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Research on the Transformation Mechanism of Enterprise Informatization Technical Achievements from the Perspective of Industry-University-Research-User Integration

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Abstract

China has sufficient scientific research reserves in informatization, yet the market-oriented transformation efficiency of relevant technologies remains relatively low. The traditional Triple Helix Theory cannot adapt to the virtualization and scenario-dependent characteristics of informatization technical achievements. Based on the revised Quadruple Helix Theory, this paper selects 1,872 sets of balanced panel data of 312 listed specialized, sophisticated, unique and innovative digital enterprises from 2019 to 2024, and adopts the two-way fixed-effects chained mediation model and fsQCA configuration analysis method to explore the mechanism of four-dimensional industry-university-research-user coupling on the transformation of informatization achievements. The research concludes that the coupling degree of industry-university-research-user integration significantly improves achievement transformation performance, with end users exerting the optimal enabling effect. Digital information asymmetry and scenario adaptation barriers play a chained mediating role, whose indirect effect accounts for 61.29%. The digital business environment and digital intellectual property protection positively strengthen the enabling effect of coupling, and the effect presents heterogeneity in enterprise property rights, achievement types and regional conditions. There are four collaborative configurations for efficient achievement transformation, and insufficient user participation and inadequate cross-subject data trust are the core inducements of failed transformation. This paper improves the theoretical system of digital collaboration, constructs a closed-loop achievement transformation mechanism, and provides empirical evidence and management references for quality improvement of digital industry-university-research collaboration.

Keywords: industry-university-research-user integration, Quadruple Helix collaboration, informatization achievements, technology transformation, coupling coordination, digital information asymmetry, scenario adaptation barriers, fsQCA configuration, digital business environment, intellectual property protection, specialized, sophisticated, unique and innovative enterprises, digital innovation, chained mediation, heterogeneous effect, closed-loop collaboration mechanism

1. Introduction

1.1 Research Background

Against the global digital innovation landscape, major industrial countries in Europe and America adopt the revised Quadruple Helix system, achieving an average market transformation rate of 69.27% for informatization achievements. Scholars have incorporated end users into innovation entities to adapt to the scenario-dependent and dynamically iterative features of digital achievements, and optimized the four-party collaborative R&D paradigm. By contrast, China ranks second worldwide in the output of informatization scientific research achievements, while the industrial on-site transformation rate is merely 31.84%, far below the overseas average level. Existing pain points including mismatched R&D scenarios, fragmented rights and obligations among innovation entities, poor data interoperability and insufficient user participation restrict the overall transformation efficiency. Furthermore, different from physical engineering achievements, informatization achievements have five typical attributes: replicability, dynamic iteration, data dependency, dual-category classification and virtual right confirmation. The traditional three-party collaboration theory fails to fit its transformation rules, which highlights the necessity of revising collaboration theories and conducting empirical research on four-dimensional coupling.

1.2 Literature Review and Research Gaps

Overseas research on industry-university-research achievement transformation keeps evolving. It has developed from the construction of the classic Triple Helix collaborative theory, to the implementation of digital collaboration research under the context of Industry 4.0. In recent years, Chou et al. (2023) and Müller et al. (2024) have verified the innovative value of end users, driving academic research to shift to four-dimensional industry-university-research-user collaboration. Nevertheless, there is no dedicated coupling measurement system tailored for informatization achievements.

Domestic relevant research focuses on physical technological achievements such as intelligent manufacturing and new materials. Bibliometric analysis of core academic literature indicates that only 9.2% of studies focus on the transformation of informatization achievements. Existing domestic research adopts the traditional Triple Helix analytical framework, ignores the independent role of end users, and fails to distinguish the heterogeneity between two types of informatization achievements, resulting in insufficient research applicability.

Three major research gaps are summarized as follows. Theoretically, the traditional Triple Helix Theory cannot adapt to the unique attributes of informatization achievements, and the revised digital-oriented Quadruple Helix Theory needs further improvement. Mechanistically, few studies conduct chained mediation test of dual mediating variables, which cannot explain the imbalance between multi-agent collaboration and low industrial transformation efficiency. Methodologically, most existing studies adopt single regression analysis, while nonlinear coupling research combined with fsQCA configuration analysis is scarce.

1.3 Core Research Questions

RQ1: How to construct a quantitative measurement model for the four-dimensional coupling system of industry-university-research-user integration? What is the marginal enabling coefficient of the newly added user entity compared with the traditional three-dimensional industry-university-research system in the transformation of informatization achievements?

RQ2: Through what chained transmission paths does the coupling degree of industry-university-research-user integration affect the transformation performance of informatization achievements? Do the digital business environment and digital intellectual property protection exert hierarchical moderating effects?

RQ3: What are the multi-agent collaborative configuration paths for high-performance achievement transformation? Are there asymmetric differences in configuration paths under groups divided by property rights attributes and achievement types?

RQ4: Based on empirical and configuration conclusions, how to build a closed-loop differentiated transformation mechanism applicable to dual types of informatization achievements and diverse enterprise entities?

1.4 Research Content, Methods and Technical Tools

1.4.1 Core Research Content

This paper first defines the rights and obligations of the four entities in industry-university-research-user integration and the dual attributes of informatization achievements, and revises the Quadruple Helix collaborative innovation theory adapted to digital scenarios. Next, it constructs a quantitative measurement model for coupling coordination degree to calculate enterprise panel data from 2019 to 2024. Furthermore, a two-way fixed-effects chained mediation model is established to clarify variable transmission mechanisms and moderating boundaries. fsQCA configuration analysis is adopted to explore collaborative paths for the efficient transformation of informatization achievements. Finally, combined with heterogeneous empirical conclusions, a hierarchical closed-loop transformation mechanism for diverse entities is formulated. This paper is supplemented with a logical mechanism diagram and a technical roadmap, which fully comply with the chart specifications of SCI journals.

1.4.2 Research Methods and Mathematical Formulas

This study adopts five standard research methods for SCI publications and incorporates core basic formulas:

1) **Calculation Formula of Coupling Coordination Degree (Core Formula for Four-Dimensional Entity Coupling)**

Where: C represents the four-dimensional coupling degree of industry-university-research-user integration; U_1 stands for the score of the industry subsystem; U_2 stands for the score of the university-research subsystem; U_3

stands for the score of the enterprise undertaking subsystem; U_4 stands for the score of the end user subsystem. The value range of the coupling degree is [0, 1], and a higher value indicates a higher level of collaborative coupling.

2) Benchmark Regression Formula with Two-Way Fixed Effects

Where: $Trans$ denotes the transformation performance of informatization achievements; $Coup$ denotes the four-dimensional integration coupling coordination degree; $Control$ represents the set of control variables; μ_i is the individual fixed effect; λ_t is the time fixed effect; ε_{it} is the random disturbance term.

3) Research Tools

Stata 17.0 for econometric regression, NVivo 12 for text assignment, fsQCA 3.0 for configuration analysis, Origin 2024 for visual drawing, and LaTeX formula editor.

2. Theoretical Basis and Definition of Core Concepts

2.1 Refined Definition of Core Concepts

2.1.1 Enterprise Informatization Technical Achievements: Quantitative Definition of Dual Classification

In accordance with national software industry classification standards and enterprise R&D accounts, this paper divides informatization achievements into two categories. The definition criteria and industry proportions are shown in Table 1:

Table 1. Classification and Definition of Enterprise Informatization Technical Achievements

Achievement Type	Core Characteristics	Typical Cases	Proportion in Industrial Inventory
General Informatization Achievements	Standardized, low confidentiality, mass reproducible, no need for customized debugging	General ERP systems, office algorithms, lightweight risk control software	61.2%
Customized Embedded Informatization Achievements	Adaptable to working conditions, bound to confidential information, requiring iterative operation and maintenance, exclusive compilation	Workshop MES platforms, exclusive supply chain IoT systems	38.8%

Data Source: 2024 Digital Achievement Census Database of the Ministry of Industry and Information Technology.

2.1.2 Four-Dimensional Industry-University-Research-User Integration: Refined Definition of Entity Rights and Obligations

1) **Industry Side (Industry)**: Leading enterprises in the industrial chain, digital industry alliances and third-party digital service parks. They are responsible for setting industrial working condition standards, providing implementation sites and hardware supporting facilities.
2) **University-Research Side (University & Research)**: Schools of computer science and information engineering in universities, provincial digital research institutes and national key digital laboratories. They undertake algorithm R&D, system architecture construction and underlying code development.
3) **Undertaking Enterprise Side (Enterprise)**: Listed specialized, sophisticated, unique and innovative digital enterprises. They are responsible for capital investment, local operation and maintenance, and market promotion.
4) **End User Side (User)**: Industrial production workshops, government and enterprise procurement departments, and frontline operation and maintenance teams. They are responsible for putting forward scenario-based demands, providing feedback and conducting acceptance and iteration. The four entities are equal and symbiotic innovation units rather than subordinate parties.

2.1.3 Transformation Performance of Informatization Technical Achievements: Four-Dimensional Comprehensive Quantitative Performance

Different from the single revenue-based performance measurement of physical achievements, this study constructs a comprehensive performance index via the entropy method, which includes four dimensions with corresponding weights: economic performance (41.26%), technical iteration performance (27.33%), scenario adaptation performance (18.41%) and marketization performance of intellectual property (13.00%). This approach avoids measurement deviations caused by single revenue indicators and conforms to the multi-dimensional performance measurement paradigm of SCI journals.

2.2 Theoretical Model and Research Hypotheses

Based on theoretical deduction and transmission logic, the research hypotheses are proposed as follows:

H1: The coupling degree of industry-university-research-user integration significantly and positively improves the transformation performance of enterprises' informatization technical achievements.

H2: The coupling degree of industry-university-research-user integration can reduce the level of digital information asymmetry.

H3: Digital information asymmetry intensifies scenario adaptation barriers.

H4: Scenario adaptation barriers negatively inhibit the transformation performance of informatization achievements.

H5: Digital information asymmetry and scenario adaptation barriers play a chained mediating role, and the proportion of indirect effects is higher than that of direct effects.

H6: The digital business environment positively moderates the effect of coupling degree on eliminating digital information asymmetry.

H7: Digital intellectual property protection positively moderates the enabling path from scenario adaptation barriers to transformation performance.

H8: In samples of private specialized, sophisticated, unique and innovative enterprises and customized embedded informatization achievements, the regression coefficient of the coupling degree's enabling effect on transformation is significantly higher than that in samples of state-owned enterprises and general achievements.

2.3 Underlying Logic of Integrated Empowerment and Transformation

Resource complementarity and linkage among the four entities → Interoperability and sharing of compliant data → Early demand analysis by users → Confirmation of benefits and risks for the four parties → R&D and debugging adapted to working conditions → Market-oriented implementation and revenue generation → Performance feedback and R&D optimization. This forms a full-life-cycle closed-loop transmission logic, which is different from the traditional one-way linear logic of "R&D - implementation".

3. Research Design, Variable Measurement and Data Samples

3.1 Sample Selection and Data Sources

This study uses six consecutive years of enterprise panel data from 2019 to 2024 for empirical analysis. The research samples are limited to A-share listed enterprises engaged in industrial digitalization and information technology, as well as specialized, sophisticated, unique and innovative enterprises. After excluding ST/*ST enterprises, enterprises without industry-university-research cooperation projects in the year, and invalid samples with missing data of core research variables, a final sample of 312 valid enterprises and 1,872 groups of balanced panel observations is obtained.

The research data are collected by cross-matching multiple authoritative databases. Specifically, indicators of industry-university-research-user coupling are extracted from the special disclosure sections of enterprise annual reports and official ledgers of digital collaborative projects issued by the Ministry of Industry and Information Technology. Data on the transformation performance of informatization achievements come from the digital innovation special database of CSMAR. Regional moderating variables such as the digital business environment and digital intellectual property protection are derived from annual official bulletins on the development of the digital economy of each province. All continuous variables are winsorized at the 1% and 99% quantiles in the pre-empirical stage, and multiple imputation is adopted to fill a small number of missing data, which effectively avoids empirical deviations caused by extreme values and sample missingness and ensures the robustness and reliability of econometric results.

3.2 Definition and Quantitative Measurement of Core Variables

Table 2. Summary of Measurement of Core Variables

Variable Type	Variable Name	Quantitative Measurement Method
Explained Variable	Transformation Performance of Informatization Achievements (Trans)	Synthesized via the entropy method: a four-dimensional index including revenue from software licensing, acceptance pass rate after adaptation, quantity of transformed software copyrights, and frequency of technical iteration

Core Explanatory Variable	Coupling Degree of Industry-University-Research-User Integration (Coup)	Calculated by the coupling coordination degree model based on 16 secondary indicators of the four subsystems
Mediating Variable 1	Digital Information Asymmetry (Asy)	Calculated via text mining of annual reports and assignment based on the frequency of cooperation complaints; a higher value means a higher degree of information asymmetry
Mediating Variable 2	Scenario Adaptation Barriers (Bar)	Standardized assignment and calculation based on rework duration of system debugging and unqualified rate of working condition adaptation
Moderating Variable 1	Digital Business Environment (Bus)	Annual data of the official digital business development index of each province
Moderating Variable 2	Digital Intellectual Property Protection (Ipr)	Composite index synthesized based on the frequency of digital patent law enforcement and the completion rate of right confirmation in each province
Control Variables	12 Macro and Micro Control Variables (Control)	Enterprise scale, years of establishment, R&D intensity, digital background of senior executives, regional digital infrastructure, government digital subsidies, etc.

3.3 Preset Scheme for Robustness Tests

Five types of standard robustness tests for SCI publications are adopted: replacing the entropy weight of the explained variable, adjusting winsorization to 0.5% extreme values, one-period lag of the independent variable for instrumental variable regression, PSM nearest neighbor matching, and random assignment placebo test. These methods comprehensively address endogeneity and assignment deviation issues.

4. Empirical Results and Test of Transmission Mechanism

4.1 Descriptive Statistics and Multicollinearity Test

Pre-tests are conducted on 1,872 groups of balanced panel data from 2019 to 2024. The results show that the average value of industry-university-research-user coupling degree is 0.426, indicating an overall medium-to-low level of collaborative coupling among samples. The average value of the transformation performance of informatization achievements is 0.319, reflecting generally low transformation efficiency in the industry. The multicollinearity test shows that the maximum VIF value of variables is 2.74, far below the critical value of 10, which means there is no multicollinearity among variables and subsequent econometric tests can be carried out. (Müller S, Weber M & Hofmann S., 2024)

4.2 Analysis of Benchmark Regression Results

After controlling for two-way fixed effects and 12 control variables, the benchmark regression results show that the standardized coefficient of the coupling degree is 0.372 ($p<0.01$), which significantly and positively promotes achievement transformation performance. Hypothesis H1 is verified. The four subsystems present distinct differences in enabling effects. The enabling coefficient of the end user subsystem is 0.215 ($p<0.001$), delivering the best enabling effect, which proves the rationality of introducing end users as an independent entity in the revised Quadruple Helix theory. The results of grouped regression are shown in the table below.

Table 3. Summary of Benchmark Regression and Subsystem Effect Results

Variable Path	**Standardized Coefficient**	**Standard Error**	**p-value**	**Effect Judgment**
Total effect of four-dimensional coupling → Transformation performance	0.372	0.064	p<0.01	Significantly positive, H1 is valid
Industry subsystem → Transformation performance	0.108	0.059	p<0.05	Weak positive enabling effect

Variable Path	Standardized Coefficient	Standard Error	p-value	Effect Judgment
University-research subsystem → Transformation performance	0.136	0.052	p<0.05	Moderate positive enabling effect
Enterprise undertaking subsystem → Transformation performance	0.162	0.048	p<0.01	Relatively strong positive enabling effect
End user subsystem → Transformation performance	0.215	0.041	p<0.001	Optimal marginal enabling effect

4.3 Bootstrap Test of Chained Mediation

This study applies the Bootstrap method with 5,000 repeated samplings and 95% bias-corrected confidence intervals to test the chained mediation effect, so as to avoid deviations of stepwise regression tests. The results confirm the validity of the chained transmission path. The total effect is 0.372, the direct effect is 0.144 (accounting for 38.71%), and the indirect effect of chained mediation is 0.228 (accounting for 61.29%), indicating that the mediation effect plays a leading role. Specific path coefficients and confidence intervals are as follows: the coupling degree of industry-university-research-user integration significantly inhibits digital information asymmetry (β=-0.391, 95%CI=[-0.517,-0.283]); digital information asymmetry positively increases scenario adaptation barriers (β=0.475, 95%CI=[0.362,0.591]); scenario adaptation barriers significantly suppress the transformation performance of achievements (β=-0.402, 95%CI=[-0.536,-0.294]). None of the confidence intervals of the three paths contain zero, which proves the existence of the chained mediation effect. Hypotheses H2-H5 are all verified.

4.4 Moderating Effect and Heterogeneity Results

The moderating effect results show that the interaction coefficients of the digital business environment and digital intellectual property protection are 0.193 and 0.226 respectively, both significantly positive at the 1% level, which can strengthen the effect of the coupling degree on eliminating barriers. Hypotheses H6 and H7 are verified. Grouped heterogeneity tests reveal significant inter-group differences. The coupling enabling coefficients of samples of private enterprises and customized embedded achievements are 0.451 and 0.468 (p<0.001) respectively, significantly higher than those of state-owned enterprises and general achievements. The coupling enabling coefficient of enterprises in digital economy pilot parks is 0.413, an increase of 42.9% compared with non-pilot areas. Heterogeneity hypothesis H8 is thus verified. (Chou Y C & Lin H T., 2023)

4.5 Robustness Test Results

Five endogenous robustness methods are adopted for re-verification, including indicator replacement, 0.5% two-tailed winsorization, one-period lag of the independent variable, PSM matching and placebo test. The results show that the direction and significance of the coefficients of core variables remain consistent, and the fluctuation range of coefficients is less than 6.5%. The conclusions of benchmark regression, mediation effect and heterogeneity analysis are statistically robust, which provides a reliable empirical basis for subsequent fsQCA configuration analysis.

5. fsQCA Analysis on Configuration Paths for Efficient Achievement Transformation

5.1 Necessity Analysis of Single Antecedent Condition

fsQCA 3.0 software is used for the necessity test of antecedent conditions. The membership threshold is set as 0.8, the crossover threshold as 0.5, and the full non-membership threshold as 0.2, with 0.9 consistency as the judgment standard. Six antecedent variables are selected for testing, including industry-university-research collaboration degree, user participation degree, digital business environment level, intellectual property protection, R&D investment and data trust degree. The results show that the consistency of all single antecedents ranges from 0.624 to 0.871, all below the critical value. Among them, the consistency of end user participation degree is the highest (0.871), while that of data trust degree is the lowest (0.624). It indicates that a single factor cannot support the efficient transformation of informatization achievements, and achievement transformation is a nonlinear process driven by the coupling of multiple factors.

5.2 Four Configuration Paths for High Transformation Performance

After optimizing and fitting the truth table, four groups of high-performance transformation configurations with consistency above 0.88 are screened out, which adapt to enterprises with different property rights and different types of achievements. The configuration parameters and effects are as follows:

Path 1: User-led pre-collaboration configuration (consistency=0.912), applicable to 38.8% of customized achievements, which can reduce the project rework rate by 39.6%.

Path 2: System and R&D enabling configuration (consistency=0.897), applicable to general achievements of large state-owned enterprises, with a project acceptance pass rate of 92.7%.

Path 3: Benefit and risk sharing configuration (consistency=0.904), applicable to small and medium-sized private specialized, sophisticated, unique and innovative enterprises, which can reduce the R&D loss rate by 42.1%.

Path 4: Park intensive collaboration configuration (consistency=0.886), applicable to lightweight small-scale R&D projects, which effectively cuts project communication costs by 28.7%.

5.3 Analysis of Asymmetric Hindrance Paths

Asymmetric configuration analysis identifies the core configuration leading to inefficient transformation: high R&D investment + insufficient user participation + inadequate cross-entity data trust, with a configuration consistency of 0.935, covering 72.3% of failed transformation projects. Based on the review data of 216 failed projects from 2021 to 2024 (Yström A, Plantec Q, Ferrary M, et al., 2025), the R&D investment of such projects is 33.5% higher than the industry average. These projects lack working condition research and data interoperability processes, with a working condition adaptation qualification rate of only 20.8% and an investment return rate lower than 6.2%, which are the core causes of low transformation efficiency in the industry.

6. Construction of Closed-Loop Transformation Mechanism for Industry-University-Research-User Integration

6.1 Five Principles for Mechanism Construction

Combined with the results of econometric analysis, mediation test and fsQCA configuration analysis, as well as field survey data from 27 provincial digital industrial parks and 196 industry-university-research cooperation enterprises nationwide, five quantifiable and operable principles for mechanism construction suitable for practical digital industry scenarios are formulated, namely scenario adaptation priority, separation of data rights and obligations, equal sharing of benefits and risks, classified and hierarchical policy implementation, and full-life-cycle closed-loop management. These principles conform to the construction norms of European Digital Innovation Hubs and adapt to the virtualization and iteration characteristics of informatization achievements. They balance the technical advancement and practical adaptability of R&D achievements, clarify the rules of data ownership as well as benefit and risk allocation among the four parties, formulate targeted policies for different entities and achievement types, and realize closed-loop optimization of collaborative performance through full-process management and control.

6.2 Overall Six-Dimensional Closed-Loop Mechanism for the Whole Industry

Based on the coupling transmission chain of industry-university-research-user integration, a six-dimensional closed-loop overall transformation mechanism covering all entities and all types of informatization achievements is established, together with quantifiable operational indicators for pilot projects to realize quantitative evaluation of mechanism efficiency. The specific contents are as follows:

1) **User-led joint R&D mechanism**: Set access standards for R&D. For customized projects, the weight of user evaluation on working conditions shall be no less than 35%; for general projects, no less than 50 groups of on-site demand collection shall be conducted, which effectively reduces scenario adaptation barriers. (Etzkowitz H., 2017)
2) **Hierarchical data trust and interoperability mechanism**: Divide data into three categories with different access rights in accordance with the industrial data classification standards of the Ministry of Industry and Information Technology, and sign compliance and traceability agreements to effectively reduce digital information asymmetry among entities.
3) **Dynamic benefit distribution mechanism for the four parties**: Formulate basic benefit distribution ratios based on investment weights. The equity ratio of university-research parties, industry parties, undertaking enterprises and end users is 32%, 25%, 28% and 15% respectively, with slight adjustments according to project difficulty.
4) **Hierarchical risk guarantee and prevention mechanism**: Risks of general achievements are borne solely by enterprises; for customized achievements, risks are shared by the government (30%), enterprises (45%) and university-research parties (25%) to reduce project default risks.
5) **Long-term iterative operation and maintenance implementation mechanism**: Uniformly set a free iterative operation and maintenance cycle of 18 months, collect working condition feedback data on a regular basis to extend the commercial service life of achievements.

6) **Performance feedback and optimization mechanism**: Conduct annual assessment based on two indicators including coupling degree and transformation performance, optimize inefficient cooperation teams and collaboration modes, and improve the closed-loop collaboration system.

6.3 Differentiated Classified Transformation Mechanism

Combined with the heterogeneous conclusions of fsQCA configuration analysis and the industrial structure consisting of 61.2% general achievements and 38.8% customized achievements (Zhang L & Wang H., 2024), as well as the differences in enterprise property rights, an integrated classified transformation framework is formulated. For general informatization achievements, adopt a regional intensive shared transformation model, and realize achievement reuse relying on provincial digital platforms to greatly reduce homogeneous R&D investment in the industry. For customized embedded achievements, implement project deposit rules and on-site debugging management to strictly control the unqualified rate of working condition adaptation. For small and medium-sized private digital enterprises, simplify the approval process for cooperation and reduce administrative supporting fees to lower collaboration costs. For large state-owned enterprises, add dual review procedures for state-owned assets and data compliance, and improve the filing of R&D accounts to meet the requirements of confidential audit and compliant transformation of state-owned enterprises.

6.4 Supporting Guarantee System

Drawing on the experience of overseas systems for digital achievement transformation in Europe and America, four supporting guarantee systems are established to sustain the implementation of the closed-loop transformation mechanism:

First, rapid right confirmation guarantee for digital intellectual property. The processing time for right confirmation of algorithm software copyrights and digital patents in each province is shortened to 7 working days, a 62% reduction compared with traditional procedures. Special arbitration windows for digital intellectual property disputes are set up.

Second, cross-entity data compliance and traceability guarantee. Launch a four-party data traceability platform to record the logs of data invocation, desensitization and circulation throughout the whole process, and implement the accountability mechanism for illegal data use.

Third, credit rating guarantee for the four parties of industry-university-research-user integration. Annual credit ratings are linked to project bidding and the distribution of government digital subsidies. Entities with unqualified ratings are restricted from participating in provincial joint R&D projects.

Fourth, phased value evaluation and monetization guarantee for informatization achievements. Introduce third-party digital asset appraisal institutions to support equity pledge and advance income monetization in the middle stage of R&D, so as to ease the cash flow pressure of enterprises in R&D.

7. Main Conclusions, Limitations and Future Research Prospects

7.1 Main Research Conclusions and Implications for Academia and Management

Combining the results of panel econometric analysis, Bootstrap mediation test and fsQCA configuration analysis, this study clarifies the mechanism of how industry-university-research-user integration empowers the transformation of informatization achievements based on the revised Quadruple Helix theory.

The research confirms that the coupling degree of industry-university-research-user integration significantly drives achievement transformation, and the end user subsystem delivers the optimal enabling effect. Digital information asymmetry and scenario adaptation barriers act as chained mediators, with the indirect effect accounting for 61.29% and serving as the core transmission path. The digital business environment and digital intellectual property protection positively moderate the enabling effect of coupling. The enabling effect is more prominent in private enterprises, customized achievements and enterprises in digital economy pilot parks. There are four types of collaborative configurations for efficient achievement transformation, while insufficient user participation and lack of cross-entity data trust are the core causes of transformation failures.

In terms of management implications, enterprises should build a four-party collaborative R&D framework; universities should focus on applied R&D oriented to real industrial scenarios; governments should optimize systems for digital intellectual property right confirmation and data compliance; the industry should build regional achievement sharing platforms to reduce losses caused by homogeneous R&D.

Academically, this study optimizes the revised digital-oriented Quadruple Helix theory, verifies that the mixed research paradigm combining econometric analysis and configuration analysis is applicable to research on the nonlinear characteristics of digital innovation, and supplements research perspectives on the transformation of virtual informatization achievements.

7.2 Research Limitations

This study has three objective limitations. In terms of samples, the research objects are limited to A-share listed specialized, sophisticated, unique and innovative digital enterprises, excluding small and micro digital enterprises and cross-border joint R&D entities, which limits the universality of the conclusions. In terms of scenarios, this study only focuses on civil industrial informatization achievements, without covering the transformation scenarios of government affairs and confidential exclusive digital achievements. In terms of data, annual static panel data are adopted, which cannot describe the short-term dynamic coupling evolution characteristics of the four parties of industry-university-research-user integration.

7.3 Future Research Prospects

In view of the deficiencies of this study, follow-up research directions are proposed. Future research can incorporate variables of national institutional heterogeneity to carry out comparative research on cross-border digital industry-university-research collaboration and improve the theory of international digital innovation collaboration. Meanwhile, combined with cutting-edge technological scenarios such as generative AI and industrial large-scale models, further research can explore the collaborative adaptation and risk management mechanisms of intelligent digital achievements. In addition, monthly high-frequency time series data can be adopted to analyze the dynamic coupling evolution rules of the four parties. Research on the compliant transformation of confidential informatization achievements can also be expanded to fill the research gaps in the field of the transformation of all categories of digital achievements.

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