM). The results indicate that the model fits well, and most of the research hypotheses are supported. Among them, the campus cultural environment has a significant positive impact on the three dimensions of students' cognition, emotion, and behavioral intention, with the strongest effect on behavioral intention. Education subjects and resources have a notable influence on students' cognition and emotions but are insufficient in transforming behavioral intentions; Educational technologies and tools consequentially impact on students' emotions and behaviors, but lack of cognition; Curriculum and textbook system, social and regional factors, and educational processes have a stable influence on students. The six major factors are significantly correlated, forming an interconnected ecosystem. Therefore, educational institutions need to strengthen the transformation of knowledge into action, deepen the integration of technology and content, and build a multi-factor collaborative network to enhance the effectiveness of talent cultivation systematically.

Keywords. Great Anti-Epidemic Spirit, College Ideological and Political Courses, Behavioral Intentions, Emotional Cognition, SEM Model

1. Introduction

The great anti-epidemic spirit is a precious spiritual asset of the Chinese nation's battle against the epidemic, embodying the most vivid and resilient elements of education in the modern era, and serving as a rich source of ideological and cultural nourishment for students' growth and development1. Ideological and political education is a key link in

[1] *Corresponding author: 369181868@qq.com*

implementing the fundamental task of fostering virtue through education. Incorporating the great anti-epidemic spirit into ideological and political education for university students can not only realize its educational value but also shape students' character, correct their conduct, and enhance their taste. This process of integration helps universities promote the main theme, spread positive energy, and thereby highlights the role of ideological and political theory courses as the principal platform and main channel for cultivating virtue and nurturing a new generation of the era. Meanwhile, it guides university students to establish correct views of the world, life, and values, while continuing the legacy of the national spirit.

Currently, academia, while elaborating on the spiritual connotation, characteristic forms, generative logic, contemporary value, and promotion methods of the great anti-epidemic spirit, has gradually begun to attach importance to its integration into ideological and political courses in universities. Therefore, academia has achieved research results in four aspects—synergistic integration, contextual integration, holistic integration, and three-dimensional integration—following the line of thinking of 'why integrate, what to integrate, and how to integrate'. However, quantitative research on the influencing factors and mechanisms of integration effectiveness remains insufficient [1]. Integrating the spirit of anti-epidemic into ideological and political education in universities is a complex systematic project, and its effectiveness is not determined by a single variable. These factors together form the 'resources—process—objectives' adaptation chain, profoundly influencing the actual pattern and effectiveness level of integration work. To advance the theoretical understanding beyond existing frameworks, this study introduces educational ecology theory and the integrated model of ‘knowledge, emotion, will, and practice’, constructing a multi-factor interaction framework that reveals the non-linear, systemic linkage mechanisms among influencing factors, thereby moving beyond single-dimensional or linear analyses [2].To put it into a nutshell, this study aims to empirically investigate the specific impact pathways of six major factors—campus cultural environment, educational subjects and resources, curriculum and textbook system, educational processes and methods, educational technologies and tools, and social and regional factors—on students' cognition, emotions, and behavioral intentions, and to reveal the network of interactions among each factors. By using SPSS and AMOS software to test, analyze, and revise questionnaires and models, data support and practical references are provided to enhance the effectiveness of ideological and political courses in educating students.

2. Research Hypothesis

Based on the theory of educational ecology and the framework of factors influencing curriculum implementation, this study categorizes the influencing factors into six major aspects: campus cultural environment (CCE), educational subjects and resources (ESR), curriculum system (CS), educational processes and methods (EPM), educational technology and tools (ETT), social resources and locational field factors (SR-LFF). Drawing on educational ecology theory, the ideological and political education system is conceptualized as an organic whole comprising micro- (teaching subjects, curriculum), meso- (campus culture, technological tools), and macro- (social-regional environment) elements. Following the ‘knowledge-emotion-will-practice’ model, the integration effects are divided into cognitive understanding (CU), emotional identification (EI), and behavioral intention (BI). The six factors were selected based on: (1) the curriculum

implementation framework; (2) educational ecology theory; and (3) a systematic review of existing studies. A limitation is that this study focuses on structural factors within the educational system, excluding students' individual psychological traits (e.g., cognitive style, personality) or family background (e.g., parental education concepts), which could be explored in future research. Moreover, all indicators are centered on the educational process and outcomes, without items related to 'political bias' in the measurement.The campus cultural environment (CCE) constitutes the deep soil for integrating the great anti-epidemic spirit. Through the guidance of values, behavioral habits, and the atmosphere of activities, it subtly influences teachers' and students' recognition of and willingness to participate in the spirit of epidemic prevention. Educational subjects and resources (ESR) determine the professional ability for spiritual transformation. The disciplinary background, practical experience, and teaching competence of educational subjects directly influence the depth of interpretation and the effectiveness of transmitting the anti-epidemic spirit. Curriculum system (CS) is the main channel for integrating spirit; Systematic curriculum design can prevent the fragmentation of the integration process. Blended teaching and practice-driven approaches enhance students' sense of experience. The educational process and methods (EPM) are dynamic executing elements for integrating the spirit of epidemic prevention, referring to a comprehensive operational system for the design, promotion, regulation, and optimization of ideological and political education, and serve as a key hub for achieving educational objectives. Educational tools and technologies (ETT) are empowering engines that transcend the limitations of time and space. Social resources and locational factors provide external support and contextual materials for the integration of the spirit. Therefore, six types of factors jointly shape the ultimate effectiveness of integrating the great anti-epidemic spirit into ideological and political education through the collaborative path of 'condition support—process implementation—effectiveness transformation.' In summary, this study proposes the following research hypotheses:

H1a-H1c: CCE has a significant positive impact on students' CU, EI, and BI.

H2a-H2c: ESR has a significant positive impact on students' CU, EI, and BI.

H3a-H3c: CS has a significant positive impact on students' CU, EI, and BI.

H4a-H4c: EPM has a significant positive impact on students' CU, EI, and BI.

H5a-H5c: ETT has a significant positive impact on students' CU, EI, and BI.

H6a-H6c: SR-LFF has a significant positive impact on students' CU, EI, and BI.

The six major influencing factors of the great anti-epidemic spirit integrated into ideological and political education in colleges and universities form an interconnected ecosystem. These factors have bidirectional or multidirectional influence paths, collectively shaping the overall pattern of the integration process. Based on this, this paper proposes the following research hypotheses:

H7a-H7e: CCE interacts with ESR, CS, EPM, ETT, and SR-LFF.

H8a-H8d: ESR interacts with CS, EPM, ETT, and SR-LFF.

H9a-H9c: CS interacts with EPM, ETT, and SR-LFF.

H10a-H10b: EPM interacts with ETT and SR-LFF

H11: There is an interaction between ETT and SR-LFF

3. Research Design and Data Collection

3.1. Data Source

The data for this study were obtained from a survey of university students in Hubei Province. This study employed stratified random sampling to select students from six universities in Hubei Province (covering "Double First-Class" universities, provincial key universities, local undergraduate colleges, and vocational colleges)—namely Wuhan University (WHU), Huazhong University of Science and Technology (HUST), Central China Normal University (CCNU), Wuhan University of Science and Technology (WUST), Hubei University of Chinese Medicine (HBUCM), and Wuhan Railway Vocational and Technical College (WRVT)—as the research subjects. The questionnaire encompassed four parts: the subjects' main characteristics, participation in the model, integration outcomes, and influencing factors, aiming to statistically analyze and evaluate the effectiveness of incorporating the great anti-pandemic spirit into ideological and political courses in various universities. A total of 625 questionnaires were distributed for the survey, and 612 valid questionnaires were collected.

3.2. Research Methods

This study used a 5-point Likert scale for scoring and employed SPSS 27.0 software for descriptive statistical analysis. Factor analysis was conducted using the principal component analysis method and varimax rotation. AMOS 25.0 software was used to construct a structural equation model of the factors influencing the integration of the great anti-epidemic spirit into ideological and political education, with parameters estimated using the maximum likelihood method. The convergent validity (AVE) and composite reliability (CR) were calculated to test the robustness and reliability of the measurement model, and indices such as the root mean square error of approximation (RMSEA) and normed fit index (NFI) were referenced to assess the overall fit of the structural equation model.To control for common method bias, the following measures were implemented during questionnaire design: (1) anonymous completion to reduce social desirability responses; (2) random ordering of items to avoid habitual answering; (3) reverse-scored items for some questions to enhance attention checks. In the data analysis stage, Harman’s single-factor test was applied; the unrotated exploratory factor analysis showed that the first factor accounted for 28.7% of the variance, below the 40% threshold, indicating that common method bias does not pose a serious threat. Additionally, this study acknowledges the inherent limitations of self-reported data—students’ self-assessments may differ from actual behavioral performance. Future research could incorporate multi-source data such as instructor evaluations, classroom observations, and behavioral records to enhance objectivity [3].

3.3. Measurement Indicator System

This study selects representative measurable indicators as observed variables and comprehensively applies exploratory factor analysis and confirmatory factor analysis to extract the key influencing factors of integrating the great spirit of pandemic resistance into ideological and political course teaching in colleges and universities as latent variables (see Table 1).

Table 1. Measurement Indicator System

Variable	Indicators	Item (Abbreviated)	No.
Participation	Frequency	Participation frequency in anti-epidemic educational activities	B1
Integration Effect	CU	Understanding of anti-epidemic spirit connotation (C1), CPC leadership advantages (C2), scientific knowledge (C3)	C1–C3
	EI	Pride in nation (C4), moved by heroic deeds (C5), emotional resonance with people-first concept (C6)	C4–C6
	BI	Willingness to take responsibility (C7), public compliance (C8), aspiration to contribute (C9)	C7–C9
CCE	—	Campus atmosphere, periodic activities (e.g., Anti-Pandemic Spirit Month), student works display	D1–D3
ESR	—	Frontline workers sharing, practice base visits, accessible learning resources, teacher research integration	E1–E4
CS	—	Systematic integration into courses, updated materials, professional adaptability, practical assessment tasks	F1–F4
EPM	—	Interactive methods, reflection-oriented activities, focus on ordinary people's contributions, cross-country comparisons	G1–G4
ETT	—	Online platforms, new media promotion, personalized content via big data, VR/AR simulation projects	I1–I4
SR-LFF	—	Personal experience of local measures, commemorative activities, community practice networks, iconic local spaces	J1–J4

Note: CCE = Campus Cultural Environment; ESR = Educational Subjects and Resources; CS = Curriculum System; EPM = Educational Processes and Methods; ETT = Educational Technology and Tools; SR-LFF = Social Resources and Locational Field Factors; CU = Cognitive Understanding; EI = Emotional Identification; BI = Behavioral Intention.

4. Data Analysis and Hypothesis Testing

4.1. Demographic Characteristics of the Survey Population

Regarding the composition of the 612 survey respondents' institutions, participation across the six universities was relatively consistent. In terms of major distribution, 20.1% of the respondents were in humanities, 23.9% in social sciences, 35.5% in science and engineering, 20.3% in medicine, and 0.3% in other majors, ensuring the representativeness of the sample. In terms of grade distribution, respondents were from

freshman to senior years, accounting for 29.2%, 24.3%, 24.3%, and 22.1%, respectively. Regarding gender composition, 56% were male and 44% were female. There were significant differences in political affiliation, with only 13.7% being party members and 24.7% being general members. In terms of experience as class officers, only 18% of respondents had served as student leaders, whereas 82% had not. Respondents who had participated in relevant volunteer activities accounted for 45.9%, while those who had not accounted for 54.1%. Details are provided in Table 2.

Table 2. Survey Demographic Analysis

Variable	Item	Count	Percentage
School	HBUCM	102	16.7
	HUST	101	16.5
	WRVT	102	16.7
	CCNU	102	16.7
	WHU	103	16.8
	WUST	102	16.7
Major	Humanities	123	20.1
	Social Science	146	23.9
	Science and Technology	217	35.5
	Medicine	124	20.3
	Other	2	0.3
Grade	Freshman	179	29.2
	Sophomore	149	24.3
	Junior	149	24.3
	Senior	135	22.1
Gender	Male	343	56.0
	Female	269	44.0
Political Affiliation	CPC Member (including Probationary Members)	84	13.7
	CYL member	345	56.4
	Public	151	24.7
	non-CPC parties	32	5.2
Whether serving as a student leader	Yes	110	18.0
	No	502	82.0
Whether to participate in anti-epidemic volunteer services	Yes	281	45.9
	No	331	54.1

4.2. Reliability and validity analysis

This paper uses Cronbach's Alpha coefficient to analyze the consistency of the data. Cronbach's Alpha coefficients for the two dimensions of influencing factors and integration effect are 0.900 and 0.826, respectively, both higher than 0.7. It indicates that the scale has good internal consistency and high reliability. Validity analysis shows that the KMO test coefficient is 0.895, the approximate chi-square value of the Bartlett's sphericity test statistic is 10610.081, the degrees of freedom are 496, and the significance is 0.000, which is below the 0.001 significance level. This indicates that the test results meet the basic requirements of factor analysis. Using principal component analysis to extract factors with eigenvalues greater than 1, it was found that the cumulative variance explained reached 74.529%, indicating that the questionnaire has good structural validity. In terms of convergent validity, the average variance extracted (AVE) for each latent variable ranged from 0.604 to 0.691, and the composite reliability (CR) ranged from

0.821 to 0.888. Regarding discriminant validity, the square root of the AVE for each latent variable was greater than the correlation coefficient between those variable and other latent variables, indicating that the constructs have good discriminant validity.

4.3. Model Fit Evaluation and Path Coefficient Analysis

4.3.1. Model Fit Evaluation

This study selected seven key model fit indicators recognized by the academic community: Chi-square degrees of freedom ratio (CMIN/DF), Root Mean Square Error of Approximation (RMSEA), Goodness of Fit Index (GFI), Adjusted Goodness of Fit Index (AGFI), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Standardized Root Mean Square Residual (SRMR). Using the criteria of 'good range' and 'acceptable range,' the model fit was analyzed, and the results are shown in Table 3 below:

Table 3. Model Fit Indices

Model Indicator	Criteria	Result	Fitting Solution
CMIN/DF	Good Range: 1-3 Acceptable Range: 1-3	1.364	Fitting Well
RMSEA	Good Range: <0.05 Acceptable Range: <0.08	0.024	Fitting Well
GFI	Good Range: >0.90 Acceptable Range: >0.85	0.944	Fitting Well
AGFI	Good Range: >0.90 Acceptable Range: >0.85	0.932	Fitting Well
CFI	Good Range: >0.90 Acceptable Range: >0.85	0.985	Fitting Well
TLI	Good Range: >0.90 Acceptable Range: >0.85	0.985	Fitting Well
SRMR	Good Range: <0.05 Acceptable Range: <0.08	0.029	Fitting Well

The results indicate that all fit indices meet or exceed the commonly accepted academic criteria. CMIN/DF is 1.364, RMSEA is 0.024, GFI is 0.944, AGFI is 0.932, CFI is 0.985, TLI is 0.985, and SRMR is 0.029, all falling within the acceptable range, indicating that the structural equation model constructed in this study fits the sample data well, thereby providing a solid foundation for subsequent path coefficient analysis and hypothesis testing.

4.3.2. Path Coefficient Analysis

Analyzing the path coefficients of the structural equation model, all 33 research hypotheses in the model are significant at a significance level of less than 0.001, indicating that all 33 hypotheses are supported. At the same time, the regression coefficients of all 33 paths are positive, indicating that the six major factors have a positive impact on the cognitive dimension (CU), the emotional dimension (EI), and the behavioral intention dimension (BI), and the six major influencing factors also have a positive impact on each other. From the perspective of the magnitude of standardized coefficients, in the cognitive and emotional dimensions, the path coefficients from educational subjects and resources to them are the largest, at 0.196 and 0.185, respectively. In terms of behavioral intention, the campus cultural environment has the

largest path coefficient to it, at 0.193. The standardized path coefficients of this model are shown in Figure 1 and Table 4.

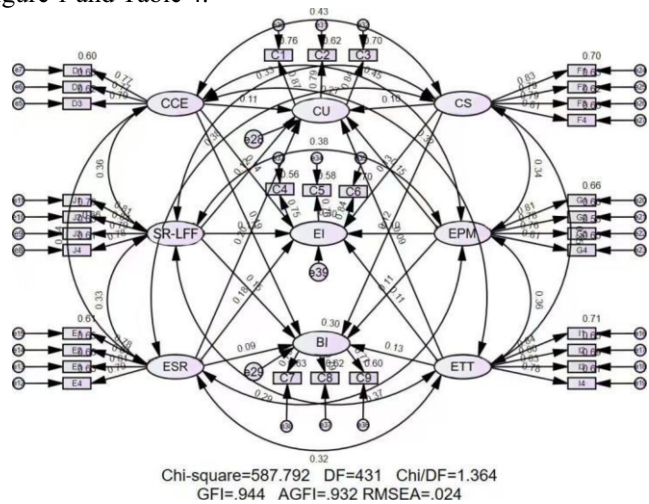


Figure 1. Path Coefficient Circle Chart

Table 4. SEM Path Coefficient Evaluation

Path Relationship	Standardized Coefficient	Unstandardized Coefficient	S.E.	C.R.	P	H(A)	Result
CCE→CU	0.113	0.124	0.06	2.069	0.039	H1a	Reject H0
CCE→EI	0.142	0.139	0.054	2.546	0.011	H1b	Reject H0
CCE→BI	0.193	0.188	0.055	3.426	***	H1c	Reject H0
ESR→CU	0.196	0.22	0.055	4.013	***	H2a	Reject H0
ESR→EI	0.185	0.184	0.05	3.685	***	H2b	Reject H0
ESR→BI	0.088	0.087	0.049	1.767	0.077	H2c	Reject H2c
CS→CU	0.103	0.107	0.052	2.045	0.041	H3a	Reject H0
CS→EI	0.132	0.121	0.047	2.561	0.01	H3b	Reject H0
CS→BI	0.121	0.111	0.047	2.342	0.019	H3c	Reject H0
EPM→CU	0.146	0.154	0.055	2.805	0.005	H4a	Reject H0
EPM→EI	0.105	0.098	0.05	1.979	0.048	H4b	Reject H0
EPM→BI	0.113	0.105	0.05	2.113	0.035	H4c	Reject H0
ETT→CU	0.085	0.083	0.046	1.817	0.069	H5a	Reject H5a
ETT→EI	0.108	0.093	0.041	2.248	0.025	H5b	Reject H0
ETT→BI	0.132	0.113	0.041	2.729	0.006	H5c	Reject H0
SR-LFF→CU	0.119	0.132	0.053	2.495	0.013	H6a	Reject H0
SR-LFF→EI	0.132	0.131	0.048	2.705	0.007	H6b	Reject H0
SR-LFF→BI	0.15	0.147	0.049	3.039	0.002	H6c	Reject H0
CCE ↔ ESR	0.336	0.295	0.046	6.453	***	H7a	Reject H0
CCE ↔ CS	0.433	0.411	0.051	8.028	***	H7b	Reject H0
CCE ↔ EPM	0.455	0.423	0.051	8.239	***	H7c	Reject H0
CCE ↔ ETT	0.318	0.323	0.052	6.244	***	H7d	Reject H0
CCE ↔ SR-LFF	0.358	0.317	0.046	6.845	***	H7e	Reject H0
ESR ↔ CS	0.382	0.357	0.047	7.531	***	H8a	Reject H0
ESR ↔ EPM	0.367	0.336	0.047	7.206	***	H8b	Reject H0
ESR ↔ ETT	0.323	0.321	0.049	6.55	***	H8c	Reject H0
ESR ↔ SR-LFF	0.325	0.283	0.043	6.556	***	H8d	Reject H0

CS ↔ EPM	0.344	0.34	0.049	6.87	***	H9a	Reject H0
CS ↔ETT	0.352	0.379	0.053	7.134	***	H9b	Reject H0
CS ↔ SR-LFF	0.333	0.313	0.046	6.749	***	H9c	Reject H0
EPM ↔ ETT	0.361	0.381	0.053	7.21	***	H10a	Reject H0
EPM↔ SR-LFF	0.381	0.352	0.047	7.508	***	H10b	Reject H0
ETT ↔ SR-LFF	0.292	0.293	0.049	6.034	***	H11	Reject H0

Note：H(A) stands for corresponding alternative hypothesis provided in Section 2
H0 stands for no effect exists in the population (Default Situation)
***** represents for P<0.001**

4.4. Model Result Analysis

The results of the structural equation modeling test indicate that the model fits well (CMIN/DF = 1.364, RMSEA = 0.024, CFI = 0.985, and other indicators all meet excellent standards). Of the 33 research hypotheses, 31 are supported, while only 2 do not pass the significance test. The six major influencing factors exhibit differentiated impact pathways on the three dimensions of students' cognition, emotion, and behavioral intention. The campus cultural environment (CCE) has a significant positive impact on all three dimensions, with the strongest effect on the behavioral intention dimension (β=0.193, $p<0.001$); The educational subjects and resources (ESR) have significant effects on the cognitive (β=0.196, $p<0.001$) and emotional dimensions (β=0.185, $p<0.001$), but their effect on behavioral intention did not pass the test (β=0.088, $p=0.077$).This result can be explained by the 'knowledge-emotion-will-practice' transformation theory: the transition from knowledge acquisition (cognition) and emotional identification (emotion) to behavioral intention (will) does not occur automatically but requires practical situations as an intermediary bridge. Educational subjects and resources primarily affect the first two stages; without supporting practical platforms, the formation of behavioral intention is hindered. This interpretation is supported by the survey finding that 54.1% of students had not participated in anti-epidemic volunteer services. This result indicates that although factors such as teacher quality and teaching team collaboration can effectively convey knowledge and stimulate emotions, their direct translation into action depends on intermediary conditions such as practical platforms. The curriculum system (CS) and educational process methods (EPM) show a consistently positive impact across all three dimensions (path coefficients ranging from 0.103 to 0.146, $p<0.05$), confirming that systematic content design and scientific teaching implementation are the main channels for spiritual integration; Educational technology and tools (ETT) have significant effects on the emotional (β=0.108, $p<0.05$) and behavioral intention (β=0.132, $p<0.01$) dimensions, but their impact on the cognitive dimension is not significant (β=0.085, $p=0.069$). This non-significant finding can be interpreted using media richness theory and cognitive load theory: while multimedia technologies and virtual simulations provide rich emotional experiences, they may increase students' cognitive load, diverting attention from core theoretical concepts. A 'heavy on form, light on content' application of technology fails to facilitate deep processing and systematic construction of abstract theoretical knowledge. This suggests that technology must be deeply integrated with teacher guidance and reflective design to effectively enhance cognitive understanding. This may be because technological tools are adept at creating emotional scenarios, yet the deepening of theoretical understanding still requires the guidance of teachers; Social

resources and contextual factors (SR-LFF) exhibit a comprehensive influence (path coefficients range from 0.119 to 0.150, $p<0.05$), and the regional resources from the primary front of epidemic prevention provide rich materials for ideological and political education.

The hypothesized interactions between the six major influencing factors (H7a-H11) were all validated ($p<0.001$), indicating that they form a closely interconnected ecosystem. The campus cultural environment (CCE), serving as a linking hub, shows strong correlations with all other factors (correlation coefficients 0.318-0.455). The symbiotic relationships between elements such as educational subjects (ESR) and curriculum system (CS) ($\beta=0.382$), as well as educational processes and technological tools (EPM & ETT) ($\beta=0.361$), highlight the importance of multi-factor synergistic resonance. The two hypotheses that failed the test (H2c, H5a) reflect the shortcomings of current practice. H2c (ESR → BI) was rejected, suggesting that high-quality teaching resources need to be coordinated with mechanisms for behavioral transformation. For example, the survey shows that 54.63% of students have never participated in volunteer services for epidemic prevention, indicating that the absence of practical platforms may hinder the formation of behavioral intentions. H5a (ETT → CU) was rejected, warning that the application of technology should avoid being 'heavy on form and light on content,' and emphasizing the need to strengthen the deep integration of technology and theoretical instruction.

This study's sample was drawn exclusively from universities in Hubei Province, the main battlefield of China's epidemic response—a regional context that offers a distinct advantage rather than a limitation. Students experienced the pandemic firsthand and participated in local prevention efforts, providing an insider perspective and deep emotional connection to the anti-epidemic spirit. This high-salience setting allows the study to capture integration effects in a uniquely meaningful context. Findings are thus especially informative for regions with similar experiences, while future research may extend the model to areas with varying epidemic impact or conduct cross-regional comparisons to explore macro-contextual moderators. Additionally, this study employs a cross-sectional design, meaning all variables were measured at a single time point; therefore, the path coefficients reflect correlations and theoretically hypothesized directionality rather than strict causality. Future research may adopt longitudinal or quasi-experimental designs to further examine causal directions and dynamic mechanisms.

5. Suggestion and Recommendation

First, embed practical components to strengthen knowledge-action transformation. Incorporate volunteer service and social practice into compulsory ideological and political courses (e.g., 8–16 credit hours), establishing a linked platform of on-campus theory and off-campus practice. Collaborate with communities, hospitals, and enterprises to build educational bases where students engage in pandemic prevention publicity and community service, facilitating the transition from cognitive recognition to habitual behavior. Verification: Conduct a quasi-experimental study in two comparable universities—one implementing the theory-plus-practice model and the other maintaining theory-only teaching—to compare changes in behavioral intention through pre- and post-tests.

Second, deepen the integration of technology and content to enhance cognitive impact. Address the insignificant effect of educational technologies and tools (ETT) on cognition by strengthening deep integration with theoretical teaching, avoiding superficial application [4]. Use virtual simulations to recreate epidemic scenarios and enhance emotional experience, paired with teacher-led explanation and guided reflection; leverage big data to personalize content while ensuring depth. Verification: Conduct teaching action research in a small class, collecting pre- and post-test cognitive scores combined with in-depth interviews to evaluate technology-content integration effectiveness.

Third, build a collaborative network to enable positive interaction among elements. Systematically examine factor compatibility, strengthen top-level design, and establish a three-level responsibility system (university—department—instructor) covering curriculum, materials, management, and evaluation. Promote linkage between campus culture and curriculum, facilitate collaboration between professional faculty and ideological educators, and integrate internal and external resources to form synergistic educational forces, transforming the anti-epidemic spirit into a rich resource for moral education [5].Verification: Develop a Quality Monitoring Indicator System for Collaborative Education, collecting process indicators (e.g., campus cultural activity participation, cross-department projects, student practice rates, teaching evaluations) each semester to continuously assess operational efficiency.

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