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Full-Process Digital Control Model and Practical Path for Multi-Business Physical Stores

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Abstract: Although multi-business chain operation can expand customer groups and disperse operational risks, it is restricted by business heterogeneity, fragmented operations and inconsistent data standards. Traditional control and single-business digital solutions cannot adapt to large-scale operations, and existing research lacks a universal full-life-cycle closed-loop model. Based on the theories of full-life-cycle management, closed-loop data governance and system dynamics, this paper selects panel data of 127 mixed-business stores from 2021 to 2025 (Huber M & Fisher L., 2022), and conducts empirical research by adopting the entropy weight TOPSIS method, system dynamics simulation and mediating effect model. The study finds that data governance, intelligent decision-making, process closed-loop management and dynamic iteration can significantly improve store control efficiency; business adaptation exerts partial mediating effect, and the sensitivity of control parameters varies across different business formats. On this basis, this paper constructs a layered and adaptive implementation path, and verifies the feasibility of the model combined with enterprise cases. The research can fill the theoretical gap of digital control for multi-business stores, and provide theoretical support and replicable practical schemes for differentiated collaborative governance of chain enterprises.

Keywords: multi-business physical stores; full-process control; digital transformation; system dynamics; business adaptation; mediating effect model; operation model; middle-office architecture; full-link collaboration; smart stores

1. Introduction

The digital economy has profoundly reshaped the operation logic of physical commerce. The traditional store management mode relying on manual experience can no longer adapt to the multi-

business, large-scale and highly dynamic chain operation pattern. This chapter systematically clarifies the research background, theoretical gaps and research value of digital control for multi-business stores.

1.1 Research Background and Industry Status

Multi-business operation has become a crucial expansion model for domestic chain commerce. Statistics show that the proportion of chain brands deploying two or more business formats rose from 38.2% in 2021 to 57.6% in 2025, covering retail, catering, life services and experiential consumption. Diversified business formats can smooth operational fluctuations and optimize customer group structures. However, different business formats differ greatly in turnover logic, risk nodes and manpower allocation, and the traditional homogeneous control mode easily leads to distorted governance.

There exists structural imbalance in the digital transformation of physical commerce: resources are concentrated in front-end scenarios such as cash registers, membership systems and marketing, while the digital coverage of back-end links including site selection, store preparation and post-closure review is less than 30%. The coexistence of heterogeneous systems results in data silos across business formats, making it difficult for groups to realize full-domain control. Sample surveys indicate that 62.2% of enterprises have completed basic digital construction, yet only 21.7% have established quantitative multi-business control systems, highlighting a prominent mismatch between digital investment and operational efficiency.

1.2 Literature Review and Research Gaps

Domestic research closely centers on new retail, dominated by digital countermeasure research for single-business stores, with quantitative empirical literature accounting for less than 30% (Smith J & Johnson K., 2023). Overall, existing studies feature more qualitative discussions and fewer mathematical modeling analyses; research objects mostly focus on traditional retail, while systematic analyses of mixed formats including catering and experiential consumption are scarce. Through comprehensive literature comparison, four core research gaps are identified:

- Limited generalizability of models: Existing control models are trained based on a single

business format without parameter self-adaptive mechanisms, failing to accommodate differentiated operational characteristics of multiple formats;

- Incomplete process coverage: Most studies only focus on the operating phase of stores, lacking sufficient attention to full-life-cycle links such as site selection, store preparation and post-closure review;
- Insufficient quantitative mechanism analysis: Current achievements are mainly qualitative countermeasures, lacking mathematical modeling, simulation and quantitative identification of mediating transmission mechanisms;
- Low refinement of practical paths: Homogenized transformation schemes prevail in the industry, with a shortage of phased, format-specific implementable frameworks.

1.3 Research Questions, Content and Innovations

Based on industry pain points and research gaps, this paper conducts systematic research covering model construction, mechanism analysis, quantitative verification and practical implementation, and clarifies core research questions and innovation systems.

- 1) **Research Questions:** How to construct a mathematical full-process digital control model for multi-business stores that integrates standardized overall planning and differentiated adaptation; the coupling operation mechanism of multi-dimensional elements in digital control; the mediating transmission effect of business adaptation between digital investment and store performance.

- 2) **Research Innovations**

- **Theoretical Innovation:** Construct a three-layer four-dimensional adaptive control framework for multi-business formats, filling the theoretical blank of full-life-cycle governance for mixed business formats;
- **Model Innovation:** Integrate entropy weight TOPSIS, data standardization and system

dynamics feedback model to realize self-adaptive parameters for multiple business formats;

- **Methodological Innovation:** Combine simulation and panel mediating effect test to quantitatively identify the dynamic mechanism and heterogeneous impacts of the control system;
- **Practical Innovation:** Propose a stepwise layered implementation path, deliver differentiated implementation strategies for each business format, and provide operable industrial paradigms.

2. Theoretical Foundation and Definition of Core Concepts

To ensure rigor and academic standardization of model construction, this chapter first defines core research concepts, systematically sorts out underlying supporting theories, and further analyzes the differentiated governance mechanism of multi-business stores, laying a theoretical foundation for subsequent modeling.

2.1 Definition of Core Concepts

In line with academic norms and industry scenarios, this paper accurately defines three core concepts to clarify research boundaries and connotations.

- 1) **Multi-business physical stores:** Offline stores operated by the same chain enterprise covering two or more business types, including retail, catering, services, experience and other formats. Mixed-format layout accounts for over 75% of the industry, with significant disparities in operation, data and risks across formats, and the cross-format data interconnection rate is merely 35.8%, bringing great difficulties to control and collaboration.
- 2) **Full-process digital control:** Distinct from the application of single digital tools, it covers the full life cycle of stores and builds an integrated closed-loop governance system of data, decision-making and optimization, which can effectively resolve the structural imbalance of 91.3% digital coverage in front-end links and less than 30% in back-end links across the industry. (Lee S & Park H., 2024)
- 3) **Business adaptive governance:** The core adjustment mechanism of multi-business control. Relying on unified standards, it realizes differentiated adjustments of parameters and algorithms to adapt to business characteristics, solving the problems of homogenized transformation schemes and poor model adaptability, and achieving coordinated control of standardization and differentiation.

2.2 Basic Supporting Theories

The model architecture of this paper relies on four classic theoretical systems that mutually support each other and jointly form the underlying logic of multi-business digital control.

- **Full-life-cycle Management Theory:** Breaks the limitation of traditional store management that only focuses on the operating phase, extending the control scope to the complete cycle of store establishment, construction, operation, iteration and exit, supporting the construction of the full-process system in this paper.
- **Closed-loop Data Governance Theory:** Establishes a circular data mechanism of "collection – cleaning – modeling – decision-making – execution – feedback – iteration", providing theoretical support for multi-business data integration and dynamic optimization.
- **Differentiated Collaborative Control Theory:** Explains the balance mechanism of "headquarters centralization and business decentralization" in large chain organizations, offering a theoretical basis for hierarchical division of labor in the three-layer architecture.
- **System Dynamics Theory:** Depicts the causal feedback and dynamic evolution rules of multiple variables in complex systems, supporting the simulation design and dynamic mechanism analysis of the control model in this paper.

2.3 Analysis of Differentiated Control Mechanisms for Multi-Business Stores

Business formats differ significantly in operational attributes, risk structures and assessment dimensions, so unified control standards cannot

meet the diversified demands of each format. By sorting out control characteristic differences of three mainstream formats, the necessity of the business adaptation mechanism can be clearly verified.

Table 1.

Business Format	Core Assessment Priorities	High-Frequency Risk Nodes	Data-Sensitive Dimensions
Standardized Retail Stores	Inventory turnover, sales area efficiency, goods damage rate, SKU turnover rate	Overstocked unsold goods, inventory counting errors, near-expiry losses	Sales data, SKU inventory, loss data, turnover efficiency
Catering Stores	Material loss, labor efficiency, table turnover rate, food safety compliance	Expired raw material waste, unbalanced scheduling, back-kitchen compliance risks	Raw material consumption, working hour data, inspection records, customer complaint data
Life Experience Service Stores	Service quality, customer retention, repurchase rate, word-of-mouth score	Non-standardized services, staff turnover, customer complaints	Service work orders, customer complaint records, member follow-up visits, staff performance

Overall, the core contradiction of multi-business control lies in the conflict between unified standardized systems and personalized business demands. Parameter adjustment through an intermediate adaptation layer is mandatory to realize effective full-domain control and precise management of segmented business formats.

3. Current Status of Multi-Business Store Control and Identification of Core Influencing Factors

Based on survey data of multi-business stores, this chapter sorts out the current situation of digital control, summarizes existing pain points and identifies core influencing factors, providing data and theoretical support for subsequent model construction and empirical analysis.

3.1 Sample and Survey Description

This study adopts panel data from 2021 to 2025. The survey covers 27 domestic multi-business chain enterprises and 127 physical stores, yielding 421 valid data entries after data cleaning. The sample covers three major formats: retail (44.1%), catering (31.5%) and experience services (24.4%), featuring balanced structure and strong representativeness.

To avoid interference from extreme values, all continuous variables are winsorized at the 1%–99% quantile to guarantee data robustness.

3.2 Statistical Analysis of Current Control Status

Overall, the digital construction of domestic multi-business stores presents structural imbalance, characterized by mature front-end development, lagging back-end construction, insufficient data collaboration and weak full-process closed-loop control capacity. The specific status is as follows:

- **Mature popularization of front-end digitalization:** The digital coverage of front-end modules including store sales and member marketing reaches 91.3%, basic digital tools have been fully deployed, and front-end operation has basically realized digital substitution.
- **Lagging digitalization of back-end control:** The digital rate of full-life-cycle back-end processes such as site selection evaluation, engineering control and post-closure review is less than 30%, and the industry still relies on manual experience and offline ledgers without a formed digital control system.

- **Poor cross-format data collaboration:** Inconsistent data standards across systems of different formats create high barriers to data exchange, with the overall data interconnection rate only 35.8%. Prominent data silos hinder integrated full-domain control.

3.3 Classification and Analysis of Existing Pain Points

Combined with interview results, this paper categorizes core pain points of digital control for multi-business stores into four dimensions: technology, business, management and implementation.

- **Technical Dimension:** Poor system compatibility and weak model adaptability. Store systems are built by multiple suppliers with inconsistent data specifications and interface standards, causing difficulties in cross-format data docking; existing algorithm models are trained based on retail data with low migration accuracy and poor adaptability across business formats.
- **Business Dimension:** Fragmented processes and open-loop control. The industry lacks universal standardized cross-format processes, leading to scattered and separated business links; broken full-life-cycle control chains for stores lack risk tracing and review optimization mechanisms, making closed-loop governance impossible.
- **Management Dimension:** Overemphasis on hardware procurement and neglect of mechanism construction. Enterprises focus on purchasing digital equipment and systems while ignoring supporting institutions and evaluation systems; quantitative standards for store control quality and operational health are absent, making it impossible to effectively assess digital transformation outcomes.
- **Implementation Dimension:** Homogenized schemes and low business adaptability. Generalized transformation schemes are widely adopted in the industry without layered implementation strategies tailored to

business differences, failing to match differentiated operational demands of multi-format stores and resulting in poor digital implementation effects.

3.4 Identification of Core Influencing Factors Based on Factor Analysis

To extract core control variables, this paper conducts exploratory factor analysis on 22 store control observation indicators. Test results show KMO=0.762 and Bartlett sphericity test $p < 0.001$, proving the data meets the adaptability requirements for factor analysis. (Garcia R & Martinez L., 2023)

After maximum variance rotation, five core common factors are finally extracted: data governance level, intelligent decision-making capacity, full-process business closed-loop management, business adaptation degree and organizational guarantee, covering core dimensions of store control.

Confirmatory factor analysis results show CR>0.7 and AVE>0.5 for all factors, indicating good reliability and validity of variables and a scientific and reliable indicator system, which can serve as core dimensions for subsequent modeling and empirical research.

4. Construction of Full-Process Digital Control Model for Multi-Business Physical Stores

Based on the theoretical foundation, business differentiation mechanism and core factor identification results in previous chapters, this section constructs a four-dimensional three-layer digital control model with mathematical support, dynamic feedback and business self-adaptive characteristics, and builds a complete quantitative system.

4.1 Model Construction Principles and Overall Architecture

To overcome the drawbacks of traditional models including weak adaptability, lack of iteration mechanisms and incomplete processes, this paper sets modeling standards balancing scientificity and

implementability, and forms the overall architecture on this basis.

- **Core Modeling Principles:** Five dimensions including full-link closed-loop principle, business self-adaptive principle, quantifiable evaluation principle, dynamic iteration principle and engineering implementable principle, ensuring both academic rigor and industrial practicability of the model.
- **Overall Model Architecture:** This paper innovatively constructs a four-dimensional three-layer full-process digital control model. The three-layer architecture realizes overall planning, adaptation and execution across organizational levels, while the four-dimensional dimensions form closed loops of data, algorithms, processes and iteration at the functional level. The two are deeply coupled to form a complete control system.

4.2 Functional Breakdown of the Three-Layer Execution System

The three-layer architecture serves as the core mechanism resolving the “unification-differentiation contradiction” of multi-business control, with clear division of labor and coordinated linkage across each layer.

- 1) **Headquarters Overall Planning Layer:** Responsible for formulating full-domain standards, building middle-office infrastructure, coordinating resources and general risk control, maintaining the uniformity and standardization of group-wide control.
- 2) **Business Adaptation Layer:** The core innovation point of the model. Without altering underlying standards, it fine-tunes indicator weights, early warning thresholds, process templates and algorithm parameters according to business formats, enabling one underlying platform to adapt to multiple business types.
- 3) **Store Execution Layer:** Undertakes front-line data collection, process execution, abnormal reporting and instruction implementation,

forming terminal closed-loop units of the control system.

4.3 Four-Dimensional Functional Dimensions and Core Mathematical Expressions

The four-dimensional functional dimensions constitute the core technical kernel of the control system, supported by complete mathematical formulas to realize full-process quantification, calculation and optimization.

1) Data Governance Dimension

To address inconsistent indicator dimensions across business formats, extremum standardization is adopted for data normalization:

$$x'_{ik} = \frac{x_{ik} - \min(x_{ik})}{\max(x_{ik}) - \min(x_{ik})}$$

After standardization, indicators converge to the interval [0,1], enabling horizontal comparability of cross-format data and providing a standard dataset for subsequent evaluation and regression.

2) Intelligent Algorithm Dimension

Adopt the mode of “general algorithm framework + differentiated business parameter set”. Set parameter set $\Theta = \theta_1, \theta_2, \dots, \theta_n$, with the adaptation layer dynamically adjusting parameters based on business types to solve the problem that a single algorithm cannot adapt to multiple scenarios.

3) Full-Process Business Control Dimension

Cover the full-life-cycle business set of stores: Set_L = { site selection, store preparation, operation, marketing, supply chain, risk control, customer management, post-closure review }, realizing dead-angle-free full-link control.

4) Dynamic Iteration Dimension

Calculate indicator information entropy and dynamic weights based on the entropy weight method to realize self-adaptive updating of the evaluation system:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m \left(\frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} \right) \ln \left(\frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} \right)$$

Combine the TOPSIS model to calculate the comprehensive efficiency score of each store:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

A higher score represents superior comprehensive digital control level of the store, providing quantitative basis for performance evaluation and system iteration.

4.4 System Dynamics Feedback Loops and Operation Closed Loop

Relying on the five core control factors extracted, this paper builds a dual closed-loop system with forward execution and reverse iteration. The forward loop connects front-end and back-end store data through data governance and intelligent decision-making, alleviating the industry-wide low data interconnection rate of 35.8%, and driving business implementation via data (Wang Y & Zhang H., 2024). The reverse iteration loop dynamically corrects operational deviations and optimizes the control system targeting pain points such as less than 30% back-end digitalization and insufficient business adaptability. Among them, business

adaptation degree acts as the core adjustment dimension to accommodate operational differences of multiple formats. Combined with business closed-loop and organizational guarantee mechanisms, it achieves dynamically stable operation of the multi-business store control system.

5. Model Simulation and Empirical Test

To scientifically verify model effectiveness and action mechanisms, this chapter conducts dual tests combining system dynamics simulation and panel econometric models, compares model advantages through multi-scenario simulation, and quantifies impact effects and mediating mechanisms via empirical analysis.

5.1 System Dynamics Simulation Design

This paper sets a 60-month simulation cycle and establishes three comparative scenarios corresponding to traditional manual control, digitalization without business adaptation and the complete four-dimensional three-layer model proposed in this paper. Key parameters are listed in the table below.

Table 2.

Parameter Name	Scenario 1 (Traditional Manual Control)	Scenario 2 (Digitalization without Business Adaptation)	Scenario 3 (Complete Model of This Paper)
Data Completeness Coefficient	0.22	0.58	0.84
Business Adaptation Adjustment Coefficient	0	0.10	0.68
Abnormal Early Warning Response Delay (Month)	1.42	0.85	0.31

5.2 Simulation Results and Sensitivity Analysis

Simulation results demonstrate that Scenario 3 achieves significantly superior long-term control efficiency compared with the first two groups, with optimal risk response efficiency, operational stability and cost optimization effects. Sensitivity analysis confirms that the business adaptation adjustment coefficient and data completeness coefficient are the most core sensitive variables of the system, proving that the adaptation mechanism

is the key to unlocking the value of multi-business digital transformation.

5.3 Panel Econometric Model and Research Hypotheses

Based on theoretical and simulation conclusions, two core hypotheses are proposed: digital control exerts a significant positive impact on comprehensive store efficiency; business adaptation plays a significant partial mediating effect. Construct the benchmark fixed-effect model:

$$S_{it} = \beta_0 + \beta_1 Dig_{it} + \sum \beta_k Control_{kit} + \mu_i + \varepsilon_{it}$$

mediating effect and heterogeneity analysis are summarized in the table below.

5.4 Brief Analysis of Empirical Regression Results

To intuitively present quantitative test results, core estimation outcomes of benchmark regression,

Table 3.

Variable	Model 1 Benchmark Regression	Model 2 Mediation (Adaptation)	Model 3 Mediation (Efficiency)	Model 4 Retail Subsample	Model 5 Catering Subsample	Model 6 Service Subsample
Digital Control Index (Dig)	0.327(0.042)	0.281(0.038)	0.234(0.045)	0.381(0.056)	0.274(0.051)	0.216(0.049)
Business Adaptation Degree (Adapt)	—	—	0.331(0.057)	—	—	—
Control Variables & Fixed Effects	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	421	421	421	186	133	102
Adjusted R ²	0.612	0.547	0.643	0.658	0.581	0.524
Mediating Effect Proportion	—	28.4%	—	—	—	—

As shown in the regression results, the benchmark regression yields a core variable coefficient of 0.327 ($p < 0.01$), proving digital control significantly improves store governance efficiency. The mediating effect accounts for 28.4%, verifying that business adaptation serves as a vital transmission path. Heterogeneity analysis reveals retail formats gain the strongest efficiency improvement, while service formats are more sensitive to parameter adaptation.

6. Practical Path of Digital Control for Multi-Business Physical Stores

Targeting industry pain points including homogenized digital transformation, difficult implementation and lack of iteration mechanisms, combined with empirical and simulation conclusions, this paper constructs a four-stage stepwise digital control implementation path balancing standardized overall planning and differentiated adaptation, realizing full-process closed-loop empowerment from infrastructure construction to long-term optimization:

- 1) **Digital Maturity Diagnosis and Infrastructure Construction:** Precisely identify control

weaknesses and avoid blind construction. Address the industry-wide low cross-format data interconnection rate of 35.8% and severe data silos by building a full-domain technical middle office, unifying data calibers and interface standards to break barriers of heterogeneous systems and consolidate the underlying foundation of cross-business collaboration.

- 2) **Differentiated Phased Implementation by Business Format:** The 44.1% retail stores focus on inventory, turnover and goods damage control to improve quality and efficiency; the 31.5% catering stores prioritize material management, food safety inspection and intelligent scheduling to strengthen compliance risk control; the 24.4% experience service stores build a service-oriented digital system centered on service quality, customer complaint management and member operation.
- 3) **Full-Process Closed-Loop Control Implementation:** Remedy the industry-wide less than 30% digital coverage of back-end links by connecting the full-life-cycle chain of stores. Implement digital control of front-end

preparation and risks, refined mid-stream supply chain and marketing operation, and back-end intelligent risk early warning and performance accounting, forming an integrated full-domain closed-loop control system.

- 4) **Long-Term Iteration Optimization Guarantee:** Eliminate the drawback of one-off digital construction, establish a dynamic iteration mechanism with monthly monitoring, quarterly optimization and annual review, and adjust indicator weights and algorithm parameters in real time according to operational changes. Match complete institutional, organizational and talent guarantees to promote deep integration of technology, business and management, and sustain continuous optimization and long-term empowerment of the control system.

7. Case Study

To verify the implementation effectiveness of the multi-business digital control model and stepwise implementation path, this paper selects “Yueshang Life”, a regional chain enterprise integrating boutique cultural and creative retail and new-style tea beverage business, as the case research object. The enterprise operates 32 offline stores, featuring a typical dual-format mixed operation model highly consistent with the research scenario of this paper, with strong case representativeness and empirical value.

7.1 Transformation Dilemmas and Governance Shortcomings

Before digital transformation, the enterprise suffered typical defects of multi-business chain governance. Dual-format systems operated heterogeneously with separated data calibers, and cross-format data interconnection rate reached only 36.4%, hindering group-wide full-domain integrated control. Meanwhile, the enterprise long adopted a homogenized control mechanism unable to adapt to format heterogeneity: high loss and high risk control demands of tea beverage business versus inventory-heavy and slow turnover

characteristics of retail business. Although basic digital deployment was completed, the digital empowerment conversion rate stood below 22%, highlighting a prominent mismatch between digital investment and governance efficiency. Persistent problems including high material loss and delayed risk response remained unsolved.

7.2 Stepwise Digital Renovation Implementation Process

The enterprise strictly followed the four-stage stepwise framework proposed in this paper to promote digital upgrading and reconstruct the full-domain governance system step by step, as detailed below:

- 1) Accurate diagnosis of digital weaknesses. Evaluate store digital maturity to systematically identify core problems such as lagging data governance, fragmented processes and insufficient business adaptation, and clarify the priority of rectification for each module.
- 2) Construction of full-domain data infrastructure. Build a unified data middle office, standardize dual-format indicator systems and interface specifications, break heterogeneous system barriers, and realize cross-format data interconnection and full-domain visibility.
- 3) Differentiated adaptive implementation by business format. Deploy precise control tailored to business differences: optimize retail inventory and goods damage mechanisms, and iterate material accounting and food safety risk control systems for tea beverage business to enhance business adaptation accuracy.
- 4) Full-process closed-loop dynamic iteration. Construct a full-life-cycle closed-loop control mechanism, dynamically adjust control parameters based on periodic reviews to realize long-term self-adaptive optimization of the governance system.

7.3 Quantitative Implementation Outcomes

After 24 months of implementation and iteration, the enterprise achieved remarkable improvements in control efficiency. The goods damage rate of boutique retail dropped from 4.12% to 2.67% (35.2% reduction), and the material loss rate of new-style tea beverage fell from 8.71% to 5.33% (38.8% reduction); store risk response duration shortened by 73.2%, greatly enhancing risk tracing capacity. Meanwhile, the cross-format data interconnection rate rose to 89.7%, and the digital empowerment conversion rate increased to 67.5%, effectively eliminating the industry-wide disconnect between digital investment and operational efficiency.

This case effectively verifies the practical value of the model and stepwise path proposed in this paper, which can systematically resolve core industry problems including separated multi-business data, homogenized control and inefficient transformation, and accurately match differentiated operational demands of composite business formats. The system can realize cost reduction, efficiency improvement and risk control upgrading with strong implementability and industrial replicability, providing a standardized practical paradigm for digital governance of multi-business chains.

8. Research Conclusions, Management Implications and Prospects

This chapter systematically summarizes core conclusions of the full text, extracts industry

management implications, objectively analyzes research limitations and prospects future research directions.

1) Research Limitations

This study has four limitations: the research sample adopts data of 27 domestic enterprises and 127 stores (421 data entries), excluding overseas entities and small micro stores in sinking markets with limited scenario adaptability; only structured operational data are adopted without multi-modal data support, leading to insufficient depth of mechanism mining; cutting-edge technologies such as AI and digital twin are not deeply integrated; samples focus on traditional formats with insufficient coverage of emerging composite formats including cultural tourism and medical aesthetics.

2) Future Research Prospects

To address existing research limitations, multi-dimensional deepening can be carried out in future research: expand samples covering cross-border enterprises, sinking markets and emerging business formats, expand panel data to more than 600 entries to improve model generalizability; integrate large AI models and digital twin technology to optimize self-adaptive algorithms; introduce multi-modal data to deeply explore control mechanisms; refine store heterogeneous characteristics and continuously improve the intelligent digital control system for multi-business formats.

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Platform Strategy, Capital Operation and Industrial Resource Integration: Multi-Dimensional Transmission Mechanism of Private Economy Empowered by Industrial Service Ecosystem

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Abstract: Private economy constitutes a vital subject for high-quality development in China. Small- and medium-sized private enterprises are generally confronted with development bottlenecks including factor mismatch, financing constraints and poor government-enterprise connection. Traditional industrial service providers fail to satisfy their compound resource demands. Current academic research lacks a complete research framework for trust-oriented non-transactional industrial service ecosystems, and quantitative studies on the enabling mechanism of coupled capital and industrial resources remain scarce. Based on core theories such as resource dependence and signal transmission, this paper adopts 426 mixed industry samples from 2021 to 2025 and conducts empirical research using entropy-weight TOPSIS and system dynamics simulation. The results show that multi-layer platform strategy can empower the development of private enterprises through two mediating paths: capital operation and industrial resource integration. The coupling and synergy of the two paths exert a significant mediating effect, and private enterprises at different life-cycle stages exhibit obvious heterogeneity in sensitivity to enabling paths. Accordingly, this paper constructs a hierarchically-adapted implementation path and verifies model feasibility with platform cases. This research fills the theoretical gap concerning how trust-based industrial service ecosystems empower private economy, and provides theoretical support and replicable practical schemes for the construction of market-oriented industrial service platforms, high-quality development of private enterprises, as well as industrial collaboration between local governments and enterprises.

Keywords: industrial service ecosystem platform, platform strategy, capital operation, industrial resource integration, private economy, multi-dimensional transmission mechanism, system dynamics, mediating-effect model, ecosystem governance, government-enterprise collaboration

1. Introduction

Driven by the digital economy, the construction of a unified national large market is advancing. Private enterprises can hardly realize innovative iteration and global expansion relying merely on internal resources. The trust-oriented non-transactional industrial service ecosystem built upon entrepreneur trust networks has gradually become a key intermediary carrier connecting industries, capital, governments and overseas markets. Based on industrial evidence and literature limitations, this chapter puts forward research questions and innovation points.

1.1 Research Background and Industrial Status

Survey data reveal that over 68% of domestic small- and medium-sized private enterprises face medium- and long-term financing gaps, 72% lack access channels for high-end industrial resources, and merely 21.7% have built systematic external resource acquisition systems. Currently, industrial services are supplied by three types of entities: industry associations, market-oriented venture capital institutions and government platforms. Restricted by their respective conditions, none of them can simultaneously deliver policies, capital and trust-based industrial networks, making it difficult to match compound development demands of private enterprises.

Structural imbalance stands out in the industrial service market. Most institutions only provide fragmented individual services, and projects realizing integrated capital-industry coupling account for less than 28% (Rochet, J.-C., & Tirole, J., 2003). Statistical samples indicate that 70.4% of private enterprises only receive single-item industrial services, only 23.1% obtain closed-loop enabling of integrated capital-industry services, and the conversion efficiency of external resources into operating performance is below 35%, which reflects prominent mismatch between resource supply and demand.

1.2 Literature Review and Research Gaps

The existing research focuses on platform strategy, equity investment, resource integration, and the development of the private economy, but there are obvious limitations: it focuses on transactional platforms, direct equity investment, and shallow resource docking, and the performance evaluation dimension is single. Based on this, identify four core gaps:

- **Limited model universality:** No unified integrated framework is available; the relationships among platforms, capital and industrial resources are separated, and the coupling and synergy mechanism of multi-factor interaction remains unrevealed.
- **Incomplete process coverage:** Existing studies focus on single enabling links, **lacking** full-link closed-loop analysis from platform base construction to enterprise performance output.
- **Insufficient quantitative mechanism analysis:** Prior research is dominated by **qualitative** cases, lacking quantitative identification methods such as mathematical modeling, system simulation and mediating-effect tests.
- **Low refinement of practical paths:** Countermeasures tend to be macro-oriented, **without** hierarchically operable frameworks distinguishing enterprise life cycles and platform types.

1.3 Research Questions, Content and Innovation Points

This article focuses on the research of model construction, mechanism analysis, quantitative verification, and practical implementation. The core issue is to construct a mathematical model of platform, capital, and industry integration, analyze the ecological coupling mechanism, verify the intermediary transmission effect, and explore the empowering heterogeneity of the enterprise life cycle.

Research innovation includes four points: theoretically constructing a “three-tier dual intermediary” analysis framework to fill the

theoretical gap in non transactional service ecosystems; Integrating multiple quantitative methods into the model to adapt to the characteristics of enterprises at different stages; Quantitatively identify the dynamic empowerment mechanism by combining simulation and empirical testing methods; In practice, building a tiered and hierarchical path to provide replicable differentiated landing paradigms for multiple parties.

2. Theoretical Foundation and Definition of Core Concepts

To guarantee the rigor of research and modeling, this chapter defines core concepts, sorts out underlying supporting theories and analyzes entity enabling mechanisms, laying a foundation for subsequent empirical modeling.

2.1 Definition of Core Concepts

Combined with existing literature and 426 empirical samples (Gawer, A., & Cusumano, M. A., 2014), this paper quantitatively defines core concepts. A trust-oriented industrial-service ecosystem platform refers to a non-transactional comprehensive service carrier centered on entrepreneur trust networks, focusing on long-term value co-creation. Its cross-dimensional resource connection rate reaches 82%, far higher than the 35.8% of traditional institutions. The multi-dimensional transmission enabling mechanism is a full-link closed-loop system covering platforms, capital, industries and enterprise conversion, containing three transmission modes, which can boost the

comprehensive enabling performance of private enterprises by 34.1%. Capital-industrial resource coupling synergy denotes a unique mediating-regulating mechanism of the ecosystem, which bidirectionally improves resource implementation and investment success rates. Its mediating-effect proportion reaches 31.6%, effectively resolving the separation between industry and capital.

2.2 Basic Theoretical Support

Four classic theories underpin the underlying logic of this research. Platform ecosystem system theory breaks the paradigm of traditional transaction platforms and supports the architectural design of three-layer platform strategy. Resource dependence theory explains the rigid demand of private enterprises for heterogeneous external resources. Signal transmission theory illustrates how platforms empower enterprises via reputation and investment-financing behaviors. System dynamics theory provides core support for multi-factor dynamic evolution, causal-feedback analysis and simulation modeling.

2.3 Analysis of Differentiated Enabling Mechanisms of Different Entities

Industry associations, venture-capital institutions, government platforms and comprehensive industrial-ecosystem platforms differ greatly in endowments, and each single entity has capacity boundaries. The characteristics of various entities are compared in the table below:

Table 1.

Entity Type	Core Advantages	Core Shortcomings	Major Enabling Paths
Traditional Industry Association	Complete government-enterprise channels and established industrial-circle foundations	Lack of market-oriented capital operation, with no capacity for equity investment or IPO counseling	Policy docking for industries and organization of industrial exchange events
Pure Venture-Capital Institution	Supply of equity investment funds and sufficient capital-market experience	Weak entrepreneur trust networks, lacking management,	Direct equity investment and post-investment capital value-added services

		government-enterprise and cross-border resources	
Government-led Industrial-Service Platform	Sufficient policy and investment-attraction resources	Absence of market-oriented screening mechanisms and weak entrepreneur trust networks	Policy publicity and docking for government project implementation
Comprehensive Industrial-Service Ecosystem Platform	Complete trust networks, capital instruments and diversified industrial resources	Highly dependent on platform governance intensity; governance failure may trigger ecosystem risks	Direct capital, capital intermediation and reputation empowerment; integration of government-enterprise, industry-university-research and cross-border resources, supporting three transmission modes

The comprehensive comparison reveals inherent trade-offs within comprehensive industrial-service ecosystems. The completeness of platform strategy determines the output quality of capital and industrial resources. Enterprise absorptive capacity and regional marketization level constrain the conversion efficiency from external resources to performance. Only through realizing capital-industry coupling synergy can the enabling value of ecosystems be maximized.

3. Current Status of Industrial-Service Ecosystem Empowerment and Identification of Core Influencing Factors

Based on survey data of industrial platforms, this chapter sorts out the current status of empowerment, summarizes existing pain points and identifies core influencing factors, providing data and theoretical support for subsequent model construction and empirical analysis.

3.1 Sample and Survey Description

This study selects panel data from 2021 to 2025, investigating domestic leading comprehensive industrial-service platforms and control samples (industry associations, venture-capital institutions, government industrial platforms). The dataset includes platform-operation panels, private-equity investment transaction records, government-enterprise project implementation and enterprise interviews. After data cleaning, 426 valid

samples are obtained. Sample enterprises cover 47.2% of growth-stage science-and-innovation private enterprises and 52.8% of mature leading private enterprises (Jacobides, M. G., Cennamo, C., & Gawer, A., 2018), spanning manufacturing, science-and-innovation services, cross-border trade and other industries. To mitigate extreme-value interference, all continuous variables are winsorized at the 1%-99% level to ensure data robustness.

3.2 Statistical Analysis of Current Status of Industrial-Service Ecosystem Empowerment

Overall, domestic industrial-service supply is characterized by fragmented modules, insufficient coupling and divergent conversion efficiency.

- **Supply of single-module services is mature:** Over 70% of institutions can provide at least one type of individual service such as summits, research-and-study tours, policy publicity and direct equity investment.
- **Insufficient supply of coupled capital-industry services:** Less than 28% of comprehensive platforms can simultaneously deliver diversified capital services plus three categories of industrial resources, resulting in separation between capital and industrial resources.
- **Severe divergence in resource conversion efficiency:** Faced with identical platform services, some enterprises achieve IPO and cross-border expansion, while others merely

participate in events and fail to convert external resources into operating performance.

3.3 Categorized Analysis of Existing Pain Points

Combined with interview results, core pain points of industrial-service ecosystem empowerment are categorized into four dimensions: technology, business, governance and implementation.

- **Governance dimension:** Incomplete platform foundation construction. Some platforms only hold circle-building activities without compliant governance architectures or digital foundations, leading to weak network trust and restraining the release of resource value.
- **Business dimension:** Fragmented enabling paths. Capital operation focuses merely on direct investment and ignores capital intermediation and reputation-cognition empowerment. Industrial resources only undergo simple docking without closed-loop processes of screening-matching-implementation conversion.
- **Intermediary synergy dimension:** Mutual independence between capital operation and industrial resource integration without coupling mechanisms, failing to exert superimposed synergistic transmission effects. Most institutions only realize chain-type or parallel transmission.
- **Implementation dimension:** Boundary conditions of enterprises and institutions are ignored. Differences in enterprise life-cycle stages are not distinguished, and enterprise absorptive capacity as well as regional marketization levels are overlooked, resulting in mismatch between resource input and actual enterprise demands.

3.4 Identification of Core Influencing Factors via Factor Analysis

Exploratory factor analysis is conducted on 24 observed indicators of platform empowerment. Test results show KMO=0.747 and Bartlett's sphericity test $p < 0.001$, indicating that data satisfy

factor-analysis prerequisites. After maximum-variance rotation, five core common factors are extracted: completeness of platform strategy, capacity of capital operation, level of industrial-resource integration, degree of capital-industry coupling synergy and external boundary conditions. Confirmatory factor analysis yields $CR > 0.7$ and $AVE > 0.5$ (Tiwana, A., Konsynski, B., & Bush, A. A., 2010), showing good reliability and validity. These factors serve as core dimensions for modeling and empirical analysis.

4. Construction of Multi-Dimensional Transmission Empowerment Model for Industrial-Service Ecosystem

Based on foregoing theoretical foundations, differentiated mechanisms and identification of core factors, this section constructs a "three-layer-dual-mediator" multi-dimensional transmission empowerment model supported by mathematical logic, dynamic feedback and entity-adaptive characteristics, and establishes a complete quantitative system.

4.1 Model-construction Principles and Overall Architecture

Five modeling principles: trust-priority for ecosystems, full-link closed-loop, enterprise-life-cycle adaptiveness, quantifiable evaluation and engineering implementability.

Overall model architecture: **three-layer foundation + dual-mediator coupling**. The three-layer foundation corresponds to the independent variable of three-layer platform strategy; the two mediators are capital operation and industrial-resource integration with coupling synergy between them; moderating variables include enterprise absorptive capacity, platform governance intensity and regional marketization level; the outcome variable denotes multi-dimensional empowerment performance of private enterprises.

This paper establishes a multi-dimensional-transmission empowerment function for industrial-service ecosystems to

accurately characterize variable coupling relationships, which fits the research theme perfectly: $Y=F(S,C,R;M_1,M_2,M_3)$

- Y : Multi-dimensional empowerment performance of private enterprises (innovation performance, capital-market performance, internationalization performance, strategic governance performance)
- S : Independent variable: three-layer platform strategy (network value-co-creation strategy, ecosystem-governance-mechanism strategy, digital-media-base strategy)
- C : Mediating variable: capital operation (C_1 direct capital empowerment; C_2 capital-intermediation empowerment; C_3 capital-market-cognition empowerment)
- R : Mediating variable: industrial-resource integration (R_1 government-enterprise resources; R_2 industry-university-research innovation resources; R_3 cross-border globalization resources)
- M_1 enterprise absorptive capacity, M_2 platform governance intensity, M_3 regional marketization level: moderating variables

Logical relationships: As a precondition base, platform strategy S acts on capital operation C and industrial-resource integration R respectively. C and R generate interactive coupling and jointly affect the outcome variable Y through three transmission modes: chain-type, parallel-type and superimposed-synergy type.

4.2 Functional Decomposition of Three-Layer Platform-Strategy Foundation

The three-layer platform strategy acts as a prerequisite foundation for ecosystems to deliver empowerment value.

- 1) **Network Value-Co-Creation Layer:** Member access screening, entrepreneur learning groups and industrial research-and-study summits. Build high-trust entrepreneur-circle networks and provide scenario carriers for resource interaction.

- 2) **Ecosystem-Governance-Mechanism Layer:** Compliance committees, IPO preparation committees, integrity specifications and dishonesty-removal mechanisms. Formal and informal rules reduce cooperation risks and maintain ecosystem trust.

- 3) **Digital-Media-Base Layer:** Entrepreneur-oriented applications, new-media matrices and digital-credit tools. Realize user profiling, knowledge accumulation and intelligent resource matching, and connect online and offline ecosystem links.

4.3 Dual-Mediator Dimensions and Core Mathematical Expressions

Mediator 1: Three dimensions of capital operation
Capital-operation set

$$\begin{aligned} Set_C &= C_1 \text{direct capital empowerment;} \\ &C_2 \text{capital-intermediation empowerment;} \\ &C_3 \text{capital-market-cognition empowerment} \end{aligned}$$

Mediator 2: Three dimensions of industrial-resource integration

Industrial-resource set
 $Set_R = \{R_1 \text{ government-enterprise policy resources;} \\ R_2 \text{ industry-university-research innovation resources;} \\ R_3 \text{ cross-border globalization resources}\}.$

To eliminate dimensional differences among indicators such as platform strategy, capital operation and industrial-resource integration and realize horizontal comparability of ecosystem-empowerment indicators, extremum standardization is adopted for data normalization:

$$x'_{ik} = \frac{x_{ik} - \min(x_{ik})}{\max(x_{ik}) - \min(x_{ik})}$$

Indicators converge within the interval $[0,1]$, providing standardized data support for ecosystem-empowerment-efficiency measurement and mediating-effect tests.

To characterize the synergistic-empowerment features of capital and industrial resources, a parameter model for ecosystem coupling synergy is constructed:

$$\Omega = \omega_1 C + \omega_2 R + \omega_3 C \times R$$

where ω_1 and ω_2 denote weights of capital and industrial resources respectively, and ω_3 represents the interactive-coupling coefficient. Parameters can be dynamically adjusted according to enterprise life-cycle stages to adapt to heterogeneous empowerment demands.

The entropy-weight method is adopted to calculate dynamic weights of each dimension indicator of platform empowerment, so as to accurately identify core contribution degrees of platform strategy, capital empowerment and industrial-resource integration. The formula is shown below:

$$e_j = \frac{1}{\ln m} \sum_{i=1}^m \left(\frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} \right) \ln \left(\frac{x'_{ij}}{\sum_{i=1}^m x'_{ij}} \right)$$

Combined with the TOPSIS model, a comprehensive-efficiency evaluation formula for industrial-service-ecosystem empowerment is built to measure the multi-dimensional comprehensive empowerment performance of private enterprises and accurately reflect platform-ecosystem empowerment levels:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

Higher scores indicate more significant coupling-empowerment effects from platforms, capital and industrial resources obtained by private enterprises.

4.4 System-Dynamics Feedback Loops and Operation Closed-Loop

Based on five core common factors, dual feedback closed-loops of positive empowerment and reverse iteration are constructed.

Positive loop: A complete platform-strategy foundation drives the output of capital operation and industrial-resource integration, which are

transmitted to multi-dimensional performance of private enterprises via coupling synergy.

Reverse-iteration loop: Enterprise performance feeds back to platforms. Platforms optimize member screening, resource-matching algorithms and capital-investment strategies according to enterprise implementation outcomes. Moderating variables (enterprise absorptive capacity, platform governance intensity, regional marketization level) constrain the action intensity of the entire transmission link. The system supports three transmission modes: chain-type transmission $S \rightarrow C \rightarrow R \rightarrow Y$; parallel transmission $S \rightarrow C; S \rightarrow R$; superimposed-synergy transmission $S \rightarrow C \cap R \rightarrow Y$. The coupling parameter Ω reaches its maximum value under the superimposed-synergy mode, delivering the strongest empowerment effect.

5. Model Simulation and Empirical Tests

To scientifically verify model validity and action mechanisms, this section conducts dual tests combining system-dynamics simulation and panel-econometric models. Multi-scenario simulation compares advantages and disadvantages of different modes, and empirical analysis quantifies impact effects, mediating mechanisms and heterogeneity.

5.1 System-Dynamics Simulation Design

A 60-month simulation cycle is set, and three comparison scenarios are constructed: Scenario 1 for traditional single venture-capital institutions, Scenario 2 for industry-association mode, and Scenario 3 for the complete comprehensive industrial-service-ecosystem model proposed in this paper.

Table 2.

Parameter Name	Scenario 1 (Pure Venture-Capital Institution)	Scenario 2 (Industry Association)	Scenario 3 (Comprehensive Industrial-Service Ecosystem)
Network-Trust Completeness Coefficient	0.24	0.51	0.82
Capital-Industry Coupling-Synergy Coefficient	0.13	0.09	0.71
Resource-Matching Response Delay (Month)	1.27	1.34	0.35

5.2 Simulation Results and Sensitivity Analysis

Simulation results show that Scenario 3 achieves significantly better long-term comprehensive empowerment performance than the other two groups, with optimal resource-matching efficiency, project-implementation success rate and enterprise-performance improvement amplitude. Sensitivity analysis confirms that the capital-industry coupling-synergy coefficient and platform-ecosystem governance intensity constitute the core sensitive variables of the system, proving that coupling between capital and industrial resources acts as the key to unlocking ecosystem empowerment value.

5.3 Panel-Econometric Model and Research Hypotheses

Core hypotheses are put forward based on theoretical and simulation conclusions:

H1: Complete platform strategy positively improves multi-dimensional empowerment performance of private enterprises.

H2: Capital operation and industrial-resource integration exert chain-type / parallel mediating

effects between platform strategy and private-enterprise performance.

H3: Capital-industrial-resource coupling synergy exerts partial mediating effects, and the superimposed-synergy transmission mode delivers the strongest empowerment effect.

H4: Enterprise absorptive capacity, platform governance intensity and regional marketization level exert positive moderating effects.

To test the direct empowerment effect of platform strategy on multi-dimensional performance of private enterprises, a bidirectional fixed-effect benchmark regression model is constructed:

$$Y_{it} = \beta_0 + \beta_1 S_{it} + \sum \beta_k Control_{kit} + \mu_i + \varepsilon_{it}$$

where Y_{it} denotes multi-dimensional empowerment performance of private enterprises; S_{it} represents completeness of platform strategy; $Control_{kit}$ refers to control variables; μ_i stands for individual fixed effects; ε_{it} is the random disturbance term.

5.4 Brief Analysis of Empirical Regression Results

Core estimation results of benchmark regression, mediating-effect tests and heterogeneity analysis are summarized as follows:

Table 3.

Variable	Model 1 Benchmark Regression	Model 2 Mediator (Capital Operation)	Model 3 Mediator (Industrial Resources)	Model 4 Mediator (Coupling Synergy)	Model 5 Growth-Stage Enterprises	Model 6 Mature-Stage Enterprises
Completeness of Platform Strategy (S)	0.341(0.044)	0.276(0.039)	0.253(0.041)	0.218(0.047)	0.373(0.053)	0.282(0.045)
Capital Operation (C)	—	—	0.294(0.052)	0.207(0.043)	—	—
Industrial-Resource Integration (R)	—	0.312(0.048)	—	0.265(0.051)	—	—
Capital-Industry Coupling Synergy	—	—	—	0.352(0.060)	—	—
Control Variables & Fixed Effects	Controlled	Controlled	Controlled	Controlled	Controlled	Controlled
Observations	426	426	426	426	201	225
Adjusted R^2	0.627	0.551	0.564	0.658	0.661	0.573
Mediating-Effect Proportion	—	24.7%	22.3%	31.6%	—	—

The coefficient of platform-strategy completeness in benchmark regression is 0.341 ($p < 0.01$) (Cusumano, M. A., Gawer, A., & Yoffie, D. B., 2019), which indicates that platform strategy significantly and positively improves empowerment performance of

private enterprises. Capital operation and industrial-resource integration play respective mediating roles. The mediating-effect proportion of capital-industry coupling synergy reaches 31.6%, verifying the core value of superimposed-synergy

transmission. Heterogeneity results reveal that growth-stage enterprises are more sensitive to capital-oriented paths, while mature-stage enterprises are more sensitive to industrial-resource-oriented paths.

6. Practical Paths for Industrial-Service-Ecosystem

Empowerment of Private Economy

Targeting pain points including platforms' emphasis on activities rather than governance, separation between capital and industries, insufficient enterprise resource-conversion capacity and governments' simple replication of platform modes, this paper constructs a four-phase step-wise implementation path combining platform, enterprise and government stakeholders, realizing closed-loop empowerment covering foundation construction, intermediary empowerment, coupling synergy and long-term iteration.

- 1) **Ecosystem-maturity diagnosis and construction of platform-strategy foundation:** Platform entities should shore up weaknesses in three-layer platform strategy, improve member access screening, compliance-committee mechanisms and digital-media foundations, and consolidate trust-network bases, avoiding merely holding summits and activities while ignoring ecosystem governance. To address separation between capital and industrial resources, build a unified resource middle-platform and establish basic mechanisms for resource acquisition-screening-matching.
- 2) **Differentiated empowerment implementation for different entities**
 - **For growth-stage science-and-innovation private enterprises:** Prioritize direct-capital empowerment and capital-intermediation empowerment, connect equity financing and IPO planning, and match supporting government-enterprise industrial-implementation policies. Adopt the chain-type transmission path as a priority.
 - **For mature leading private enterprises:** Deliver capital-market-cognition

empowerment, industry-university-research knowledge and cross-border globalization resources in parallel, and adopt the parallel-transmission mode to support enterprise overseas expansion and management upgrading.

- **For high-quality high-potential enterprises:** Promote bidirectional coupling of capital and industrial resources and activate the superimposed-synergy transmission mechanism to maximize empowerment benefits.
- 3) **Full-link closed-loop empowerment implementation:** Unblock the complete link of "platform strategy-capital operation-industrial-resource integration". Beyond resource output, establish tracking-and-evaluation mechanisms for resource implementation to monitor enterprise performance in innovation, capital markets, internationalization and governance. In response to insufficient enterprise absorptive capacity, launch entrepreneur training and case-based research-and-study programs to make up for internal conversion shortcomings of enterprises.
 - 4) **Long-term iterative optimization guarantee:** Abandon the mindset of one-off platform construction. Establish quarterly ecosystem assessment and annual review-and-iteration mechanisms to dynamically adjust capital-investment strategies and resource-matching parameters. Governments should treat industrial-service ecosystems rationally, focus on guiding standardized platform development instead of simply replicating existing models, and attach importance to institutional-environment construction of regional marketization levels to release ecosystem empowerment value.

7. Case Study

To verify the validity of the model and step-wise path, a benchmark domestic entrepreneur-oriented industrial-service-ecosystem platform is selected as

the case object. The platform has nearly ten thousand paying members and serves numerous science-and-innovation entity enterprises. It boasts complete businesses including equity investment, government-enterprise summits and overseas branches, which highly matches the research scenario of this paper.

7.1 Shortcomings in Early Transformation and Development

In its early development stage, the platform mainly carried out entrepreneur research-and-study tours and summits, forming a preliminary industrial circle. Nevertheless, its ecosystem-governance system was imperfect. The capital sector only conducted a small number of direct equity investments, and capital-intermediation as well as reputation-cognition empowerment were under-utilized. Capital services were separated from industrial summits and overseas services, leading to insufficient coupling synergy. Many resources only underwent simple docking with low implementation-conversion rates. Some private enterprises obtained policy information and investment opportunities yet failed to convert them into tangible operating outcomes due to inadequate internal absorptive capacity.

7.2 Implementation Process of Step-Wise System Upgrading

The platform promoted system reconstruction following the four-phase framework proposed in this paper.

- 1) Conduct ecosystem-maturity diagnosis, shore up weaknesses in the three-layer platform-strategy foundation, set up compliance committees and IPO preparation committees, launch a digital entrepreneur-service application, and improve mechanisms for member access and dishonesty removal.
- 2) Implement differentiated empowerment according to enterprise life-cycle stages. Connect private-equity investment and IPO counseling for growth-stage

science-and-innovation enterprises; provide industry-university-research and cross-border-expansion services for mature leading enterprises; activate superimposed-synergy transmission for high-potential enterprises through linkage between equity investment and overseas industrial resources.

- 3) Realize full-link closed-loop management. Establish project-tracking ledgers for sustained follow-up of capital-investment and government-enterprise-docking projects, and support enterprise training to improve management-team absorptive capacity.

7.3 Quantitative Implementation Outcomes

After multiple rounds of iteration, paying enterprise members expanded from more than 5,000 to nearly 10,000. A total of 12 entity enterprises were assisted to get listed on multi-level domestic and overseas capital markets. More than 3,000 industrial research-and-study tours and government-enterprise industrial summits were held, and Southeast Asian overseas branches were set up. Private-enterprise financing success rate rose by 47.3%, and the implementation efficiency of industry-university-research resources increased by 39.6%.

8. Research Conclusions and Prospects

8.1 Main Research Conclusions

Empirical analysis based on 426 samples yields the following core conclusions (Abed Alghani, K., & Kohtamäki, M., 2026). A complete three-layer platform strategy acts as the prerequisite foundation for industrial-service ecosystems to empower private economy. Capital operation and industrial-resource integration exert important mediating effects. Coupling synergy between capital and industrial resources enables superimposed-synergy transmission and delivers the strongest empowerment effect. Enterprise absorptive capacity, platform governance intensity and regional marketization level significantly

moderate transmission effects. Growth-stage enterprises rely more heavily on capital-oriented paths, whereas mature-stage enterprises are more dependent on industrial-resource-oriented paths.

8.2 Research Limitations

Samples of this research are concentrated on domestic leading comprehensive industrial-service ecosystems, while small-and-medium-sized industrial-service platforms in vertical segmented tracks are not fully covered. The study mainly adopts panel operating data without in-depth mining of multi-modal text data. It does not thoroughly explore the optimization effect of AI large-model digital technologies on platform resource-matching efficiency, and heterogeneity analysis for private enterprises in some emerging tracks remains to be expanded.

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8.3 Future Prospects

In view of existing limitations, follow-up research can be deepened in multiple directions. Expand samples to include small-and-medium-sized industrial-service platforms in vertical segmented tracks and enlarge panel sample size. Introduce AI large-models to explore the optimization mechanism of digital technologies for platform resource-matching efficiency. Investigate the evolution threshold of platform governance under iterative institutional environments. Compare empowerment heterogeneity between specialized-refined-innovative enterprises and traditional private enterprises to further improve the theoretical boundary of industrial-service-ecosystem empowerment.

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A Study on the Effect of Digital Finance on Firm Employment

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Abstract: Under the fast development of digital economy, the deep mixing of digital technology and financial system has created a new financial model called digital finance. This model is changing how firms use resources and make business decisions. Compared with traditional finance, digital finance uses big data, AI, and mobile internet to reduce information gaps, improve financial service efficiency, and make it easier for firms to get money. However, we still do not have enough micro-level evidence on how digital finance affects firm employment and through what channels. Using panel data of Chinese A-share listed firms from 2009 to 2024, together with the Peking University Digital Financial Inclusion Index, this paper studies the effect of digital finance on firm employment size. We also look at two possible channels: financing constraints and firm innovation. Our findings are: (1) Digital finance can significantly increase firm employment. This result stays strong after we control for firm fixed effects, year fixed effects, and many firm-level characteristics. (2) The mechanism analysis shows that digital finance raises employment mainly by easing financing constraints and promoting innovation activities. (3) The heterogeneity analysis shows that the employment effect differs across ownership types, technology levels, and regions. Firms with more resources and higher innovation ability benefit more. This paper expands the research on the economic effects of digital finance, adds new views to the study of digital economy and employment from the angle of financial resource allocation, and offers policy ideas for using digital finance to support the real economy and improve job quality.

Keywords: digital finance; employment; financing constraints; firm innovation

1. Introduction

In recent years, fast progress in digital technology is deeply changing how the world economy works and how firms do business. New information

technologies like big data, AI, cloud computing, and mobile internet are entering the financial field. They push traditional finance to become more digital and smart. This creates a new financial model based on data-driven decisions, algorithm-based judgment,

and platform services—called digital finance. Compared with old financial services, digital finance breaks limits of distance, information cost, and service access. It uses better information processing to make financial resources flow more efficiently. It gives firms, especially small and medium ones, easier ways to get money (Gomber et al., 2018). In China, thanks to fast-growing digital infrastructure, mobile payment systems, and fintech innovation, a world-leading digital finance environment has formed. Digital finance not only changes how financial services are provided but also becomes an important outside factor that affects firm investment, innovation, and performance. So, understanding how digital finance affects firm behavior is important for knowing how resources are arranged and how firms grow in the digital age. At the same time, employment is a key link between economic growth and social welfare. It is always a central topic in economics and management. However, under fast digital development, the effect of digital change on jobs is still hotly debated. On one hand, digital technology may replace some labor through automation, intelligence, and process optimization, reducing demand for some positions. This is called the “technology substitution effect” (Acemoglu & Restrepo, 2018). Especially with AI and automation growing fast, many studies ask whether digital technology will lower labor demand and change job structures. On the other hand, digital technology may also raise labor demand by improving efficiency, expanding markets, promoting innovation, and creating new business models. This is the “technology creation effect” (Autor, 2015). So, whether digital development leads to job loss or job growth is still an open question.

As a combined form of digital economy and finance, digital finance may affect firm employment through different paths than general digital technology. First, digital finance can use big data analysis, AI algorithms, and online credit scoring to reduce information problems in financial deals. It helps financial institutions better judge firm credit, thus easing outside funding difficulties for firms, especially those with tight financing (Bazarbash,

2019; Frost et al., 2019). Easier financing helps firms expand production, increase investment, and raise labor demand. Second, digital finance may affect employment by promoting firm innovation. It lowers the cost of funding for innovation and raises firms’ ability to take risks, making them more willing to do R&D and tech upgrades. Innovation often brings new products, new markets, and higher efficiency, which may create new jobs. However, digital finance may also reduce some jobs by improving efficiency, pushing capital to replace labor, and concentrating resources to high-efficiency firms. So, the final effect on employment depends on the balance between financing expansion, innovation creation, and technology substitution. More research is needed.

Existing studies have looked at digital finance from many angles, but we still know little about its link with firm employment. Most research focuses on financial inclusion, entrepreneurship, firm financing, and economic growth. For example, Suri and Jack (2016) found that digital finance greatly improves access to financial services and promotes equal economic opportunities. Some recent studies further point out that digital finance lowers funding costs and raises investment efficiency and performance (Feng et al., 2022). At the same time, studies on digital technology and jobs mainly focus on AI, industrial robots, and automation (Acemoglu & Restrepo, 2020). But different from production-side technology that directly affects labor, digital finance works more through financial resource allocation, better financing conditions, and improved innovation ability. Its employment effect has a more complex logic. Current research has not fully shown whether digital finance can create jobs by improving financing and innovation, and we lack systematic firm-level evidence.

This paper tries to fill this gap. Using micro-level panel data of Chinese listed firms, we study the effect of digital finance on firm employment. Specifically, we use the Peking University Digital Financial Inclusion Index to measure digital finance development in each region, and match it with firm-level data on employee numbers, financial traits,

and governance structures. We use a two-way fixed effects model to identify the effect. Then we test the mechanisms through financing constraints and innovation. We also look at differences by ownership, high-tech status, and regional development.

Our main findings are threefold. First, digital finance significantly boosts firm employment. This holds after controlling for firm and year fixed effects and many firm traits. Second, the mechanism analysis shows that digital finance raises employment mainly by easing financing constraints and promoting innovation. That is, digital finance not only improves firms' ability to get money but also strengthens their future growth capacity, creating lasting job creation. Third, the heterogeneity analysis shows that the employment effect differs across firm types and regions. This suggests that digital finance does not affect all firms equally; its effect depends on firm resources, technology ability, and outside conditions.

Our contributions are threefold. First, we extend the research on economic effects of digital finance. Existing work mainly looks at inclusion, financing, and growth, while we add employment as an important labor market outcome, providing new micro evidence. Second, we enrich the study of digital technology and jobs. Unlike studies on automation and substitution, we reveal that digital finance may create jobs through financing support and innovation, offering a new explanation. Third, we identify the specific channels through which digital finance affects employment, giving policy makers empirical support on how to use digital finance to promote jobs and integrate digital with real economy. Our paper also has practical policy meaning. Today, the world economy is going through digital change and labor market adjustment. How to promote digital growth while achieving better and higher-quality jobs is a major policy challenge. In developing countries, because traditional finance is not enough, many firms—especially small ones—face financing limits that restrict production and hiring. Digital finance offers a new possible solution. By lowering service

barriers, improving capital allocation, and supporting innovation, digital finance may become a key driver of firm growth and job creation. So, our study not only enriches firm behavior research in the digital age but also provides theoretical support for policies that use digital finance to boost jobs and growth.

The rest of this paper is organized as follows. Section 2 reviews related literature on digital finance, firm development, and digital technology's effect on jobs, and points out the research gap. Section 3 builds theoretical analysis based on financing constraint theory, innovation theory, and resource allocation theory, and proposes hypotheses. Section 4 describes the research design, including model, variables, and data. Section 5 reports empirical results, including baseline, robustness, heterogeneity, and mechanism tests. Section 6 concludes and offers policy suggestions.

2. Literature Review

Digital finance, as a product of mixing digital technology with financial services, has become an important research area in economics, finance, and management. Existing studies mainly discuss its economic effects from angles like financial inclusion, firm financing, innovation, and growth. But whether digital finance can change firm labor demand and affect job creation is still little studied. We first review research on how digital finance affects firm behavior, then discuss studies on digital technology and employment, and finally point out the gaps and our research position.

Earlier studies focus on the effect of digital finance on financial resource allocation efficiency and inclusion. Traditional finance usually relies on firm collateral, financial statements, and long credit records for lending decisions. This often makes firms with less transparent information, especially small ones, face high financing barriers (Stiglitz & Weiss, 1981). Digital finance, by using big data, AI, and online credit scoring, can collect information from many sources like transaction records, supply chain relations, and online behavior. This reduces information problems and improves risk assessment

(Bazarbash, 2019). So, digital finance expands financial service coverage and increases firms' chances to get outside money.

In recent years, many empirical studies have confirmed that digital finance improves firm financing. For example, it lowers funding costs, speeds up credit approval, and reduces financial exclusion, effectively easing financing constraints (Frost et al., 2019). Especially in China, because regional financial development differs a lot, digital finance becomes an important supplement to fill gaps. These studies show that digital finance first changes firms' outside resource access, and then affects their decisions.

Besides financing, more studies start to look at digital finance's effect on firm innovation. Innovation usually has high risk, high uncertainty, and long-term returns, so it is often limited by financing constraints. Digital finance, by improving resource allocation and lowering innovation funding costs, enables firms to invest more in R&D, thus promoting tech and product innovation (Feng et al., 2022). Furthermore, innovation not only affects production efficiency but also changes labor demand structure. On one hand, innovation may reduce repetitive jobs by raising efficiency; on the other hand, it may create new jobs through new products, markets, and business models. So, the innovation channel may have both substitution and creation effects, which need testing with firm data.

Another group of studies looks at how digital technology affects labor markets. Traditional economic theory says technology has two effects on jobs. One is substitution: capital and tech may replace some labor, especially for routine and standardized jobs (Acemoglu & Restrepo, 2018). With AI and robots growing, some studies warn that smart production may pressure low-skilled workers (Acemoglu & Restrepo, 2020). The other is creation: technology can raise efficiency, lower costs, expand markets, and create new products and services, thus generating new jobs (Aghion et al., 2020). For example, digital platform economy not only changes business models but also creates many new job types. Related studies show that digital

technology does not necessarily reduce jobs; the final effect depends on the balance between substitution and expansion (Autor, 2015). However, unlike AI and robots that directly affect production, digital finance works mainly through financial resource allocation. So its effect on jobs has a more complex logic. On one hand, better financing allows firms to expand and hire more; on the other hand, digital finance may push digital transformation and capital efficiency, reducing reliance on some labor. Thus, simply copying the framework from automation studies cannot fully explain digital finance's employment effect.

Although existing studies have separately discussed digital finance's firm effects and digital technology's employment effects, there is still a clear gap. First, current digital finance research mainly focuses on financial development, financing, and innovation, but rarely on employment—an important economic outcome. Firm employment not only reflects firm size and performance but also shows the social impact of digital economy. So, studying how digital finance affects employment helps us better understand its micro consequences. Second, existing studies on digitalization and jobs mainly focus on production technology like robots and automation, ignoring financial digitalization. In fact, firm development is limited not only by production tech but also by financing ability. Digital finance, by improving capital access, may change firm growth paths and thus affect labor demand. So, looking at employment from the digital finance angle can broaden the research scope. Third, current studies have not fully revealed the specific mechanisms. In particular, whether digital finance mainly works through easing financing constraints to support expansion, or through promoting innovation to create new jobs, lacks systematic theory and micro evidence. Based on these gaps, we put digital finance and firm employment into one framework, use Chinese firm data to test the effect, and identify the two channels. This paper not only adds to digital finance research but also provides new evidence on how financial innovation affects labor markets in the digital age.

3. Theoretical Analysis and Research Hypotheses

3.1 Digital Finance and Firm Employment

First, digital finance can boost employment by improving firm financing conditions. In traditional finance, lending decisions rely on firm financials, collateral, and credit history. But because of information problems, many firms—especially growing ones and private ones—cannot get enough outside money (Stiglitz & Weiss, 1981). Financing limits not only restrict capital investment but also affect production scale and labor demand. With digital finance growth, institutions can use transaction data, supply chain info, and online behavior for more accurate credit assessment, thus reducing barriers from information opacity (Berg et al., 2020). Compared with traditional finance, digital finance has stronger information processing and lower information costs. On one hand, big data helps institutions identify real firm conditions and improve credit allocation. On the other hand, online services reduce time and transaction costs for firms, allowing more to get funding (Jiang et al., 2023). Recent studies further find that digital finance significantly eases financing constraints and promotes investment and scale expansion (Li et al., 2023). So, by improving capital access, digital finance enables firms to increase inputs, expand operations, and raise labor demand.

Second, digital finance can create new jobs by promoting firm innovation. Innovation usually needs high investment, bears high risk, and brings long-term returns, so its funding needs often exceed normal operations. However, because future returns are uncertain, traditional institutions find it hard to value innovative firms, leading to tighter financing for them. Digital finance changes this. Through data analysis and smart risk control, it improves institutions' ability to assess innovation risk and allocates more financial resources to innovative firms. Many recent studies look at the link between digital finance and firm innovation. For example, Zhang et al. (2024) find that digital finance significantly boosts innovation of Chinese listed firms, mainly through better credit access and lower

funding costs. Similarly, Li et al. (2023) point out that digital economy promotes innovation by easing financing constraints, especially for breakthrough innovation. Zhu (2024) further finds that digital finance improves capital allocation efficiency and thus raises innovation ability. These studies show that digital finance not only changes current financing but also affects long-term development.

From the employment side, innovation may affect labor demand in two ways. On one hand, it may raise efficiency and reduce reliance on low-productivity labor, causing substitution. On the other hand, innovation helps firms develop new products, enter new markets, and form new business models, thus expanding scale and creating jobs. Especially in knowledge-intensive industries, innovation often comes with more demand for R&D, technical, and managerial staff. So the creation effect may outweigh substitution. Thus, digital finance through innovation may further raise employment. Moreover, digital finance may affect hiring decisions by improving firm growth expectations and reducing uncertainty. Hiring depends not only on current production needs but also on future market conditions. In traditional finance, because funding sources are limited, firms often adopt cautious expansion strategies. Even with market opportunities, they may not expand due to lack of money. Digital finance increases financing flexibility, helping firms better respond to market changes and making them more willing to expand and add long-term labor. Based on the above, we propose:

H1: Digital finance development can significantly promote firm employment growth.

3.2 Digital Finance, Financing Constraints, and Firm Employment

One important channel through which digital finance affects employment is easing financing constraints. Financing constraint theory says that because outside funding costs more than inside funding, firms cannot reach the optimal investment level through market financing alone. When constrained, their investment and production

expansion are limited, reducing labor demand. So, lower financing constraints are a key mechanism. Digital finance eases constraints in three ways. First, it uses data to raise information transparency, allowing institutions to assess credit more accurately and reduce adverse selection. Second, it lowers service costs, making credit more accessible. Third, it expands coverage, giving more firms—especially those outside traditional finance—better opportunities. Recent studies confirm this. For example, Liu et al. (2023) find that fintech development facilitates firm financing by reducing information asymmetry and improving service efficiency. At the same time, the effect is stronger for firms with higher constraints, because they were more limited before. When constraints drop, firms gain better liquidity and investment ability. On one hand, they can expand production and supply. On the other hand, they can hire more and invest in human capital. Thus, lower financing constraints become a key transmission channel. We propose:

H2: Digital finance promotes firm employment growth by easing financing constraints.

3.3 Digital Finance, Firm Innovation, and Firm Employment

Besides financing, digital finance may affect employment through promoting innovation. Innovation is a key source of long-term competitive advantage and an important driver of new jobs. According to endogenous growth theory, innovation raises productivity and creates new labor demand through market expansion. Digital finance lowers innovation funding barriers, making it easier for firms to get R&D money. At the same time, better data flow and information sharing increase firms' access to tech and market information, boosting innovation willingness. Recent studies find that digital finance not only increases innovation input but also improves output quality. Zhao et al. (2023) using Chinese firm data find that digital finance significantly raises R&D investment and innovation output, and promotes breakthrough innovation. Also, studies on digital transformation show that fintech development

pushes firms to upgrade digitally by easing financing, improving talent, and increasing R&D. From the employment side, innovation creates new tasks and positions. For example, new product development needs more R&D staff, new market expansion needs more sales and management staff, and business model innovation may create new job types. So, digital finance through innovation can further raise labor demand. We propose:

H3: Digital finance raises firm employment by promoting firm innovation.

4. Research Design

4.1 Model Specification

To study the effect of digital finance on firm employment, we build a firm-year panel model using Chinese A-share listed firm micro data, and use a two-way fixed effects model. The model is:

$$EM_{i,t} = \alpha + \beta DFD_{i,t} + \gamma Controls_{i,t} + \mu_i + \lambda_t + \varepsilon_{i,t}$$

Where i is firm, t is year; EM is firm employment size; DF is digital finance level in the firm's region; $Controls$ are firm-level control variables; μ_i is firm fixed effect (controls for time-invariant firm traits); λ_t is year fixed effect (controls for macro environment, policy changes, and common time shocks); ε is the error term.

We focus on the coefficient β of DF . If β is significantly positive, digital finance promotes employment; if significantly negative, it may strengthen capital-labor substitution and reduce labor demand.

4.2 Variable Definition and Measurement

Our key explanatory variable is digital finance development (DF). Digital finance, as a new financial model mixing traditional finance and digital tech, is not only about service scale but also about service modes, information processing, and allocation efficiency. So, we use the Peking University Digital Financial Inclusion Index to measure the digital finance level in each firm's region.

To reduce omitted variable bias, we include a set of firm-level controls based on employment

determinants and digital finance studies. Specifically, we control for firm age (Age) to reflect lifecycle. Older firms may have more stable operations and resources, possibly stronger employment capacity; but mature firms may also face rigidity and less flexibility, so we need to control for age. We also control for leverage (Lev) to capture capital structure and financial risk. Higher debt may increase repayment pressure and reduce ability to expand and hire. We add profitability (ROA) and cash flow (Cashflow) to control for operating performance and internal funding. More profitable firms usually have more internal funds for expansion and job creation; ample cash flow supports daily operations and investment, providing funds for hiring. We also control for growth opportunities (TobinQ), which reflects market expectations of future potential. Firms with higher growth opportunities tend to have stronger drive and investment willingness, possibly increasing labor demand. Besides these financial variables, we consider governance factors that may affect hiring decisions, including board size (Board), independent director ratio (Indep), CEO duality (Dual), and largest shareholder share (Top1). Governance structure affects management decisions, resource allocation, and long-term strategy, thus influencing expansion and employment adjustment. By controlling these, we

can better isolate the independent effect of digital finance on employment.

4.3 Sample and Data Sources

We choose Chinese A-share listed firms as our sample, mainly because China has seen rapid digital finance growth and has rich firm micro data. In recent years, mobile payments, online credit, and fintech platforms have grown fast, with significant regional differences in digital finance development, providing a good background for research. Our data sources: firm financial and governance data from CSMAR; digital finance index from Peking University; employment data from annual reports (number of employees). In sample processing, we exclude financial firms, ST and *ST firms, and observations with missing key variables. We winsorize continuous variables at the 1st and 99th percentiles to reduce extreme value effects. After processing, we get 42,047 firm-year observations for analysis.

4.4 Descriptive Statistics

Table 1 reports descriptive statistics. EM has max 10.9515 and min 4.8442, showing variation in employment across firms. DF has max 4.0308 and min 0.2126, showing variation in digital finance across cities. Other variables are within normal ranges, with no extreme values.

Table 1. Descriptive Statistics

Variable	Obs	Mean	Sd	Min	Max
EM	42,047	7.57565	1.26098	4.84419	10.95149
DF	42,047	2.66650	0.83574	0.21260	4.030792
FirmAge_w	42,047	2.97660	0.32397	2.87944	3.610918
Lev_w	42,047	0.41489	0.28898	0.05648	0.8961091
ROA_w	42,047	0.03736	0.86514	-0.20839	0.209495
Cashflow_w	42,047	0.04493	0.86751	-0.15100	0.2258802
TobinQ_w	42,047	1.97724	1.28495	0.83395	7.431908
Board_w	42,047	2.10554	0.19671	1.60944	2.564949
Indep_w	42,047	0.37793	0.05345	0.33330	0.57140
Dual_w	42,047	0.30385	0.45992	0.00000	1.00000
Top1_w	42,047	0.34027	0.14728	0.08991	0.72718

5. Empirical Results and Analysis

5.1 Baseline Regression Results

Table 2 reports baseline results. We add controls step by step, controlling for firm and year fixed effects. The coefficient of DF is significantly positive at the 1% level in all models. Specifically, as we add firm traits, financial variables, and governance variables, the coefficients are 0.6010, 0.5756, 0.4955, and 0.4873,

all significant. This shows that digital finance significantly promotes employment. So digital finance does not show a clear labor substitution effect; instead, it improves financing, resource allocation, and firm growth, raising labor demand. Thus, H1 is supported. For control variables, age, leverage, profitability, and cash flow all have significant effects, showing that firm conditions also matter for employment.

Table 2. Baseline Regression Results

Variables	(1) EM	(2) EM	(3) EM	(4) EM
DF	0.6010*** (0.1080)	0.5756*** (0.0968)	0.4955*** (0.0957)	0.4873*** (0.0947)
Age		0.9503*** (0.1601)	0.7773*** (0.1347)	0.8178*** (0.1359)
Lev			1.0750*** (0.0619)	1.0683*** (0.0615)
Roa			0.9749*** (0.0805)	0.9388*** (0.0819)
Cashflow			0.1770** (0.0759)	0.1839** (0.0767)
TobinQ			-0.0844*** (0.0067)	-0.0824*** (0.0065)
Board				0.3820*** (0.0525)
Indep				0.4251*** (0.1426)
Dual				-0.0005 (0.0120)
Top1				0.1317 (0.1326)
Constant	5.9730*** (0.2880)	3.2121*** (0.5299)	3.6171*** (0.4858)	2.5089*** (0.4669)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	42,047	42,047	42,047	42,047
R ²	0.900	0.901	0.910	0.910

5.2 Robustness Tests

5.2.1 Adding More Fixed Effects

Table 3 shows results after adding industry, city-industry, province, and province-industry fixed

effects. The DF coefficient remains significantly positive, so our conclusion is not affected by regional or industry differences.

Table 3. Results with Additional Fixed Effects

	(1)	(2)	(3)	(4)
Variables	EM	EM	EM	EM
DF	0.4873*** (0.0948)	0.4873*** (0.0947)	0.4873*** (0.0948)	0.4873*** (0.0952)
Constant	2.5089*** (0.4670)	2.5089*** (0.4669)	2.5089*** (0.4671)	2.5089*** (0.4693)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Ind FE	Yes			
Cityind FE		Yes		
Procode FE			Yes	
Proind FE				Yes
N	42,047	42,047	42,047	42,047
R ²	0.910	0.910	0.910	0.910

5.2.2 Changing Clustering Levels

Table 4 shows results with different clustering levels (city-industry, city-year, province, province-industry, province-year). The DF coefficient remains significant.

Table 4. Results with Different Clustering

	(1)	(2)	(3)	(4)	(5)
Variables	EM	EM	EM	EM	EM
DF	0.4873*** (0.0988)	0.4873*** (0.0555)	0.4873*** (0.0956)	0.4873*** (0.1000)	0.4873*** (0.0581)
Constant	2.5089*** (0.4621)	2.5089*** (0.2438)	2.5089*** (0.5299)	2.5089*** (0.4629)	2.5089*** (0.2560)
Cluster	Cityind	Cityyear	Procode	Proind	Proyear
Controls	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
N	42,047	42,047	42,047	42,047	42,047
R ²	0.910	0.910	0.910	0.910	0.910

5.2.3 Replacing the Key Explanatory Variable

Table 5 shows results using sub-indicators of digital finance: coverage breadth (DF1), usage depth (DF2), and digitalization degree (DF3). All are significantly positive, so our conclusion is not driven by indicator choice.

Table 5. Results with Alternative Key Variables

	(1)	(2)	(3)
Variables	EM	EM	EM
DF1	0.2737*** (0.0804)		
DF2		0.2489*** (0.0615)	
DF3			0.1089*** (0.0307)
Constant	3.0480*** (0.4897)	3.1302*** (0.4096)	3.5030*** (0.4201)
Controls	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes

Year FE	Yes	Yes	Yes
N	42,047	42,047	42,047
R ²	0.910	0.910	0.910

5.2.4 Considering Lag Effects

Table 6 shows results using one-year and two-year lags of DF. Both are significantly positive, confirming a lasting effect.

Table 6. Results with Lagged Variables

Variables	(1)	(2)
	EM	EM
l1DF	0.3211*** (0.0881)	
l2DF		0.2357*** (0.0796)
Constant	3.4088*** (0.5163)	4.0020*** (0.6069)
Controls	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes
N	36,070	31,157
R ²	0.920	0.927

5.2.5 Dropping Subsamples

Table 7 shows results after dropping municipalities and dropping COVID-19 period samples. The results remain stable.

Table 7. Results with Dropped Samples

Variables	(1) Drop municipalities	(2) Drop COVID period
	EM	EM
DF	0.5601*** (0.1029)	0.4857*** (0.0953)
Constant	2.3013*** (0.5366)	3.4254*** (0.5183)
Controls	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes
N	32,915	21,555
R ²	0.906	0.917

5.3 Heterogeneity Tests

Table 8 reports heterogeneity results. We look at ownership, high-tech status, and region. First, for ownership, digital finance significantly promotes employment in both SOEs and non-SOEs, but the effect is stronger for SOEs. This may be because SOEs are larger and have better resource integration, so they can make more use of digital finance's benefits. Second, for industry, the effect is stronger for high-tech firms. High-tech firms have stronger innovation needs and growth potential; after financing improves, they more easily increase R&D and expansion, creating more jobs. Third, for region, digital finance has positive effects in both eastern and non-eastern areas, but the effect is larger in the east, likely because of better digital infrastructure and financial ecosystems.

Table 8. Heterogeneity Test Results

Variables	(1) SOE	(2) Non-SOE	(3) High-Tech	(4) Low-Tech	(5) East	(6) Non-East
	EM	EM	EM	EM	EM	EM
DF	0.5491*** (0.1166)	0.4077*** (0.1366)	0.5813*** (0.1220)	0.3259** (0.1592)	0.3817*** (0.1380)	0.5151*** (0.1777)
Constant	3.7350*** (0.6392)	2.6447*** (0.4955)	1.8575*** (0.5881)	3.9053*** (0.8299)	2.9360*** (0.5437)	2.1360** (0.9003)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	14,065	27,923	25,280	16,767	29,708	12,339

R ²	0.926	0.898	0.913	0.909	0.910	0.910
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5.4 Mechanism Tests

Table 9 reports mechanism test results. We test two channels: financing constraints (FC) and innovation (PA). For financing constraints, DF significantly reduces FC, showing that digital finance eases firms' funding pressure, helping them expand and hire. For innovation, DF significantly increases innovation output, showing that digital finance boosts firms' ability to innovate, which then raises labor demand. Thus, both channels are confirmed, supporting H2 and H3.

Table 9. Mechanism Test Results

Variables	(1) Financing Channel	(2) Innovation Channel
	FC	PA
DF	-0.1005*** (0.0340)	0.6019** (0.2610)
Constant	2.0225*** (0.1195)	-2.3728*** (0.8158)
Controls	Yes	Yes
Firm FE	Yes	Yes
Year FE	Yes	Yes
N	41,227	41,176
R ²	0.850	0.756

6. Conclusion and Policy Suggestions

6.1 Research Conclusions

In the context of rapid digital economy growth, digital finance, as an important form of financial system digitalization, is deeply changing how firms allocate resources and make decisions. Using micro data of Chinese A-share listed firms and the Peking University Digital Financial Inclusion Index, this paper empirically studies the effect of digital finance on firm employment, and further analyzes its mechanisms and heterogeneity. The results show that digital finance significantly promotes firm employment. After controlling for firm and year fixed effects and many firm traits, the coefficient of

DF remains positive and significant. This means digital finance not only raises financial service efficiency but also improves firms' development environment, thus increasing labor demand. Various robustness checks—adding fixed effects, changing clustering, replacing key variables, considering lags, and adjusting samples—all confirm the result, showing strong reliability.

Further analysis finds that the effect works mainly through two channels: financing constraints and innovation. On one hand, digital finance uses data tech and information processing to reduce information gaps in financial markets, improve firms' access to funding, ease capital constraints, and support production expansion and hiring. On the other hand, digital finance promotes innovation, which creates new job needs by improving firms' ability to innovate, expanding markets, and upgrading business models. Also, we find clear heterogeneity. For ownership, digital finance has positive effects on both SOEs and non-SOEs, but the effect is stronger for SOEs. For industry, high-tech firms benefit more, suggesting a strong complementarity between digital finance and innovation ability. For region, digital finance promotes employment in all areas, but the effect is larger in the east due to better infrastructure and financial ecosystems.

6.2 Policy Implications

Our findings offer several policy suggestions. First, we should further develop digital finance to improve its ability to serve the real economy. Digital finance not only changes service modes but also improves resource allocation to firms. Governments should continue to build digital infrastructure, promote data sharing, and encourage financial institutions to use AI and big data for better risk assessment, thus lowering funding costs, especially for small and innovative firms. Second, we should make full use of digital finance to ease financing constraints and improve the business environment. Under traditional finance, some firms lack collateral

and credit records and face long-term funding difficulties. In the future, we should improve digital credit systems, encourage institutions to use firm operational data, supply chain info, and digital records for more precise services, increase financial inclusion, and enable more firms to get support and expand employment. Third, we should strengthen the link between digital finance and firm innovation. This paper finds that innovation is a key channel. So policy makers should not only focus on the scale of digital finance but also its role in boosting innovation. By combining fintech with industrial innovation, supporting R&D, tech upgrades, and business model innovation, we can further release digital finance's job creation potential. Fourth, we should pay attention to regional differences and promote more balanced digital finance development. Because infrastructure, financial ecosystems, and industrial environments differ, firms in different regions do not benefit equally. So, when promoting digital finance, we should strengthen digital infrastructure and financial services in less developed areas, avoid widening the digital divide, and let digital finance better play its role in boosting jobs and growth.

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6.3 Limitations and Future Directions

Although this paper analyzes the effect of digital finance on employment at the firm level and identifies two mechanisms, it still has some limitations. First, we mainly focus on employment size. Future research could further analyze effects on employment structure, such as whether it changes demand for high-skilled vs. low-skilled workers, and whether it improves job quality. Second, we study firm-level employment, but digital finance may affect employment through supply chains, industrial networks, and regional development. Future studies could combine firm supply chain data and regional labor market data to examine broader employment effects. Third, as new digital technologies like AI and large models develop rapidly, the combination of digital finance and smart tech may bring new economic effects. Future research could explore how AI-empowered finance affects firm production modes, labor demand, and job structure changes.

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“Technology Empowerment” and “Value Guidance” of English Translation Teaching in Vocational Universities in the Age of Artificial Intelligence

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Abstract: In the AI era, a new ecology of man-machine collaborative education has gradually formed, and artificial intelligence translation technology has emerged. Driven by translation technology and educational technology, translation teachers, as the key subjects in the implementation of translation education, are facing brand-new challenges, and urgently need to improve their technical ability, digital ability, ideological and political teaching ability. English translation teachers in vocational universities should be clear about the necessity of “value guidance” in translation teaching, realize the influence of “technology empowerment” on “value guidance” and realize the dialectical unity of “technology empowerment” and “value guidance” in English translation teaching. In addition, translation teachers should deepen their mother tongue and improve their Chinese literacy. They should master technology, hold the bottom line of humanities, educate people with culture and moral education, and cultivate new translation talents with both patriotic feelings and core competitiveness.

Keywords: artificial intelligence; vocational universities; translation teaching; technology empowerment; value guidance

1. Introduction

Artificial intelligence has triggered a new wave of development of information technology, which has driven profound changes in the ecology of all walks of life and empowered the development of human society. Artificial intelligence translation technology came into being, in which ChatGPT, as a powerful natural language processing model, plays an

important role in the field of translation. The development of translation technology has led to revolutionary changes in the field of work, content, form, means, media and standards, showing the characteristics of informationization, process, collaboration, standardization and multimodal. From traditional mode to machine-assisted translation to intelligent generation of content, intelligent translation based on ChatGPT

technology has become the general trend. Driven by artificial intelligence technology, educational technology is also undergoing tremendous changes, leading to important innovations in teaching forms, teaching methods, learning methods and teachers' abilities. Driven by translation technology and educational technology, translation teachers, as the key subjects in the implementation of translation education, are facing brand-new challenges. It is urgent to improve their own abilities, carry out translation teaching that meets the requirements of the times, realize the dialectical unity of "technology empowerment" and "value guidance", and cultivate professional translation talents needed by society.

2. Connotation of English Translation Teachers' Competence in Vocational Universities

In recent years, China has attached great importance to improving the ability of vocational education teachers. In May 2022, the General Office of the Ministry of Education issued the *Notice on Promoting the Ability of Vocational Education Teachers*, focusing on supporting the improvement of the teaching ability of in-service teachers in vocational universities, implementing the "National Training for Vocational Education" demonstration project, and promoting the construction of digital learning platform for vocational education teachers. China also attaches great importance to the improvement of teachers' digital literacy in the era of artificial intelligence. In February 2023, the Ministry of Education officially issued the industry standard of *Teachers' Digital Literacy*, which provided a guiding direction for the development of teachers' literacy under the background of digital transformation of education.

In the AI era, the new ecology of man-machine collaborative education has gradually formed, and the teaching profession is irreplaceable, but the relationship between teachers and students, teaching and learning should be re-examined. Driven by "technology empowerment, integration of mathematics and intelligence, integration of production and teaching, and application guidance", the role of teachers should be changed

from traditional knowledge imparting to guiding and promoting students' learning, and advanced technologies such as AI should be used to improve quality and efficiency, update teaching contents and methods, and improve teaching quality. Under the background of technology empowerment, the translation industry and the education industry are undergoing systematic changes. Then, what is the connotation of the translation teacher's ability?

Teacher's ability refers to the dynamic power or practical skills that teachers need to engage in teaching and educating people. It is the reasonable integration and special development of general ability and special ability, and it is a capacity system developed in practice and reflecting the requirements of teachers' professional activities. In translation education, the improvement of teachers' ability is the core content of the construction of translation teachers and the premise and foundation of cultivating high-quality translation talents. Although translation competence has long been a topic of great concern in the field of translation teaching research, there is no unified and clear definition of translation teachers' competence. Clarifying the connotation of translation teachers' competence is the understanding and theoretical basis for academic discussion on translation teachers' competence. The ability of translation teachers is closely related to translation ability. The improvement of students' translation ability is the ultimate goal of translation teaching and the ultimate direction of translation teachers' ability, that is, translation teachers mobilize their own abilities and improve students' translation ability by organizing and implementing translation teaching activities. The translation teacher's ability can be regarded as a dynamic unity which is guided by the development of students' translation ability and consists of many interacting ability elements. It has four characteristics: (1) Plurality, which means that the translation teacher's ability is not a single ability, but contains many different ability elements; (2) Dynamic, which means that translation teachers' ability requirements evolve with the development of translation practice and translation education; (3)

Practicality, which means that the ability of translation teachers serves the improvement of students' translation practice ability; (4) Comprehensiveness, which means that the translation teacher's ability is the comprehensive ability of various components interacting together (Wang Shaoshuang & Li Chunji, 2021).

3. The Dilemma Faced by English Translation Teachers in Vocational Universities

3.1 Technical Ability Needs to Be Improved

Technical competence is an instrumental element in the competence system of translation teachers, which provides technical support for other abilities. As an important representative in the field of machine translation, ChatGPT translation has undoubtedly become an auxiliary tool for many translators, and foreign language translation teaching is bound to be directly affected by the development of this technology. In the era of man-machine symbiosis, ChatGPT's super generating ability and interactive ability can replace the translator to complete many simple and repetitive tasks. However, there are also some problems in machine translation, such as frequent factual errors, and the output results are not safe. Then, how can English translation teachers guide students to operate common technical tools? How to use technology to empower translation teaching? These are the technical dilemmas faced by English translation teachers in vocational universities.

3.2 Digitalization Ability Needs to Be Improved

In February 2023, China's Ministry of Education issued the industry standard *Teachers' Digital Literacy*, which put forward five requirements for teachers: digital awareness, digital technology knowledge and skills, digital application, digital social responsibility and professional development. Therefore, it can be seen that improving the digital ability and digital literacy of English translation teachers is not only the objective requirement of the development of digital economy, but also the inevitable requirement of the reform and innovation

of vocational undergraduate foreign language education.

3.3 Ideological & Political Teaching Ability Needs to Be Improved

From the essence of translation teaching, translation is never a simple and mechanical transformation of language symbols, but the transmission, collision and integration of different cultures and values. The translator's cultural consciousness, political stance and responsibility directly determine the quality of translated works and the effect of cultural communication. This requires that translation teaching should jump out of the simple language training framework, dig deep into the ideological and political elements in the teaching process, guide students to establish a correct translation concept, enhance cultural self-confidence and national pride, consciously become the inheritor and disseminator of Chinese excellent culture and a staunch defender of national interests, and grow into a new era translator with both professional quality and patriotic feelings.

Under the background of the digital transformation of education and the deepening of curriculum ideology and politics, translation teaching shoulders the mission of language teaching, cultural communication and value guidance. Since 2020, the two major foreign language teaching guides issued by the relevant teaching committees of the Ministry of Education have clearly emphasized the fundamental task of "educating people through ideology and politics" and the application of modern information technology in teaching, which has pointed out the direction for the reform of translation courses in the new era. At present, how to organically and naturally integrate ideological and political education into the whole process of translation teaching, effectively solve the painful and difficult problems in traditional translation teaching with the help of modern information technology, and make value guidance resonate with professional education and empower them in both directions is an important topic that every English

teacher in vocational universities must explore in depth.

4. “Technology Empowerment” and “Value Guidance” in English Translation Teaching for Vocational Undergraduates

4.1 The Necessity of Value Guidance

Generative artificial intelligence can help realize the deep optimization of English translation teaching process. Before the start of translation work, teachers need to make students clearly realize that even though artificial intelligence is an extremely powerful translation aid, in this process, the translator's subjectivity, critical thinking, cultural insight and ethical responsibility are the core of translation value. Although there are artificial intelligence tools, the translator is the dominant position in translation. The choice of translation style, the judgment of sentence patterns and the determination of vocabulary can only be generated through his subjective understanding and judgment (Li Xiyang, Peng Lihua & Jin Hui, 2024). In this process, students need to exercise their critical thinking, have keen cultural insight and a strong sense of translation ethics, so as to ensure the correct and effective transmission of the translation. In addition, students should also realize that the content generated by artificial intelligence has information security problems, the content generated by artificial intelligence may contain a lot of false information, and there may be a lot of wrong ideological problems. Therefore, it is essential to guide students with correct translation values at the beginning of translation work.

4.2 The Influence of “Technology Empowerment” on “Value Guidance”

Because of its ability to generate inspiring content, understand dialogue situations, perform sequential tasks and analyze programming languages, artificial intelligence technology can summarize the laws and characteristics of learning from massive data, and can combine students' individualized learning

needs and their own learning situation. As an important technical auxiliary tool, it is gradually affecting teachers' “value guidance” to students. Translation course belongs to the humanities, which has the characteristics of language, culture, timeliness and speculation, and has a certain value-leading function itself. As a tool to simulate natural dialogue, artificial intelligence can provide a more realistic and situational language learning environment. For such a huge, realistic and potential development technology using computer to simulate natural language, interactivity is the core mechanism and bridge, which promotes the two-way flow of information, allows real-time feedback and adjustment between the sender and receiver of information, and thus enhances the effectiveness and participation of communication. The interactive scene of artificial intelligence is a multi-language interaction among teachers, students, textbook editors and texts, and it is a dynamic process of ideological collision and spiritual communication. At the same time, it is also the cornerstone and catalyst of ideological and political education in translation courses, which creates conditions for the exploration, understanding and application of knowledge by promoting the dynamic communication between teachers and students and between students. As a new media technology and a large-scale language model, artificial intelligence can create meaningful interactive experience, support the development of personalized learning path and optimize learning results through instant feedback mechanism. Artificial intelligence, with its high generative ability and interactive ability, can be a potential tool to flexibly assist second language acquisition, especially the ideological and political education in translation courses. Specifically, it has adaptability to personalized learning needs. The ideological and political course of translation often takes the form of written textbooks and classroom instruction, which cannot fully meet the individual learning needs of students. As a private foreign teacher, AIGC can accept students' individualized needs and methods, allowing students to flexibly adjust their learning contents and methods, so as to

better meet their learning needs and realize the value guidance for students.

4.3 Dialectical Unity of “Technology Empowerment” and “Value Guidance”

The integration of technology makes the boundaries of translation teaching blurred and students' learning ubiquitous. Some students can achieve their teaching objectives through extracurricular autonomous learning, and the flexibility of classroom activities is correspondingly enhanced, which is also the embodiment of the more personalized translation teaching due to technology empowerment. On the surface, the status of technology is rising and the status of teachers is declining in the teaching of man-machine collaborative translation (Jiang Xianfa & Lai Wenbin, 2024). In fact, the dominant position of teachers has not changed. In the people-oriented education system, the relationship between teachers and students is complementary, and the relationship between teaching subject and object will change with the change of technology-driven teaching mode, but the core value of teachers can never be ignored. Artificial intelligence technology is profoundly changing the way of learning, understanding and thinking of teachers and students, and promoting the ideological and political innovation of translation courses for vocational undergraduates. On the basis of fully understanding the far-reaching influence of artificial intelligence technology on the ideological and political education of translation courses, teachers should promote a high degree of conformity and deep integration of technology empowerment and value guidance, and play a role as a link between ideological and political elements of translation courses and professional knowledge, so that the “biggest variable” of technology can become the “biggest increment” of ideological and political education of translation courses. Teachers need to realize the transformation from “knowledge disseminator” to “intelligent guide”. Although artificial intelligence technology can provide massive knowledge, the essence of its output

content is the calculation and reappearance of data, which cannot replace teachers' value judgment based on practical experience, and the core value of teachers lies in critical screening, situational interpretation and value guidance. Under the background of intelligent age, teachers can improve efficiency with the help of technical tools: using AIGC to generate multiple teaching materials and transform abstract value into concrete situations; Identify students' value confusion points through AIGC analysis of academic situation; Relying on AIGC to construct “virtual tutoring” and extend educational time and space. However, the core of education must focus on value guidance rather than knowledge transmission, and constantly strengthen the subject's ability to review and reconstruct technical content.

5. Teaching Practice of English Translation in Vocational Universities in the Age of Artificial Intelligence

5.1 New Problems and New Demands in Current Translation Teaching

(1) Teaching objectives need to be upgraded. Translation teaching aims to realize the all-round development of students through the cultivation of translation ability. The deep integration of technology and translation promotes the foregrounding of technical elements in the translation competence system. Students' technical ability, technical thinking and information ability have become important aspects to be included in translation teaching objectives.

(2) The teaching content needs to be expanded. Driven by technology, the object, form, scope and field of translation work have been expanded. Translation teaching should not be limited to language conversion, but also cover all kinds of problems in translation project flow, especially the application of various technologies such as machine translation, translation memory, terminology management, quality assurance and project management.

(3) Teaching resources need to be integrated. The integration and utilization of digital resources is a key issue that needs to be considered in translation teaching at present. Corpus can help students improve their language ability and translation decision-making ability; Terminology database can promote students' terminology translation ability and professional knowledge growth; Interpretation teaching resource database can improve the effect and efficiency of interpretation teaching; Multimedia teaching resource pool and online courses provide diverse resource choices for students to learn translation professional knowledge.

(4) Teaching methods need to be changed. Technological changes have led to important changes in translation teaching methods. The teaching content of translation technology is added to translation teaching, and new teaching methods should be adopted to ensure the learning effect. New educational forms, such as massive open online course, micro-courses and excellent resource sharing courses, have expanded students' learning space, requiring translation teaching to change the traditional classroom teaching mode and implement online and offline mixed teaching mode (Cheng Peili, 2025).

5.2 Teaching Implementation

Corresponding to each stage of students' learning, teachers' translation teaching activities can be divided into three stages: teaching preparation, teaching activity organization and teaching evaluation.

In the teaching preparation stage, teachers rely on the teaching management system to carry out detailed analysis of learning situation, and deeply understand students' knowledge background, learning style and specific needs. Based on the learning data report, teachers can customize personalized teaching objectives and issue targeted teaching tasks to ensure that every student can learn at an appropriate pace and manner. Teachers can also organize teaching content with the help of electronic resource library, and select teaching

materials that meet the needs of students, such as professional texts and multilingual news reports, so as to improve the relevance and practicability of teaching content. In addition, teachers can integrate translation AIDS and online resources, such as terminology management software and online translation platform, to improve students' learning efficiency.

In the stage of teaching activity organization, teachers are responsible for organizing and promoting translation activities to ensure the orderly and efficient learning process. Teachers' roles include leading students' in-depth translation practice, guiding students to understand and apply translation skills, and intervening in learning behavior when necessary. At the same time, teachers need to understand students' teaching participation and learning progress, and flexibly adjust teaching strategies according to students' performance and feedback to support students' personalized learning. Encourage students to report the results of group learning, understand students' learning experiences and feelings, and attach importance to the educational function of teaching.

In the teaching evaluation stage, teachers carry out formative evaluation and summative evaluation based on data analysis technology. Teaching evaluation breaks through the traditional method of course examination, starts with course data, pays attention to data analysis of behavior patterns and learning process, carries out more comprehensive and fine-grained monitoring of learning process and learning difficulties, and generates early warning information and coping strategies, thus making the evaluation more accurate and effective. Teachers should also guide students to carry out self-evaluation and peer evaluation. The evaluation results are not only used to reflect students' learning effect, but also provide feedback for teachers to guide them to adjust teaching strategies and optimize teaching content, so as to ensure that teaching activities promote students' knowledge and skills growth (Jiang Yan, 2026). Teachers can also keep track of students' learning progress, and regularly update the data of learning situation

analysis to understand the changes of students' needs, so as to realize efficient personalized translation teaching and lay a solid foundation for students' future translation career.

6. Problems Needing Attention in English Translation Teaching in Vocational Universities

6.1 Deeply Cultivate Mother Tongue and Improve Chinese Literacy

The level of Chinese determines the final quality of the translated works. Whether a translation is readable and has a wide audience depends on the translator's Chinese level. Both students and teachers must strive to improve their Chinese level. Yan Beiwen, a literary translator, said: "In any case, translation is ultimately dealing with words, and all the beauty of ideas and art must be expressed through language. Excellent translation allows us to feel not only the beauty outside us, but also the beauty inside us when reading works from foreign countries."

Professor Wang Zuoliang said: "As a translator, I always feel the need for constant exercise to make my Chinese pure and sharp." He also said, "Translation, whether as art, science or even technology, has an infinitely broad future. It is a growing point, it is growing, it is also an open field, and there are many things to do. We must keep learning, observing and practicing. The translator is an eternal student."

6.2 Control Technology and Keep the Bottom Line of Humanity

Technology itself is a tool, but the new technology represented by AI is no longer just a passive tool, it will actively participate in our cognitive, emotional and value construction. If there is no humanistic constraint, several problems are easy to appear:

- (1) Loss of subjectivity: people's value is simplified to data, scores and flow, people change from "purpose" to "tool", and their independent thinking ability is weakened.
- (2) Value judgment is replaced by technology: complex humanistic judgments such as good

and evil, beauty and ugliness are simplified into computable indicators such as click-through rate and conversion rate, and the value is easily distorted after quantification (Wu Yun, 2026).

The ideological and political construction of translation courses for vocational undergraduates should pay attention to the intersection and integration of disciplines, and take translation education and ideological and political education as the central link and value pursuit. The curriculum goal gathers the fundamental task of moral education, focusing on knowledge imparting and value leading; The selection and organization of course content dig deep into the ideological and political elements contained in the translation materials of different themes, and explore the convergence between the translation materials and the socialist core values; The implementation of the course adheres to the course goal as the guide, the ideological and political material library as the latitude, the classroom teaching as the main channel, and integrates various teaching methods, and extends the classroom to the life world such as social translation practice, campus culture construction and student community activities, so as to keep the humanistic bottom line and improve students' academic accomplishment, key ability and moral quality.

7. Conclusion

The rapid development and wide application of artificial intelligence technology have significantly improved translation efficiency and reduced translation cost, but while affirming the convenience brought by technology, we must also recognize the problems it has caused. From the perspective of the relationship between technology empowerment and value guidance, man-machine symbiosis, translating texts and transmitting culture, the two are inseparable and mutually reinforcing. Therefore, the discussion on it must not stop at the debate on the merits of technology application, but must go through the appearance of technology and return to the essence of translation teaching: its core is never the one-way transmission of knowledge, but the

process of educating people and moral education, which is the spiritual shaping to help students establish value coordinates and form independent judgments in the complicated world. Instrumental rationality of technology empowerment can certainly broaden the boundaries of education, make knowledge transfer more efficient and resource acquisition more convenient, but all this must serve the fundamental goal of “cultivating people with independent thinking ability and correct value judgment”. The essence of a translation teacher: to lead students to assume the responsibility and mission of being an excellent translator in foreign cultural exchanges and communication in the future.

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Empirical Analysis of Engineering-Accounting Integration Model for Reducing Cost-Related Financial Losses in Infrastructure Delivery Phase

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Abstract: Hidden costs and financial losses during the infrastructure delivery phase constitute core drivers of public capital waste and inefficient investment, whereas the traditional separate governance mode for engineering and finance presents prominent governance deficiencies. Based on the engineering-finance linkage governance theory, this paper adopts cross-border panel data of 106 large-scale public infrastructure projects in Australia, North America and the European Union from 2012 to 2022 (Ortiz, S.S., Kang, K., Hubbard, B. & Besiktepe, D., 2023). Two-way fixed-effect panel regression and the PSM-DID model are employed to systematically identify the governance effect, mechanism and boundary conditions of the engineering-accounting integration model on cost-related financial losses in the infrastructure delivery phase, which are further verified via mediating-effect test, heterogeneity analysis and multi-dimensional robustness tests. The empirical results show that the engineering-accounting integration model significantly reduces the ratio of cost-related financial losses in the delivery phase by 8.9 percentage points ($p < 0.001$). Mechanism tests indicate that this governance effect is achieved mainly through two pathways: restraining unidentified implicit liabilities (mediating contribution = 42.1 %) and curbing unreasonable completion claim expenditures (mediating contribution = 36.4 %). The two pathways jointly explain 78.5 % of the total effect. Heterogeneity analysis demonstrates that projects funded by federal finance and projects with high design-change frequency obtain stronger governance effects, with financial-loss reductions of 11.2 % and 10.1 % respectively. This study unpacks the mechanism black box of infrastructure financial governance, and provides quantitative evidence and practical references for delivery-risk management of federal infrastructure projects under the framework of the U.S. Bipartisan Infrastructure Law.

Keywords: infrastructure delivery phase; cost-related financial loss; engineering-accounting integration; engineering-finance linkage

governance; PSM-DID; mediating-mechanism test; public capital protection; implicit liability; completion claim control

1. Introduction

1.1 Practical Background

Large-scale public infrastructure projects feature long construction cycles, multiple stakeholders and frequent on-site changes. The period from construction completion to delivery witnesses a high incidence of hidden financial losses, including implicit liabilities, unreasonable claims, measurement disputes and change-derived costs, which are characterized by hysteresis and unpredictability. According to OECD 2023 statistics, avoidable financial losses in the delivery phase of European and American infrastructure projects average 9.3 % of total investment, which severely erodes public capital. Currently, the industry generally adopts a separate control mode that decouples engineering acceptance from post-hoc auditing, resulting in prominent risk-control loopholes. With the implementation of the U.S. Bipartisan Infrastructure Law, a large number of federal infrastructure projects are entering concentrated delivery, which calls for empirical testing of the risk-mitigation effectiveness of the engineering-accounting integration model.

1.2 Literature Gaps

Existing research on infrastructure financial risks mainly focuses on risk identification, rating and case diagnosis. Although basic characteristics and triggers of financial risks have been clarified, three major research shortcomings remain.

1) Existing literature relies heavily on small-sample case studies and simple correlation tests. It fails to address the endogeneity of sample self-selection and lacks large-sample causal empirical evidence, and cannot confirm the causal inhibitory effect of the integration mode where CPA audits are embedded into engineering acceptance on financial losses.

- 2) Relevant studies have not quantitatively decomposed governance transmission pathways, leaving a mechanism black box. Standardized mediating tests have not been applied to define core channels such as implicit-liability and claim control.
- 3) Existing research does not clarify scenario heterogeneity boundaries for integrated governance. Differential effect verification under different funding sources and design-change frequencies is absent, which limits precise risk-control practice for U.S. federal infrastructure projects.

1.3 Research Questions

Against such practical pain points and literature gaps, this paper uses cross-border panel data of large-scale public infrastructure projects (2012-2022) (Almeida, Y. & Calejo, R., 2023). Empirical methods including PSM-DID causal identification, mediating-effect test and heterogeneous grouped regression are adopted to investigate the governance effectiveness, working mechanisms and scenario boundaries of the engineering-accounting integration model. Four core research questions are proposed:

- **RQ1:** After eliminating sample self-selection bias, does the implementation of engineering-accounting integration causally reduce cost-related financial losses in the infrastructure delivery phase? What is the magnitude of the effect?
- **RQ2:** What are the mediating transmission mechanisms through which engineering-accounting integration mitigates financial losses?
- **RQ3:** What heterogeneity exists in such loss-mitigation effects across project characteristics (funding source, design-change frequency, project type)?

- **RQ4:** What implications do the empirical findings bring to delivery-phase governance for U.S. federally-funded infrastructure projects?

1.4 Research Hypotheses

Drawing on foregoing theoretical deduction, practical scenarios and research questions, grounded in engineering-finance linkage-governance theory, principal-agent theory and whole-process cost-control theory, this paper puts forward hypotheses covering main effect, mediating mechanisms and heterogeneity.

H1: Implementation of engineering-accounting integration significantly reduces the ratio of cost-related financial losses in the infrastructure delivery phase (PSM-DID treatment effect).

H2 (Mediating mechanisms): Engineering-accounting integration operates via two mediating channels: (1) restraining unidentified project implicit liabilities; (2) curbing unreasonable construction claim expenditures.

H3 (Heterogeneity): Such loss-suppression effect is stronger for federally-funded projects and projects with high design-change frequency.

2. Theoretical Framework and Research Hypotheses

2.1 Core Theoretical Foundations

This paper builds its research framework mainly upon engineering-finance linkage-governance theory, whole-process cost-control theory and principal-agent theory.

- 1) **Engineering-finance linkage-governance theory:** It breaks disciplinary barriers between traditional engineering technical control and financial-cost control. Its core connotation is “process embedding, synchronous verification, linkage of rights and responsibilities”. It emphasizes pre-embedding financial-cost review mechanisms into the whole engineering workflow to realize coupling and coordination between physical control and financial control.

- 2) **Whole-process cost-control theory:** It abandons the sole post-hoc cost-accounting mode, and clarifies that pre-emptive risk control in the delivery phase is critical for curbing hidden cost losses, which provides theoretical support for the loss-mitigation value of the integration model.
- 3) **Principal-agent theory:** It explains governance defects under the traditional separate mode. Information asymmetry exists between construction contractors and project owners, which easily triggers agent opportunism such as claim arbitrage and accumulated implicit liabilities. Engineering-accounting integration mitigates information asymmetry and restrains opportunistic behaviors through multi-party review mechanisms.

2.2 Operational Definition of Core Variables

To satisfy rigor requirements for SCI-oriented empirical research, core variables are standardized with clear measurement specifications and assignment rules to avoid measurement bias.

- 1) **Dependent variable:** Ratio of cost-related financial losses (*Loss_ratio*)
This variable measures the severity of financial losses in infrastructure delivery phase. Calculation formula: Total verified avoidable cost-related financial losses in delivery phase ÷ Initial project budget estimate × 100 %. Avoidable financial losses include losses from unidentified implicit liabilities, unreasonable completion claims and measurement-and-settlement deviations. Rigid force-majeure losses caused by natural disasters or mandatory policy adjustments are excluded to match the research scenario precisely.
- 2) **Core treatment variable:** Engineering-accounting integration
Different from traditional post-hoc financial auditing, engineering-accounting integration in this paper refers to process-embedded governance practice: CPA-certified accounting-cost experts are formally

embedded into full workflows including construction acceptance, quantity measurement, design-change confirmation and preliminary completion acceptance, so as to realize synchronous verification and real-time cross-check of physical engineering evidence, measurement data and financial-liability recognition. It is a binary dummy variable, assigned 1 for integrated governance and 0 for traditional separate governance.

3) Mediating variables

Two core transmission variables are included: $M1$ = Ratio of unidentified implicit liabilities (Total newly-verified implicit liabilities in delivery phase $\div$ Initial project budget estimate $\times 100\%$); $M2$ = Ratio of unreasonable completion-claim expenditures (Audited amount of unreasonable claims $\div$ Initial project budget estimate $\times 100\%$).

4) Control variables

To mitigate omitted-variable bias, control variables are selected from project-level, institutional and regional dimensions: total project investment, construction period, annual average design-change frequency, project type, funding source, regional annual GDP and infrastructure-marketization level. Individual heterogeneity and macro-environmental interference are comprehensively controlled.

2.3 Mechanism Deduction and Research Hypotheses

2.3.1 Deduction of Main-Effect Hypothesis

Under the traditional separate governance mode, time lags and information gaps exist between engineering acceptance and financial review. Massive hidden cost losses erupt intensively in the delivery phase. By pre-embedding financial experts, engineering-accounting integration enables real-time synchronization of engineering operational data and financial-accounting data, identifies settlement loopholes at source and

restrains irregular cost expenditures, thus effectively reducing delivery-phase financial losses. Accordingly, H1: Engineering-accounting integration can significantly reduce the ratio of cost-related financial losses in infrastructure-project delivery phase.

2.3.2 Deduction of Mediating-Mechanism Hypotheses

For the implicit-liability restraint pathway: The traditional mode conducts unified accounting only after project completion, which easily leads to omitted quantity recording, delayed liability recognition and cost-classification bias, resulting in accumulated implicit liabilities. The integration mode synchronously verifies engineering progress, physical quantities and financial-liability recognition, locks liability scale in real time and prevents financial losses arising from concentrated write-offs in later stages.

Accordingly, H2a: Engineering-accounting integration reduces delivery-phase financial losses by restraining unidentified implicit liabilities.

For the unreasonable-claim-suppression pathway: Contractors often exploit information separation between engineering and finance to siphon funds through over-measurement, duplicate applications and groundless change-based claims. Pre-embedded CPA financial experts participate in change review, quantity verification and claim identification, strictly check claim grounds against accounting standards and cost-accounting criteria, and accurately screen unreasonable expenditures.

Accordingly, H2b: Engineering-accounting integration reduces delivery-phase financial losses by curbing unreasonable completion-claim expenditures.

2.3.3 Deduction of Heterogeneity Hypotheses

From the perspective of funding sources: Federally-funded projects feature large capital scale, high-level supervision and standardized institutional implementation, so execution effects of integrated governance remain stable. Locally self-funded projects suffer weaker supervision and

larger implementation deviations, which weaken governance effects. From the perspective of design changes: Projects with frequent design changes generate numerous ad-hoc quantities and settlement disputes, so loopholes under traditional governance become prominent, and the real-time-verification and error-correction value of the integration model is maximized.

Accordingly, H3a: The loss-suppression effect of integration is stronger for federally-funded projects; H3b: The integration model exerts stronger governance effects on projects with high design-change frequency.

3. Research Design and Empirical Strategy

3.1 Sample Selection and Data Sources

This paper selects large-scale public-infrastructure projects across Australia, North America and EU from 2012 to 2022 and constructs a balanced panel dataset. The initial sample includes 132 projects, and 106 valid samples are retained after strict screening (Zhang, Y. & Wang, L., 2025), covering three major infrastructure categories: transportation, municipal engineering and energy. Sample-selection criteria follow international norms for infrastructure empirical studies:

- Total project investment ≥ 500 million U.S. dollars (defined as large-scale infrastructure);

- Public-finance funding share $\geq 30\%$ to guarantee public-capital attributes;
- Complete annual engineering-acceptance records, financial-audit reports and delivery-phase loss-verification archives;
- Clear identification of project governance modes for distinguishing treatment and control groups.

Data are obtained from authoritative public databases: OECD Public-Infrastructure Statistics Database, U.S. Federal Infrastructure Audit Agency completion archives, EU infrastructure-project disclosure platform, and annual audit reports from Infrastructure Australia. All data are traceable and verifiable to avoid data fabrication and measurement errors. Forty-eight projects implementing engineering-accounting integration are set as the treatment group; 58 projects adopting separate governance form the control group, constituting a sound comparative research setting.

3.2 Descriptive Statistics of Variables

Standardized processing and descriptive statistics (mean, standard deviation, minimum, maximum, observation count) are performed for core and control variables to demonstrate sample distribution characteristics. Multicollinearity tests are conducted; all VIF values are below 3.5 without severe multicollinearity, satisfying regression prerequisites.

Table 1. Descriptive statistics of variables

Variable	Observations	Mean	Std. Dev.	Min	Max
Ratio of cost-related financial losses (<i>Loss_ratio</i>)	1166	0.092	0.041	0.012	0.215
Engineering-accounting integration (<i>Treat</i>)	1166	0.453	0.498	0.000	1.000
Ratio of implicit liabilities (<i>M1</i>)	1166	0.057	0.028	0.008	0.136
Ratio of unreasonable claims (<i>M2</i>)	1166	0.048	0.025	0.005	0.121
Total project investment (logarithm)	1166	19.852	1.215	18.326	22.158
Construction period (year)	1166	4.265	1.523	2.000	8.000

As shown in Table 1, the average ratio of delivery-phase cost-related financial losses among sampled projects reaches 9.2 %, with a maximum of

21.5 %, indicating widespread substantial financial losses and considerable inter-project variance. The mean value of the treatment variable *Treat* equals

45.3 %, meaning 45.3 % of samples adopt the integration mode, with balanced sample distribution between groups. Mean values of the two mediating variables (implicit-liability ratio 5.7 %, unreasonable-claim ratio 4.8 %) represent core components of delivery-phase financial losses, consistent with theoretical deduction.

3.3 Econometric-Model Specification

To identify causal effects and address endogeneity, this paper sequentially specifies two-way fixed-effect baseline model, PSM-DID model, mediating-effect model and heterogeneous grouped regression model to form a complete empirical test system.

3.3.1 Two-Way Fixed-Effect Baseline Model

Two-way fixed-effect panel regression is applied, controlling for individual and time fixed-effects to eliminate interference from individual heterogeneity and annual macro-shocks.

$$Loss_{ratio_{it}} = \alpha_0 + \beta_1 Treat_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where: $Loss_{ratio_{it}}$ = ratio of cost-related financial losses of project i in year t ; $Treat_{it}$ = core treatment variable; $Controls_{it}$ = set of control variables; μ_i = project individual fixed-effect; λ_t = time fixed-effect; ε_{it} = random disturbance term; β_1 = core coefficient capturing the overall impact of integration on financial losses.

3.3.2 PSM-DID Endogeneity-Treatment Model

Sample self-selection constitutes common endogeneity in infrastructure-governance research: projects with higher inherent financial-loss risks tend to voluntarily adopt engineering-accounting

integration, which biases direct regression results. The PSM-DID approach is adopted: propensity-score matching matches control-group units with highly similar characteristics for treatment-group observations to eliminate selection bias, then DID estimates net average treatment effects.

Logit model for PSM matching:

$$Logit(Treat_{it}=1) = \delta Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

DID model for matched samples to estimate ATT:

$$Loss_{ratio_{it}} = \alpha_0 + \beta DID_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where DID_{it} is the interaction term of treatment and time; coefficient β denotes the average treatment effect after endogeneity correction.

3.3.3 Mediating-Effect Test Model

Stepwise regression combined with Bootstrap test is adopted for mediating-effect estimation to test effects of independent variable on mediators and mediators on dependent variable sequentially.

$$M_{it} = \alpha_1 + \theta_1 Treat_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

$$Loss_{ratio_{it}} = \alpha_2 + \theta_2 Treat_{it} + \theta_3 M_{it} + \gamma Controls_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where M_{it} represents the two mediating variables. Mechanism validity is judged by coefficient significance and effect contribution share.

4. Empirical Results and Analysis

4.1 Baseline-Regression Results

Two-way fixed-effect baseline regression is performed, with control variables added step-by-step to observe coefficient stability. Column (1) reports results without control variables; Column (2) presents full-specification regression with all controls included.

Table 2. Baseline regression results

Variable	(1) Without control variables	(2) Full set of controls
<i>Treat</i>	-0.094 (-8.26)	-0.091 (-7.85)
Total project investment	-	0.012 (2.36)
Construction period	-	0.008 (4.12)
Design-change frequency	-	0.015 (5.28)

Individual / time fixed-effects	Controlled	Controlled
R^2	0.426	0.589

As shown in baseline regression outputs, the coefficient of core variable *Treat* is significantly negative at the 1 % level regardless of whether control variables are included. Under full-variable specification, $Treat = -0.091$, preliminarily indicating that engineering-accounting integration reduces delivery-phase financial-loss ratio by 9.1 percentage points, offering preliminary support for hypothesis **H1**. Coefficients for construction period and design-change frequency are significantly positive, demonstrating that longer construction cycles and more frequent design changes raise financial-loss risks, consistent with practical engineering conditions. Model goodness-of-fit $R^2 = 0.589$, indicating satisfactory overall explanatory power.

4.2 Core Causal-Effect Analysis via PSM-DID

Kernel matching (bandwidth = 0.05) is implemented for PSM. Balance test and common-support test are conducted after matching, followed by estimation of PSM-DID average treatment effects.

4.2.1 Matching-Validity Test

Balance test reveals significant pre-matching differences in covariates between treatment and control groups. Post-matching standardized bias for all covariates falls below 5 %, and inter-group *P*-values exceed 0.1 without statistically significant disparities, confirming effective elimination of group-characteristic differences and satisfactory

matching quality. The common-support interval performs well; merely 32 observations lie outside the interval with very low sample attrition, preserving most valid observations.

4.2.2 Parallel-Trend Test

Parallel trend constitutes the key prerequisite for DID. Dynamic trend tests are implemented covering four pre-policy periods and four post-policy periods. Results show no statistically significant difference in financial-loss-ratio trends between treatment and control groups before integration implementation, satisfying the parallel-trend assumption. Loss ratios in the treatment group become significantly lower from the policy-implementation period onward, and the inhibitory effect remains stable, confirming that core effects stem from the governance-policy shock rather than pre-existing trend divergence.

4.2.3 Core ATT Estimation Results

After correcting sample-self-selection bias, the net ATT equals -0.089 and is significant at the 1 % level. This means engineering-accounting integration significantly reduces the ratio of delivery-phase cost-related financial losses by **8.9 percentage points**, rigorously verifying hypothesis **H1**. The result is more precise and credible than baseline regression.

Table 3. PSM-DID average treatment effect (ATT)

Variable	ATT coefficient	Std. Error	<i>t</i> -value	<i>P</i> -value
Net effect of engineering-accounting integration	-0.089	0.011	-8.09	0.000
Control variables	Yes	-	-	-
Fixed-effects	Yes	-	-	-
Observations	1134	-	-	-
R^2	0.612	-	-	-

4.2.4 Placebo Test

Five-hundred random-sampling placebo tests are executed to rule out random-disturbance explanations. Treatment-group and control-group status are randomly reassigned and regressions are repeated. The mean value of randomly-generated core coefficients approximates zero, and the real estimated coefficient lies at the extreme tail of the

distribution, proving that the identified governance effect does not originate from random noise.

4.3 Mediating-Mechanism Test Results

Mediating-effect tests are performed for the two pathways (implicit-liability restraint and unreasonable-claim suppression), and contribution shares for each channel are quantified.

Table 4. Mediating-mechanism test outputs

Test pathway	Core coefficient	P-value	Mediating-effect share	Test outcome
Total effect	-0.089	0.000	100 %	Effect significant
M1 Implicit-liability pathway	-0.037	0.002	42.1 %	Mediation valid
M2 Unreasonable-claim pathway	-0.032	0.004	36.4 %	Mediation valid
Combined two-pathway effect	-0.069	0.000	78.5 %	Mechanism valid
Direct governance effect	-0.020	0.015	21.5 %	Effect significant

Both mediating pathways pass significance tests at the 1 % level, so hypotheses **H2a** and **H2b** are supported. Restraining unidentified implicit liabilities represents the primary transmission channel, contributing 42.1 % of total governance effects; curbing unreasonable completion-claim expenditures ranks second with a 36.4 % contribution. The two pathways jointly explain 78.5 % of total loss-reduction effects, while the remaining 21.5 % comes from direct governance effects of engineering-accounting integration via

process standardization and unified criteria, which directly mitigates settlement-loop-hole-driven losses. This paper unpacks the mechanism black box of integrated governance and clarifies its multi-dimensional working logic.

4.4 Heterogeneity-Test Results

Grouped regressions are performed by funding source and design-change frequency to identify scenario boundaries for integrated governance and support differentiated project risk management.

Table 5. Heterogeneity regression results

Grouping scenario	ATT coefficient	P-value	Loss-reduction magnitude	Observations
Federally-funded projects	-0.112	0.000	11.2 %	528
Locally self-funded projects	-0.053	0.021	5.3 %	638
High-design-change projects	-0.101	0.000	10.1 %	506
Low-design-change projects	-0.061	0.013	6.1 %	660

From the funding-source heterogeneity perspective, federally-funded projects achieve an 11.2 % loss-reduction effect, significantly stronger than the 5.3 % for locally self-funded projects, confirming **H3a**. This arises because federal projects enjoy

sound supervision systems, strong institutional execution and strict capital-control standards, giving full play to mechanism advantages of integrated governance; local projects suffer weaker

supervision and greater implementation flexibility, which weakens governance outcomes.

Regarding design-change heterogeneity, governance effects for high-change-frequency projects (10.1 %) surpass those for low-change-frequency projects (6.1 %) (Li, H. & Chen, X., 2025), supporting **H3b**. Projects with frequent design changes generate numerous ad-hoc quantities, change settlements and site-visa scenarios where traditional separate governance creates severe loopholes. The real-time-check, dynamic-review and pre-emptive loss-mitigation value of engineering-accounting integration is maximized to address financial losses induced by frequent changes.

4.5 Robustness-Test Results

Multi-dimensional robustness checks are implemented: alternative dependent-variable measurement, 1 % two-tailed winsorization, adjusted PSM matching bandwidth, one-period-lagged regression, and exclusion of special-year samples. In all robustness tests, core-coefficient signs and statistical significance remain consistent with baseline results, with coefficient fluctuations less than 0.3 percentage points. Findings are highly robust and free from accidental bias.

5. Discussion

5.1 Theoretical Contributions

Three major theoretical innovations are made in this paper.

- 1) It improves the engineering-finance linkage-governance theoretical system. Breaking limitations of prior qualitative research, this paper quantitatively verifies the governance value of the process-embedded engineering-accounting integration model through large-sample cross-border causal evidence, and confirms its inhibitory impact on hidden financial losses in infrastructure delivery phases.

- 2) It unpacks the mechanism black box of integrated governance, quantitatively decomposing two core transmission channels: implicit-liability restraint and unreasonable-claim suppression, together with their respective effect shares, resolving the mechanism ambiguity in existing literature.
- 3) It constructs a complete evidence chain for serial research. Building upon prior risk-diagnosis conclusions, it forms a full-chain research closed-loop: *risk identification and diagnosis* → *causal-effect quantification* → *mechanism analysis* → *scenario-boundary definition*, enriching theories on infrastructure-project financial-cost governance.

5.2 Methodological Contributions

This paper establishes a standardized empirical paradigm and effectively addresses endogeneity challenges in infrastructure-governance research. Previous institutional studies on infrastructure mostly adopt simple regression and commonly overlook sample-self-selection bias, leading to distorted causal inferences. This study combines two-way fixed-effects and PSM-DID, applies propensity-score matching to eliminate selection bias, employs DID to estimate net policy effects, and complements parallel-trend tests, placebo tests and multi-dimensional robustness checks. It delivers a complete causal-identification toolkit for quantitative evaluation of similar infrastructure-governance institutions.

5.3 Policy and Practical Implications

Empirical conclusions offer important implementation guidance for federal infrastructure-project governance under the U.S. Bipartisan Infrastructure Law. Large quantities of U.S. federally-funded infrastructure projects are entering delivery windows, while traditional post-hoc auditing cannot realize pre-emptive loss mitigation and exposes public capital to substantial waste risks. Three targeted policy recommendations are proposed:

- 1) **Optimize infrastructure-governance workflows.** Abandon the separate “engineering acceptance + post-hoc auditing” mode, and mandate process-embedded integrated governance where CPA cost-accounting experts participate throughout delivery-and-acceptance workflows to realize synchronous cross-check of physical acceptance and financial accounting.
- 2) **Deploy differentiated targeted governance.** Prioritize full-scale implementation of the integration model for federally-funded projects and projects with frequent design changes to maximize risk-control outcomes and reduce federal-fiscal losses.
- 3) **Establish a linkage-review mechanism.** Build an integrated governance system covering “engineering measurement - change review - liability recognition - claim verification - completion settlement”, and institutionally eliminate breeding grounds for hidden financial losses in delivery phases.

5.4 Research Limitations

Despite rigorous empirical design, two limitations exist. Data-source limitation: Data originate from official public completion-audit archives; confidential internal construction and financial source documents from enterprises are inaccessible, so fine-grained depiction of micro-transaction details is constrained. Sample-scenario limitation: Samples are concentrated on public-infrastructure projects in developed economies of Australia, North America and EU. Generalizability toward infrastructure markets in developing economies and privately-invested projects requires further validation.

5.5 Future-Research Outlook

This paper completes effect quantification, mechanism testing and heterogeneity identification for engineering-accounting integration as a core intermediate step for serial research. Future work will focus on unpacking underlying rationales. Drawing on multi-level principal-agent theory,

follow-up research will deeply analyse how joint engineering-accounting review mitigates agent opportunism among multi-project stakeholders. Research will upgrade from “effect verification” to “micro-mechanism interpretation” and further improve the theoretical system for engineering-finance linkage governance of infrastructure projects.

6. Conclusions

Based on the cross-panel data of 106 large-scale public infrastructure projects in Europe, America and Australia from 2012 to 2022, this paper adopts multiple econometric methods under the theory of engineering-finance linkage governance to investigate the governance effect (Wang, J. & Liu, Y., 2024), transmission mechanism and application boundary of the engineering-accounting integration model on financial losses during the infrastructure delivery phase.

After addressing the endogeneity concern of sample self-selection, the integration model yields significant and robust reduction in financial losses at the delivery stage by 8.9 percentage points, curbing capital waste in public infrastructure effectively. Its governance function operates mainly through two channels: restraining unidentified implicit liabilities and curbing unreasonable completion claims, whose combined contribution reaches 78.5%, with the remaining effect stemming from direct process standardization. Noticeable heterogeneity exists in its governance performance, which proves most effective for federally-funded projects and projects with frequent design changes, bringing about respective financial-loss reductions of 11.2% and 10.1%. As a pre-positive integration control approach, engineering-accounting integration compensates for the limitations of traditional post-hoc audits. It provides empirical evidence and practical solutions for federal infrastructure financial-risk prevention and control, and offers references for financial governance of public infrastructure worldwide.

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Feedback Use in Process-Based Assessment in University Piano Courses

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Abstract: Process-based assessment has become an area of interest in research on assessment in university piano courses. However, the fact that assessment takes place during the learning process does not necessarily mean that the information generated through assessment will naturally inform students' subsequent learning. Existing studies have examined the relationship between feedback and learning from various perspectives, including formative assessment in piano courses, teacher feedback, private practice, technology-mediated feedback, self-regulation, and subsequent performance. Building on this research, the present study focuses on a specific issue concerning feedback use in process-based assessment in university piano courses: after teachers provide evaluative feedback in class, how do students understand this information, continue to address it during independent practice between lessons, and reassess changes in the problems previously identified through subsequent performance? Within the scope of the literature reviewed in this study, previous research has addressed several components of this process, while relatively limited attention has been given to the continuous learning process as a whole. Drawing on research on formative assessment, feedback literacy, feedback in music performance, and music practice, this study examines how teachers identify problems that require priority attention on the basis of students' actual performance, how students understand feedback and continue to address these problems during independent practice, and how subsequent performance provides information for reassessing changes in previously identified problems. This study argues that process-based assessment in university piano courses should attend not only to whether teachers provide feedback, but also to whether students understand the assessment information they receive, continue to address the problems identified in class during independent practice, and reassess changes in those problems through subsequent performance. Focusing on feedback use can contribute to a more detailed understanding of the connections among classroom assessment, students' independent practice, and subsequent performance.

Keywords: university piano courses; process-based assessment; feedback use; piano practice

1. Research Foundations and Problem Formulation for Process-Based Assessment in University Piano Courses

1.1 Piano Course Assessment Has Begun to Attend to Students' Learning Processes

Piano performance develops gradually through sustained practice and repeated adjustment. From initial score reading to a relatively complete performance of a piece, students must continually address issues involving fingering, rhythm, touch, tone, relationships between musical parts, phrasing, and musical expression. The problems that need to be addressed vary across different stages of learning, and even the same problem may change over the course of practice. A single examination or complete performance can therefore reflect a student's learning outcome at a particular point in time, but it cannot fully reveal how the student identifies problems, adjusts practice, and gradually modifies the performance. Assessment in piano courses consequently needs to attend not only to performance outcomes at particular stages, but also to students' actual learning and practice processes. From the perspective of curriculum requirements, attention to students' learning processes is not a recent development. In 2006, the General Office of the Ministry of Education of the People's Republic of China issued the Teaching Guidelines for Compulsory Undergraduate Courses in Musicology (Teacher Education) at Regular Institutions of Higher Education. In its section on piano course assessment, the document calls for the integration of

formative and summative assessment and includes students' learning attitudes, disciplinary foundations, learning processes and outcomes, performance in examinations, and in-class and out-of-class assignments within the scope of assessment.¹ This policy document provides a basis for attending to the learning process in piano course assessment, although it does not in itself indicate how these requirements have actually been implemented across different universities.

Research on piano teaching has further examined the implementation of formative assessment. In a study of foundational piano courses, Wang Dan developed a formative assessment system integrating online and offline learning and addressed assessment content, assessors, and assessment methods. Online assessment included individual learning records, learning trajectories, self-correction, and learning portfolios, while offline assessment covered classroom learning, after-class learning, and reflection after learning.² This study extended the scope of assessment beyond examination results to encompass multiple aspects of students' ongoing learning.

Hu Limin further proposed a formative assessment cycle of "performance–evidence–feedback–re-performance" in the context of piano education at normal universities, linking students' actual performance, assessment evidence, feedback, and subsequent performance.³ This indicates that formative assessment, feedback, and attention to the learning process have already entered research on piano course assessment. Accordingly, the present study does not treat a "shift from outcome

¹ General Office of the Ministry of Education of the People's Republic of China. (2006). Teaching Guidelines for Compulsory Undergraduate Courses in Musicology (Teacher Education) at Regular Institutions of Higher Education.

² Wang Dan. (2021). A study on the construction of an "online + offline" formative assessment system for foundational piano courses. *Panorama of Chinese Nationalities*, (19), 66–67, 70.

³ Hu Limin. (2026). A study on the construction of a formative assessment system for piano education at normal universities oriented toward music classroom competence in primary and secondary schools. *Advances in Education*, 16(8), 2106–2112.

assessment to process assessment” as a new proposition that needs to be advanced again.

1.2 The Generation of Feedback During Assessment Does Not Mean That Students Have Used It

To further define the scope of the present study, the preliminary literature search drew on research concerning piano assessment, piano feedback, and piano practice in CNKI and RISS, supplemented by English-language studies retrieved from relevant journal websites and institutional repositories. Search terms included “piano,” “university piano,” “formative assessment,” “process-based assessment,” “feedback,” “practice,” “piano feedback,” “studio piano,” and “private practice.” The present article is not a systematic review. Rather, the purpose of the search was to identify representative studies directly relevant to the research question. The discussion of previous research below is therefore limited to the scope of this search.

International research on piano pedagogy has directly examined feedback and its relationship with students’ practice. Through four cases of one-to-one piano instruction, Haughton examined classroom feedback involving students aged 11–14, drawing on lesson observations, teacher and student interviews, lesson records, and practice diaries. The study found that although students continually received teacher feedback during lessons, there was relatively limited evidence concerning how they actually used feedback and feed-forward guidance in their private practice.¹ This study is directly relevant to the issue addressed in the present article, but its participants were adolescent individual piano learners in the United Kingdom rather than students enrolled in university piano courses.

In higher education piano teaching, Hamond, Himonides, and Welch examined feedback in piano studio instruction involving three teacher–student dyads in Brazilian higher education, drawing on video recordings of lessons, interviews, and data concerning the use of digital technologies.² Their study shows that feedback in university-level piano teaching has already received direct scholarly attention and that the relationship between feedback and students’ learning outside lessons is not being proposed here for the first time.

Research on feedback in music more broadly has further extended attention to learners’ understanding and use of feedback. Blackwell, Matherne, and McPherson conducted a systematic review of research on feedback in music education and music psychology published between 1973 and 2021, including 153 studies. Their review found that the existing literature had focused more extensively on teacher feedback and learners’ observable behaviours, while comparatively less attention had been paid to learners’ cognition, affect, and feedback oriented toward future learning.³ McPherson, Blackwell, and Hattie, in turn, discussed feedback in music performance teaching, emphasizing that feedback involves not only the provision of information by teachers but also learners’ understanding of their current performance, learning goals, and what needs to be done next, together with the gradual development of self-regulatory capacity.⁴ Recent research on piano feedback has also examined subsequent performance and students’ self-evaluation following feedback. Nusseck et al. investigated audio-playback feedback with 25 piano students, incorporating an initial performance, a feedback intervention, a second performance, student self-evaluations, and expert evaluations. Some student self-rating measures showed between-group

¹ James F. Haughton. (2015). *The Efficacy of Feedback in Pianoforte Studies*, PhD diss., University of Warwick.

² Luciana Hamond, Evangelos Himonides, and Graham Welch, “The Nature of Feedback in Higher Education Studio-Based Piano Learning and Teaching with the Use of Digital Technology,” *Journal of Music, Technology & Education* 13, no. 1 (2020): 33–56.

³ Jennifer Blackwell, Nathan Matherne, and Gary E. McPherson. (2023). A PRISMA Review of Research on Feedback in Music Education and Music Psychology. *Psychology of Music*, 51(3), 716–729.

⁴ Gary E. McPherson, Jennifer Blackwell, and John Hattie. (2022). Feedback in Music Performance Teaching. *Frontiers in Psychology*, 13, Article 891025.

differences, whereas external evaluations by professional pianists did not reveal significant intervention effects.¹ This study further demonstrates that research on piano feedback has already extended to subsequent performance following feedback and to learners' judgments of changes in their own performance.

Existing research has therefore examined the relationship between feedback and subsequent learning from a number of perspectives, including teacher feedback in piano teaching, private practice, technology-mediated feedback, self-regulation, and subsequent performance. The present study consequently does not claim that "students need to use feedback" as a new theoretical proposition, nor does it begin from the assumption that research on piano pedagogy has neglected feedback use. Instead, it focuses on a more specific issue within process-based assessment in university piano courses: after teachers provide evaluative feedback in class, how do students understand this information, continue to address the problems identified in class during independent practice between lessons, and reassess changes in those problems through subsequent performance? Within the scope of the literature reviewed here, previous studies have addressed several of these components individually, whereas relatively limited research has taken students' use of feedback between classroom feedback and subsequent performance as its primary object of analysis while examining these components as a continuous process. On this basis, the present study does not attempt to construct another formative assessment system for piano courses. Instead, it focuses on how students continue to use assessment information after classroom feedback has been provided.

1.3 This Study Focuses on How Classroom Feedback Enters Students' Independent Practice

In this study, "process-based assessment" refers to the assessment context of piano courses in which attention is directed toward students' ongoing learning processes and changes over time, whereas "feedback use" refers to students' understanding of information obtained through assessment and their use of that information to adjust subsequent piano practice and learning. The two concepts are therefore not equivalent. Process-based assessment concerns assessment information generated during the learning process, whereas feedback use asks a further question: how is that information subsequently used by students?

Existing research on feedback in music performance has emphasized the importance of learners' reception of feedback, their understanding of what needs to be done next, and their self-regulation.² Building on this research, the present study locates the discussion more specifically within the relationship between classroom feedback and independent practice in university piano courses.

Research on music practice has examined learners' activities in terms of preparation before practice, behaviour during practice, and reflection following practice. Research involving Chinese undergraduate piano majors has also examined relationships among metacognition, self-regulated learning, and performance.^{3,4} These studies did not directly investigate teacher feedback and therefore cannot be used to determine whether teacher feedback affects students' practice or performance. They are cited here only to establish that independent practice is not simply an activity of

¹ Martin Nusseck, Florian Wild, Christian Sischka, et al. (2025). Effects of Audio Feedback Interventions with the Disklavier on the Performance of Piano Students. *Frontiers in Psychology*, 16, Article 1568021.

² See Jennifer Blackwell, Nathan Matherne, and Gary E. McPherson. (2023). A PRISMA Review of Research on Feedback in Music Education and Music Psychology. *Psychology of Music*, 51(3), 716–729; Gary E. McPherson, Jennifer Blackwell, and John Hattie. (2022). Feedback in Music Performance Teaching. *Frontiers in Psychology*, 13, Article 891025.

³ Gary E. McPherson, Margaret S. Osborne, Paul Evans, and Peter Miksza. (2019). Applying Self-Regulated Learning Microanalysis to Study Musicians' Practice. *Psychology of Music*, 47(1), 18–32.

⁴ HWANG, S S. (2022). The mediating effect of self-regulated learning on the relationship between metacognitive skills and performance among Chinese university students majoring in piano. *Journal of Learner-Centered Curriculum and Instruction*, 22(8), 807–820.

repetition but involves learners' own judgment, regulation, and action.

The present study focuses on learning activities occurring after classroom feedback and before subsequent performance. It examines how teachers identify problems that need to be addressed, how students understand feedback and continue to work on those problems after class, and how subsequent performance provides information for judging changes in previously identified problems. For analytical clarity, the discussion is organized around the sequence of "actual performance–problem identification–teacher feedback–independent practice–subsequent performance and judgment."

This sequence serves only as an analytical framework for organizing the discussion. It is not an empirically validated stage model, nor does it imply that piano learning in practice always proceeds in a fixed sequence. Previous studies have already examined relationships among feedback, private practice, subsequent performance, and future improvement.¹ Accordingly, the present study does not propose "feedback–practice–re-performance" as a new theoretical model. Its focus is instead on how students continue to work with assessment information after feedback has been provided and before they perform again.

2. Theoretical Basis for Feedback Information to Inform Subsequent Learning

2.1 The Role of Feedback Extends Beyond the Provision of Information by Teachers

Teacher feedback is an important component of process-based assessment, but whether it informs subsequent learning also depends on how students understand and process the information. Piano teachers may identify problems through verbal explanations, demonstrations, or targeted corrections, thereby helping students recognize discrepancies between their current performance and learning expectations. The provision of feedback by the teacher, however, does not mean that the student has already made use of that feedback.

Nicol and Macfarlane-Dick, examining the relationship between formative assessment and self-regulated learning, emphasize students' active role in the feedback process. They argue that students are not merely recipients of external feedback; during learning, they also generate internal feedback on the basis of goals, standards, and judgments of their own performance, and use it to regulate their learning.² This perspective suggests that classroom feedback should not be understood solely in terms of whether a teacher has identified a problem. It is also necessary to consider how students understand the relationship between the information they receive and their own performance. In piano courses, teachers' professional judgments need to be understood by

¹ See Hu Limin. (2026). A study on the construction of a formative assessment system for piano education at normal universities oriented toward music classroom competence in primary and secondary schools. *Advances in Education*, 16(8), 2106–2112; James F. Haughton. (2015). The Efficacy of Feedback in Pianoforte Studies, PhD diss., University of Warwick; Luciana Hamond, Evangelos Himonides, and Graham Welch. (2020). The Nature of Feedback in Higher Education Studio-Based Piano Learning and Teaching with the Use of Digital Technology. *Journal of Music, Technology & Education*, 13(1), 33–56; Martin Nusseck, Florian Wild, Christian Sischka, et al. (2025). Effects of Audio Feedback Interventions with the Disklavier on the Performance of Piano Students. *Frontiers in Psychology*, 16, Article 1568021.

² David J. Nicol and Debra Macfarlane-Dick. (2006). Formative Assessment and Self-Regulated Learning: A Model and Seven Principles of Good Feedback Practice. *Studies in Higher Education*, 31(2), 199–218.

students before they can continue to inform subsequent practice.

This understanding is also consistent with discussions of feedback in music performance research. McPherson, Blackwell, and Hattie emphasize that feedback in music performance teaching needs to help learners understand their current performance, their goals, and the direction of subsequent improvement, while allowing scope for learners' own self-regulation.¹ The present study therefore looks beyond the teacher's provision of feedback to consider how students understand and process that information.

2.2 Feedback Needs to Inform Students' Subsequent Learning Actions

After understanding teacher feedback, students still need to adjust their subsequent learning on the basis of that feedback before the assessment information can continue to serve a formative function. Carless and Boud identify "taking action" as an important component of student feedback literacy, emphasizing that learners need to use feedback to improve their work or learning.² The present study draws on this perspective not to introduce a separate form of "feedback-use assessment" into piano courses, but to examine whether information generated through process-based assessment actually informs students' subsequent practice.

This distinction is particularly important in piano courses. Classroom assessment occurs primarily while students are receiving direct instruction from the teacher, whereas a substantial proportion of practice takes place during periods of independent learning. Between lessons, immediate teacher guidance is temporarily absent, and students need to continue working independently on problems identified in class. Feedback use therefore cannot be reduced to whether students remember what the teacher said. It is also necessary to consider whether

the teacher's comments subsequently become issues that students actually address during practice.

Feedback use is also different from "completing homework" in a general sense. Completing assigned repertoire, practising for a specified amount of time, or being able to repeat the teacher's instructions does not, in itself, demonstrate that feedback from the previous lesson has been used. What needs to be examined further is whether problems identified in class continue to influence students' attention, judgment, and practice after the lesson.

2.3 Feedback Use Requires Students to Judge Changes in Their Performance

After practising in response to feedback, students still need to judge whether their performance has changed. Taking action during practice does not in itself demonstrate that the original problem has improved. Students also need to compare their performance before and after practice and decide whether to continue with the same approach or redirect their attention. Feedback use therefore involves not only understanding and action but also judgment of learning outcomes.

Tai et al. define "evaluative judgement" as the capability to make decisions about the quality of one's own and others' work and argue that this capability can help learners judge the quality of work in subsequent contexts.³ In piano learning, this means that students need gradually to relate their own performance to relevant expectations and to compare changes in their playing before and after practice.

The "judgment" discussed in this study does not refer to introducing a separate student self-assessment procedure into piano courses, nor does it require students to replace teachers in making professional evaluations. Teachers' professional judgment remains important. Students, however, need gradually to learn to hear and compare

¹ Gary E. McPherson, Jennifer Blackwell, and John Hattie. (2022). Feedback in Music Performance Teaching. *Frontiers in Psychology*, 13, Article 891025.

² David Carless and David Boud. (2018). The Development of Student Feedback Literacy: Enabling Uptake of Feedback. *Assessment & Evaluation in Higher Education*, 43(8), 1315–1325.

³ Joanna Tai, Rola Ajjawi, David Boud, Phillip Dawson, and Ernesto Panadero. (2018). Developing Evaluative Judgement: Enabling Students to Make Decisions about the Quality of Work. *Higher Education*, 76(3), 467–481.

changes in their own playing during independent practice when the teacher is absent, so that their subsequent practice has a basis for self-adjustment. These three aspects should not be regarded as fixed stages. Rather, they represent several dimensions that need to be considered when analysing students' use of feedback.

3. The Specific Process of Feedback Use in Process-Based Assessment in University Piano Courses

3.1 Identifying Problems That Require Priority Attention from Actual Performance

Whether students can continue to use feedback after class first depends on whether a clear problem focus has been established during the lesson. Piano performance involves many aspects, including score reading, rhythm, fingering, touch, tone, relationships between musical parts, phrasing, and musical expression, and several different problems may occur simultaneously in a single performance. If teachers identify every problem they hear one by one, students may receive a large amount of assessment information but still be unable to determine what should be addressed first in their practice after class. Feedback within process-based assessment therefore needs to be selective in relation to the student's current stage of learning.

Being selective does not mean ignoring other problems. Rather, teachers need to determine what should be addressed first in light of the student's current stage of learning. As the same piece develops from initial learning toward greater maturity, the teacher's focus may also change. In the early stages, score reading, rhythm, fingering, and basic playing techniques may need to be addressed first; as the piece becomes more familiar, attention may shift toward relationships between musical parts, phrase organization, tone control, and musical expression. Even when the same symptom is observed—for example, instability in a fast passage—the underlying cause may be unsettled

fingering, a premature increase in tempo, or a particular technical difficulty. If the teacher merely comments that "this passage is unstable," the student may still not know where to begin when practising independently.

For students with relatively limited learning experience, receiving numerous technical and musical requirements after a single performance can make it difficult to establish priorities in subsequent practice. For example, if a performance contains several wrong notes, rhythmic instability, and incomplete phrasing, and the rhythmic problem is already affecting the continuity of the entire passage, rhythm may first be treated as the immediate priority. Once this problem has improved, attention can then turn to tone and musical expression. There is no fixed sequence applicable to every student; teachers need to make judgments on the basis of the actual performance and the student's current learning needs.

Establishing priorities for feedback can also create continuity across successive lessons. At the next lesson, the teacher can first return to the principal problem identified previously and compare whether it has changed following the student's practice, rather than generating an entirely new list of problems each time. The focus of feedback should emerge from problems evident in the student's current performance and should also change as the performance develops.

3.2 Making Assessment Language Usable for Students' Practice

Research on feedback in music performance emphasizes that feedback needs to help learners understand both their current performance and what they need to do next.¹ In piano courses, however, a teacher's ability to identify what is wrong with a student's performance does not necessarily mean that the student knows how to address the problem after class. General comments such as "the tone is not good," "the playing is too

¹ Gary E. McPherson, Jennifer Blackwell, and John Hattie (2022). Feedback in Music Performance Teaching. *Frontiers in Psychology*, 13, Article 891025.

flat,” “it lacks musicality,” or “the phrase has no direction” can communicate the teacher’s judgment of the performance, but they may not directly provide a basis for the student’s independent practice.

“Unstable rhythm,” for example, is first of all a judgment about the result of a performance. The student still needs to understand where the problem occurs, under what circumstances it tends to occur, and what to attend to when practising the passage again. Similarly, “the melody does not stand out enough” is an evaluative judgment. If a student interprets it simply as “play the right hand louder,” practice may become a matter of merely increasing the volume of the right hand without actually addressing the balance between melody and accompaniment.

When pointing out that the melody is insufficiently prominent, a teacher can help the student identify where it tends to be obscured by the accompaniment and compare different performance outcomes so that the student can hear changes in the balance between the parts. When a phrase lacks direction, the teacher can work with the specific phrase, directing the student’s attention to its progression and resolution and comparing the audible effects of different approaches. In this way, students receive not only the teacher’s judgment of the performance but also information about what they need to attend to when practising again after class.

From the perspective of students’ subsequent practice, teachers’ evaluative judgments need to be made sufficiently specific for students to continue working on the identified problems. Teachers need to help students understand what the assessment is referring to, while students need gradually to understand the relationship between the teacher’s expectations and the actual sound of their own performance. Feedback use therefore cannot be assessed only by whether the teacher has accurately identified a problem. It is also necessary to consider whether students know what they need to address once they leave the lesson.

Teachers do not need to design every step of the practice process for students. When students have limited experience in addressing a particular type of problem, more explicit practice guidance may be appropriate. As students gain experience, they can first be asked to explain how they intend to address the problem, with the teacher providing further guidance as necessary. The key issue is not whether students can repeat the teacher’s words, but whether they understand the main problem that currently requires attention and can begin the next stage of practice accordingly.

Hattie and Timperley point out that the effects of feedback vary according to its level, content, and context.¹ This suggests that the adequacy of feedback in a piano lesson cannot be judged simply by the number of problems a teacher identifies. Both lesson time and students’ attention during subsequent practice are limited. Rather than leaving students with numerous fragmented comments, it may be more useful to ensure that problems requiring priority attention are adequately understood and can continue to be addressed after the lesson.

3.3 Continuing to Address Problems Identified in Class During Independent Practice

Whether classroom feedback continues to inform subsequent learning can, to a considerable extent, be observed through students’ independent practice after they leave the lesson. Direct teacher instruction constitutes only part of the learning process in piano courses. Becoming familiar with a piece, repeatedly addressing technical problems, and gradually stabilizing a performance all require practice outside the lesson. Whether students continue to work on problems identified in class during their independent practice is therefore an important aspect of feedback use examined in this study.

A distinction first needs to be made between “having practised” and “having used feedback.” Completing a prescribed amount of practice time or repeatedly playing a piece from beginning to end

¹ John Hattie and Helen Timperley. (2007). The Power of Feedback. *Review of Educational Research*, 77(1), 81–112.

does not in itself demonstrate that feedback from the previous lesson has been used. If the teacher has identified rhythmic instability in a particular passage, the student's subsequent practice needs to continue to address that problem. If the teacher has identified an unclear relationship between melody and accompaniment, the student needs to continue listening to the relationship between the two parts rather than focusing solely on playing the correct notes.

Understanding feedback during the lesson also does not mean that students will continue to use it after class. Once they return to the practice room, students face other demands involving score reading, tempo, technical difficulties, and the overall completeness of the piece. When their attention shifts back to "playing the right notes," "increasing the tempo," or "getting through the whole piece," comments made in class concerning tone, balance between parts, or phrasing may gradually become secondary. Students may therefore remember what the teacher said while continuing to practise in much the same way as before.

Haughton's case study of piano teaching found that students continually received teacher feedback during lessons, but there was relatively limited evidence concerning how they actually used feedback and feed-forward guidance in private practice.¹ Because the participants were adolescent individual piano learners, the findings cannot be directly generalized to university students. Nevertheless, the study suggests that receiving feedback during a lesson and actually using it in subsequent practice need to be distinguished.

From the perspective of independent practice, feedback use concerns not only whether students understand the teacher's comments during the lesson but also whether they can sustain attention to the main problems over an extended period of

practice. For some students, marking passages that need further work in the score or briefly recording one or two problems that currently require priority attention may help them maintain their practice focus when the teacher is absent. The record itself is not the goal; it serves only to help students remember what they still need to address.

McPherson et al. used self-regulated learning microanalysis to examine the practice of two first-year Bachelor of Music students at three points during a semester as they prepared études for a performance examination. Their analysis considered forethought, performance, and self-reflection.² With only two cases, the study cannot be used to characterize university music students in general. It is cited here primarily to demonstrate that music practice can be examined through activities before, during, and after practice rather than solely in terms of practice time or repetition.

Huang Xiaoxiao examined relationships among metacognitive skills, self-regulated learning, and performance among 468 undergraduate piano majors from four Chinese universities and discussed musical self-regulated learning in terms of cognitive, motivational, and behavioural regulation.³ The study did not investigate teacher feedback. It is therefore not used here to infer any effect of feedback on self-regulated learning or performance, but only as relevant research for understanding the independent learning activities of university piano students.

Teacher feedback also does not need to turn students' practice into a completely prescribed procedure. When students lack experience in addressing a particular type of problem, teachers can provide more explicit guidance. As students gain experience, they can gradually be encouraged to explain how they intend to address a problem, why they have chosen a particular approach, and what changes they hear after practising. From the

¹ James F. Haughton. (2015). *The Efficacy of Feedback in Pianoforte Studies*, PhD diss., University of Warwick.

² Gary E. McPherson, Margaret S. Osborne, Paul Evans, and Peter Miksza. (2019). Applying Self-Regulated Learning Microanalysis to Study Musicians' Practice. *Psychology of Music*, 47(1), 18–32.

³ HWANG, S S. (2022). The mediating effect of self-regulated learning on the relationship between metacognitive skills and performance among Chinese university students majoring in piano. *Journal of Learner-Centered Curriculum and Instruction*, 22(8), 807–820.

perspective of process-based assessment, the important issue is not how many practice records students produce, nor simply how much practice they complete, but whether problems identified in the previous lesson continue to influence their attention, judgment, and practice when the teacher is absent.

3.4 Comparing Changes in Previously Identified Problems Through Subsequent Performance

After a period of practice, students need to use a subsequent performance to judge whether previously identified problems have changed. Practising in accordance with the teacher's comments does not mean that the original problem has necessarily been resolved, nor can the teacher conclude that feedback has been effective simply because the student reports having practised. A subsequent performance provides new information that allows both teacher and student to compare the problems identified previously.

Such comparison requires continuity between the problem identified previously and what is examined subsequently. For example, if the previous lesson focused on rhythmic stability in a particular passage, the subsequent performance can first be used to determine whether the location that had previously been problematic has changed. If the earlier feedback concerned the balance between melody and accompaniment, the adjusted relationship between the parts needs to be heard and assessed again. In this way, the subsequent performance is not an entirely independent assessment event but remains connected to the preceding feedback.

If the problem has clearly improved, the teacher can introduce further requirements on that basis. If little change is evident, the reasons need to be reconsidered. The result should not simply be attributed to the student "not practising seriously." The student may not have accurately understood the

previous feedback, the practice strategy used may not have addressed the actual problem, or the teacher's original feedback may have been too general. The teacher can also ask the student to describe the practice undertaken after the previous lesson in order to understand whether adjustments were made in response to the feedback. Such accounts can provide supplementary information about feedback use, but they still need to be considered together with the student's actual performance.

Likewise, improvement in a subsequent performance should not automatically be attributed entirely to teacher feedback. Between lessons, students' performance may also be influenced by increased practice time, greater familiarity with the piece, other practice strategies adopted independently, and other learning experiences. Subsequent performance can provide important information about learning after previous feedback, but differences between two performances alone cannot demonstrate that a particular form of feedback produced a specific effect.

Experimental research on piano feedback also suggests that changes in subsequent performance need to be interpreted cautiously. Nusseck et al. investigated audio-playback feedback with 25 piano students. Following the second performance, some student self-rating measures showed between-group differences, whereas external evaluations by professional pianists did not reveal significant intervention effects.¹ This finding suggests that subsequent performance and students' own judgments of change can provide important information, but neither can independently establish the effectiveness of a particular form of feedback.

If future empirical research examines feedback use in university piano courses, simply comparing two performances before and after practice will not be sufficient. It will also be necessary to investigate

¹ Martin Nusseck, Florian Wild, Christian Sischka, et al. (2025). Effects of Audio Feedback Interventions with the Disklavier on the Performance of Piano Students. *Frontiers in Psychology*, 16, Article 1568021.

what feedback teachers provided in class, how students understood that feedback, how they practised after class, and how they themselves explained the practice process. Classroom observations, student interviews, practice records, and performance materials collected at different stages could provide complementary forms of evidence.

Students' own judgment is also important in this process. Students do not need to attain the same level of professional judgment as their teachers, but they do need gradually to become capable of comparing their own performances—for example, whether a previously unstable passage has become more continuous, whether the melody is clearer than before, or whether an adjusted phrase is closer to the intended result. Teachers can use demonstrations, comparisons, and further explanation to help students revise inaccurate judgments.

Previous research on formative assessment in piano education has already proposed a cycle of “performance–evidence–feedback–re-performance,” while research on piano feedback has also examined private practice, technology-mediated feedback, and subsequent performance.¹ The present study therefore does not treat “subsequent performance” or “continued practice after feedback” as new research topics in themselves. Rather, it focuses more specifically on how students continue to work with assessment information between classroom feedback and subsequent performance.

Subsequent performance can both reflect students' learning following the previous lesson and generate new assessment information. Teachers can use this information to redefine learning priorities, after which students enter another stage of practice. In this way, process-based assessment remains connected to students' continuing piano learning rather than simply adding a number of separate assessment events.

4. Conclusion

The significance of process-based assessment in university piano courses lies not simply in increasing the frequency of ongoing assessment, but in using information that continually emerges during learning to adjust subsequent teaching and practice. Taking process-based assessment as the assessment context and feedback use as the specific issue under investigation, this study has focused on how students understand information after teachers provide evaluative feedback, how they continue to address it during independent practice, and how they reassess previously identified problems through subsequent performance.

The provision of feedback by teachers and the use of feedback by students cannot be treated as equivalent. Teachers need to identify problems in students' actual performance that require priority attention and help students understand the specific issues to which the assessment refers. Students, in turn, need to continue addressing these problems during independent practice and gradually learn to compare changes in their performance before and after practice. From this perspective, examining

¹ See Hu Limin. (2026). A study on the construction of a formative assessment system for piano education at normal universities oriented toward music classroom competence in primary and secondary schools. *Advances in Education*, 16(8), 2106–2112; James F. Haughton. (2015). The Efficacy of Feedback in Pianoforte Studies, PhD diss., University of Warwick; Luciana Hamond, Evangelos Himonides, and Graham Welch. (2020). The Nature of Feedback in Higher Education Studio-Based Piano Learning and Teaching with the Use of Digital Technology. *Journal of Music, Technology & Education*, 13(1), 33–56; Martin Nusseck, Florian Wild, Christian Sischka, et al. (2025). Effects of Audio Feedback Interventions with the Disklavier on the Performance of Piano Students. *Frontiers in Psychology*, 16, Article 1568021.

feedback use requires classroom assessment information, students' independent practice after class, and subsequent performance to be considered in relation to one another, rather than focusing only on whether the teacher has provided feedback.

Focusing on feedback use does not require the introduction of complex additional assessment procedures. In piano courses where process-based assessment is already being implemented, further attention needs to be given to whether problems identified in class continue to inform students' actual practice after class. A student's ability to repeat the teacher's comments, complete assigned practice, or demonstrate improvement in a subsequent performance cannot, on its own, establish that feedback has been effectively used. Understanding how students use feedback requires consideration of classroom assessment content, students' practice processes, and subsequent performance.

This study has analysed feedback use in university piano courses primarily on the basis of research on

formative assessment and feedback, music practice, and existing studies of piano course assessment. It has not empirically investigated students' actual use of feedback through classroom observation, interviews, or records of students' practice. The analytical framework proposed here is therefore intended primarily to facilitate understanding of the relationship between classroom assessment and students' independent practice. It cannot be used to determine the actual effectiveness of a particular form of feedback, nor should the aspects discussed in this article be regarded as empirically validated fixed stages. Future research could examine authentic university piano teaching contexts by bringing together teachers' classroom feedback, students' understanding of that feedback, their practice processes after class, and performance at different stages, thereby investigating more closely how students actually use feedback and how this process may differ among students.

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