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Application of Functional Regression Model on OADR-YADR Relation: The Case of Greece

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Abstract

In the social security system and healthcare system, the process of demographic aging is of major interest. The current research work provides a statistical method based on functional time series regression analysis to improve old-age dependency ratio modeling for the Greek population. The functional time series regression-based model was applied to the old-age dependency ratio and young-age dependency ratio of the Greek population over the years from 1980 to 2023. The estimation of the functional regression model was used to model the relationship between the two age dependency ratios. Therefore, the functional regression model was used to measure the impact of the functional coefficient on young–age dependency ratio and old-age dependency ratio differences. The research findings revealed a varying functional-coefficient with a strong negative function of young-age dependency of the Greek population over the last years. The results confirm a broader usage of the functional regression models to provide more accurate estimates in demography, public health, and age-related policy studies.

Keywords: functional time series regression analysis, old-age dependency ratio, young-age dependency ratio, population aging, Greece

1. Introduction

As many countries face the phenomenon of demographic aging, the budgetary impact of aging has become an important topic in contemporary economic literature. Increased life expectancy and falling birth rates have led to an increase in the dependency ratio, meaning fewer workers are supporting a growing number of retirees (Prohnitchi, 2024; Agnihotri, 2023). Old age is going through significant demographic changes; potentially exceeding the working-age group and having an impact on labor markets; financial systems; and the pressure for major services, including healthcare, social security, housing, and technologies (Rashmi & Paul, 2024). There are rising concerns about the adverse effect of population aging on economic growth. These concerns are particularly very marked in advanced economies and in some of the Asian economies that are facing fast aging (Park & Shin, 2023). An aging society has the potential to develop unfavorable socio-economic effects. The phenomenon of the aging population places pressure on society with large healthcare costs and other age-related expenses, especially through the pension system, which can significantly damage Gross Domestic Product (GDP) growth (Jayawardhana et al., 2023). The interconnection of aging and economic well-being is a key point in this debate (Agnihotri, 2023). Thus, governments and global research worldwide are interested in the connection between the aging population and economic growth since the impact of different age groups has varying degrees of productivity and financial needs.

Using probabilistic population projections for the whole world, Gerland et al. (2014), indicated that the ratio of working-age people to older people will almost certainly decline considerably in all of the countries. Population aging is not a challenge only to those within the age of 65+ but to the younger generations as well, who are supposed to invest time and resources in care for the elderly population (Thobekile et al., 2023). The old-age dependency ratio defined as the proportion of the population aged 65+ to the proportion of the population aged 15–64 in the EU almost doubled from 15.2% in 1960 to 29.9% in 2016, therefore, maintaining fiscal sustainability will become extremely difficult in front of such a serious demographic change (Jayawardhana et al., 2023). One in every six people in the world will be over 65 years old in 2050, and the proportion will rise to one in four by 2100, compared to one in 11 in 2019 (Abio et al., 2023). Among the most affected by this change in the age structure of the population are Europe, and especially the countries of Southern Europe. Thus, one in five Europeans was over 65 in 2019, and it is expected that this will be the case for one in four by 2050, and one in three by 2100 (Abio et al., 2023). On the other side, the young-age dependency ratio is defined by Eurostat (2025) as a proportion of young people at an age when they are generally considered economically inactive, (i.e. under 15 years), compared to the proportion of people of working age (i.e. 15-64).

From the perspective of this paper, an increasing dependency ratio is thus far carrying out substantial influence and causing policy challenges to arrange and maintain public financing of healthcare, pensions, and social protection for the older population (Sheraz et al., 2023). The division of the total dependency ratio into the young and old populations is marked by a good reason, to be specific; the trend of the old population has been rising since the 1990s whereas the young population has been found to reduce in the time of the same period. Therefore, the old-age dependency ratio presents the number of older people 65+ relative to the working age population (commonly defined as aged 20 to 64); the total age dependency ratio takes into account the total number of economically dependent persons (those persons below age 15 plus persons 65+) relative to the working age persons (defined as aged 15 to 64), (Kelin et al., 2023).

Implications of aging can increase the economic burden brought by the proportion of people aged 65+ to the total population or working-age population (Friedlander & Klinov-Malul, 1980). This process of aging population is led by two key factors: increasing life expectancy and low fertility (Kelin et al., 2023). In this case, an economic burden is increased when there is a substantial decline in the proportion of young and an increase in the proportion of old as well as a decrease in the share of the working-age population (Friedlander & Klinov-Malul, 1980). The recipients of services such as healthcare, pensions and long-term care are children and the elderly, who are a dependent part of the population and financed mainly by the working-age population (Kelin et al., 2023). Lee and Shin (2019) employed a panel model from 142 nations between 1960 and 2014, to explore the impact of population aging on economy growth. These scholars found that the population aging rate, reflected by the old-age dependence ratio, harms economic development when it crosses a particular threshold, while the negative effects become larger as population aging moves forward. Additionally, Lee and Shin (2019) discovered how population aging has hindered growth in economies in the last few decades, especially in older industrialized nations.

Mortality and its transition in Greece are well-studied phenomena and some subsequent analyses showed the almost constant increase in average longevity in a few ages. These developments follow the decline in infant and child mortality, the temporal changes in the age of prominence of the accident, and the development of mortality among middle-aged and older adults (Zafeiris, 2023). As a result, compared to other countries in Southeastern Europe, mortality and health transition have progressed in Greece (Zafeiris, 2023), on the contrary, the mortality pattern prevailing in Greece has more similarities with Western and Southern Europe. From 2008 on, Greece experienced a very great financial and socio-economic crisis that required an examination of the crisis' effects on mortality. Some researchers pointed out a "crude mortality" increase in 2009–2015 that did not only arise from the economic crisis but also from population aging (Zafeiris, 2023). In countries like Italy, Greece, and France, the impact of the aging population is fairly low compared to other European countries (Jayawardhana et al., 2023). This is because these nations place a strong emphasis on the engagement after retirement of the elderly population, thus a lot of the aged population serves in hotels and restaurants and such kinds of opportunities enable the elderly population to be economically active. Together with this mortality transition, the country has also experienced a continuous decline in fertility rates, so that the proportion of the population under 15 has decreased with a proportional increase in the adult and elderly population. As a consequence, the old-age dependency ratio in Greece increased substantially reaching 37.3 in 2023, and the young-age dependency ratio decreased to 21.6 in 2023 (World Bank, 2025). This means that for every 100 working-age Greeks (considering the interval between 15 and 64 years old), there are 37.3 seniors aged 65+.

The principal contribution of this study is to examine the relationship between old-age dependency ratios with young-age dependency ratios about the population aging process in Greece. This work aims to adapt the functional-coefficient modeling technique concerning actual demographic time series. Therefore, the study adapts the local linear regression techniques to estimate the coefficient functions analyzing the changes in the contributions of young-age dependency on the old-age dependency trend in Greece from 1980-2023. The functional coefficient modeling perspective is shown to be a more informative approach with outstanding advantages. It is especially relevant in modeling time series data where it is practical to presume that the coefficients change over time *t* and also this model is important for modeling the population dynamics where it is reasonable to expect different behaviors based on the population size (Cai, Fan & Yao, 2000). The rest of the paper is organized as follows. After the Background, Section 2 provides an overview of the methodology and data. The results of the estimation of the functional regression model are provided in Section 3. The discussion is presented in Section 4. Section 5 provides the conclusion.

2. Data and Methods

The data for the old-age dependency and youth dependency ratios for Greece were retrieved from the World Bank's World Development Indicators (https://data.worldbank.org/indicator), (World Bank, 2025). These are annual time series data for the period from 1980-2023 for the population of Greece. Data are presented as the proportion of dependents/seniors per 100 working-age population. World Bank estimates are based on age distributions of the United Nations Population Division's World Population Prospects. It is important to emphasize that dependency ratio data show only the age composition of a population, but not economic dependency.

In this research study, a functional coefficients regression model was estimated. Functional coefficient regression is a kind of semi-parametric approach that extends the standard regression framework allowing for non-linear, dynamic coefficients in regression estimation as well as β_j to be functions of the variable Z_t (Fan & Gijbels, 1996; Cai, Fan, & Yao, 2000). In the standard linear regression assumptions, the relationship between a dependent variable and explanatory variables is shown in eq. (1).

$$Y_t = \beta_0 + \sum_{i=1}^{k} \beta_i X_{it} + \epsilon_t \qquad (1)$$

For most applications, this framework is usually enough, but the condition that coefficients are the same for all observations is quite restrictive and in practice is broken many times. Otherwise, nonparametric modeling is skeptical as to the nature of the relationship between variables, presuming a basic functional relationship between the dependent and explanatory variables as presented in eq. (2).

$$Y_t = f(X_{1t}, \dots X_{kt}) \qquad (2)$$

The flexibility of this specification is challenging as it can be tough to explain nonparametric estimates, for instance, discussing the marginal effects of a given variable upon Y_t can be difficult. A more flexible, area of compromise between these two extremes is the functional coefficients model in eq. (3).

$$Y_t = \beta_0(Z_t) + \sum_{i=1}^{k} \beta_i(Z_t) X_{it} + \epsilon_t \qquad (3)$$

In eq. (3), β_0 are no longer simple coefficients, but they are functions of the variable Z_t (IHS, 2024). Accordingly, the relationship is linear in variables, but non-linear in parameters. Compared to the specification of linear regression in eq. (1), the coefficients are no longer constant but rather vary over observations. Thus, non-linear occurrences easily fit in with this framework, coefficient relationships are dynamic, and the explanation of coefficient relationships is still intuitional, i.e. unlearned. The estimation of functional-coefficient models is based on local polynomial regression which incorporates two different techniques: the non-linear functions are approximated $\beta_j(z)$ using Taylor's Theorem and local regressions are estimated with penalizing of observations using a kernel function. The basic idea is that for each z of interest, a local regression is estimated with kernel-weighted squared residuals. Then, estimating this regression for a corresponding set of points z discovers the functional coefficients relationship. However, there are some major points to highlight: functional coefficient estimation is a set of coefficients estimated at a corresponding set of points z and the objective function depends on the kernel bandwidth (IHS, 2024).

The most important step in estimating functional-coefficient regressions is the optimal selection of the bandwidth parameter. The bandwidth is selected between two extremes that balance bias and variance, i.e. when, the functional coefficient estimator reduces to interpolating the data points in (small bias, large variance) and when, the functional coefficient estimator reduces to the mean of (large bias, small variance). The data-driven method, Akaike Information Criterion (AIC) calculates the optimal bandwidth using non-parametric AIC with non-parametric degrees of freedom. The idea comes from Hastie and Tibshirani's (1990) degrees of freedom smoothing literature, and the actual bandwidth methodology proposed in Cai, Fan, and Yao (2000) and Cai (2003). Thus, for each estimation point and a given bandwidth, the functional coefficients are estimated and then used to calculate the standard error of the local polynomial regression residuals. The standard error and the estimated nonparametric degrees of freedom are then used to obtain a functional AIC value. The optimal bandwidth is obtained as the one that minimizes the AIC summed over z. The optimal estimation bandwidth estimators themselves seek preliminary-functional coefficient estimates to obtain standard errors, covariance matrix, and bias estimates. These preliminary estimates seek their pilot bandwidth, which is mostly determined using one of the following methods which do not depend on other bandwidths: Modified Multi-Cross-Validation (MMCV) and Auxiliary Polynomial Degree (Cai, Fan, & Yao, 2000; Fan & Gijbels, 1995a; Fan & Gijbels, 1996). The optimal predictor is given by the well-known conditional expectation of the forecast value conditional on the observable information up to time. This predictor may be evaluated in one of the following ways: Plug-in Method, Monte Carlo (asymptotic), Monte Carlo (bootstrap), and Full bootstrap methods (Fan & Yao, 2003; Davison & Hinkley, 1997).

3. Results

The dependent variable is followed by functional-coefficient regressors. The LOGOADR (-1) is the dependent variable, and the lag variable LOGYADR (-2) has functional coefficients. Therefore, the variable upon which the functional coefficients depend and will vary is LOGLYNX (-2). The settings of bandwidth selection methods are associated with the data-driven method such as Multi Cross-validation and the Epanechnikov is the type of kernel used in the estimation. Figure 1 shows the functional coefficient relationships for the regressor.

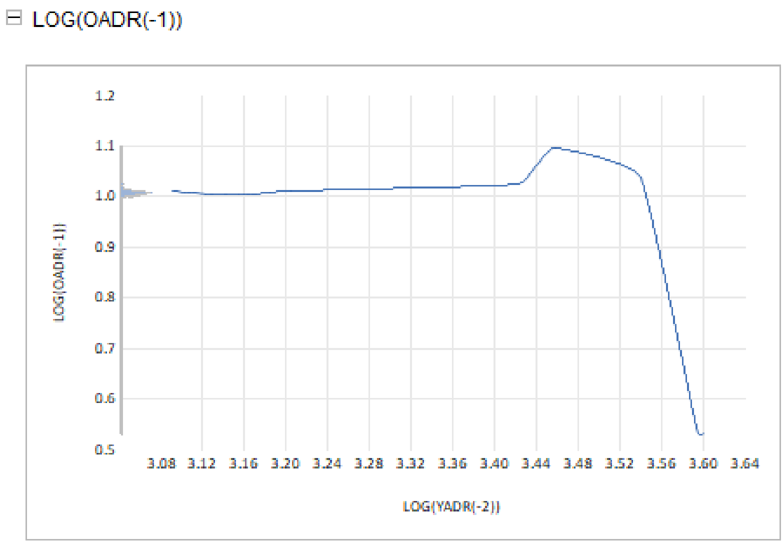

Figure 1. Functional coefficients relationships

Source: Author's design.

The coefficient function YADR (-2) is negative and strongly decreasing during the decrease phase. Given the necessary time, the coefficient function varies concerning the young-age dependency time series. Thus, at the first period of the time series, the coefficient corresponds roughly to the young-age dependency increase phase, and in the later period of the time series, the coefficient corresponds to the young-age dependency decrease phase. This means that both the old-age dependency ratio and the young-age dependency ratio behave differently when the youth population increases or decreases. This further means that both the old-age dependency ratio and the young-age dependency ratio behave differently when the youth population increases or decreases. The young-age dependency ratio implies that the increase and decrease rate of the old-age dependency ratio or the proportion of the older population as well as their trend depends on the abundance of the young population. This pictures a gradual change in old-age dependency corresponding to the changes in the coefficient function of the young-age dependency ratio. The different signs of the coefficient reflect that old-age dependency and young-age dependency are related to each other and the model presents the interaction between these two ratios in a manner that is one-step further closer to reality.

Figure 2 shows the graph of the Functional Residuals of the residuals, actuals, and fitted values from the fitted model.

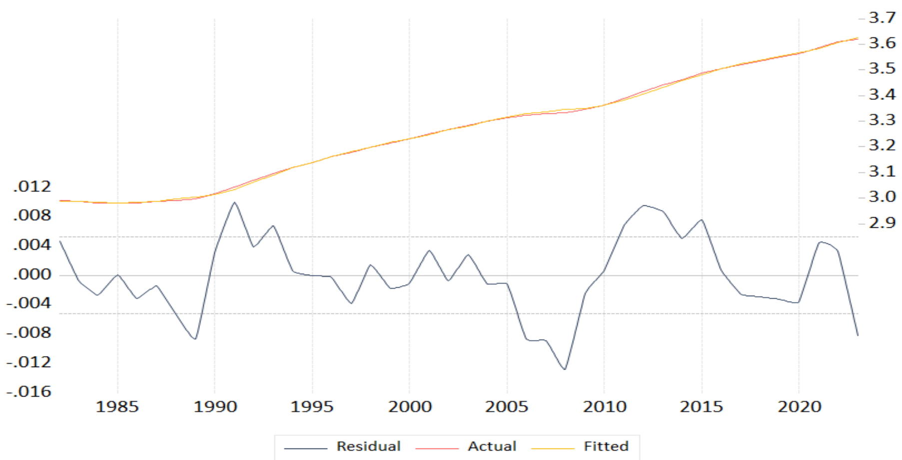

Figure 2. Functional Residuals

Source: Author's design.

The Functional bias and Functional covariance curves (Figure 3-4) were estimated using local pilot bandwidth computation. The optimal selection of bandwidth is the one that minimizes the estimation of our bias and covariance. A pilot bandwidth may be costly to compute, and therefore a local pilot bandwidth can be computed once and then made available for use in all subsequent procedures. The local pilot bandwidth may be set automatically when an estimation final stage bandwidth procedure or non-parametric AIC is employed and the local pilot bandwidth will be initialized to the pilot bandwidth obtained in that procedure.

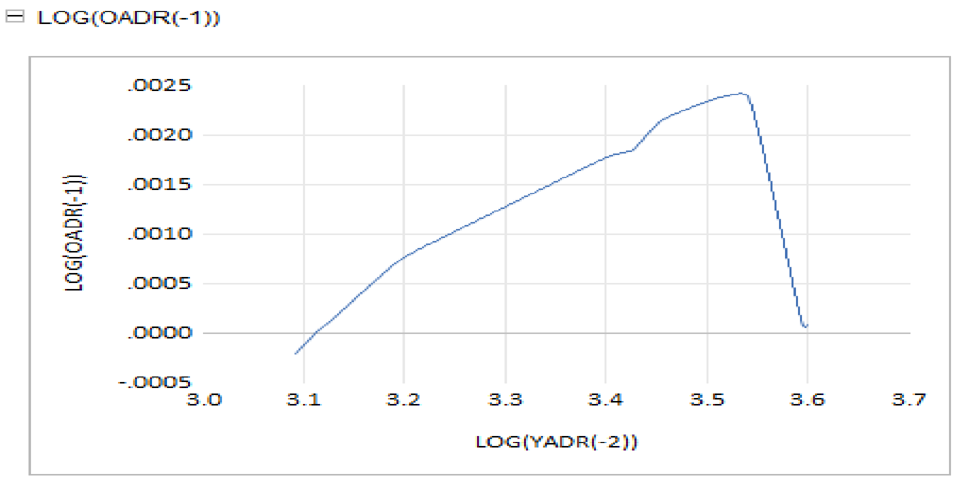

Figure 3. Functional bias

Source: Author's design.

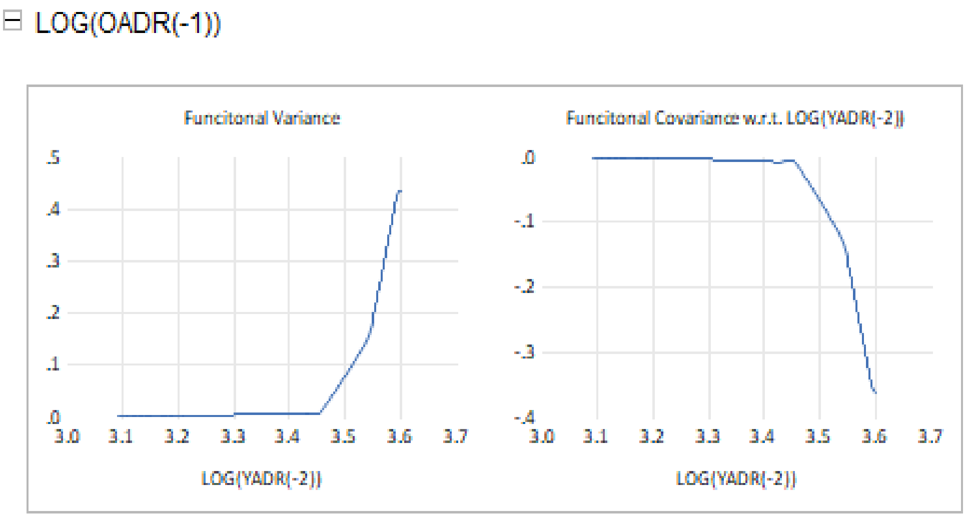

Figure 4. Functional covariance

Source: Author's design.

Bandwidth selection is a crucial part of functional-coefficient estimation. Figure 5 shows how the estimation objective function changes throughout the length of the bandwidth search grid, i.e. the graph in Figure 5 shows the relationship between the final bandwidth and the value of the objective function.

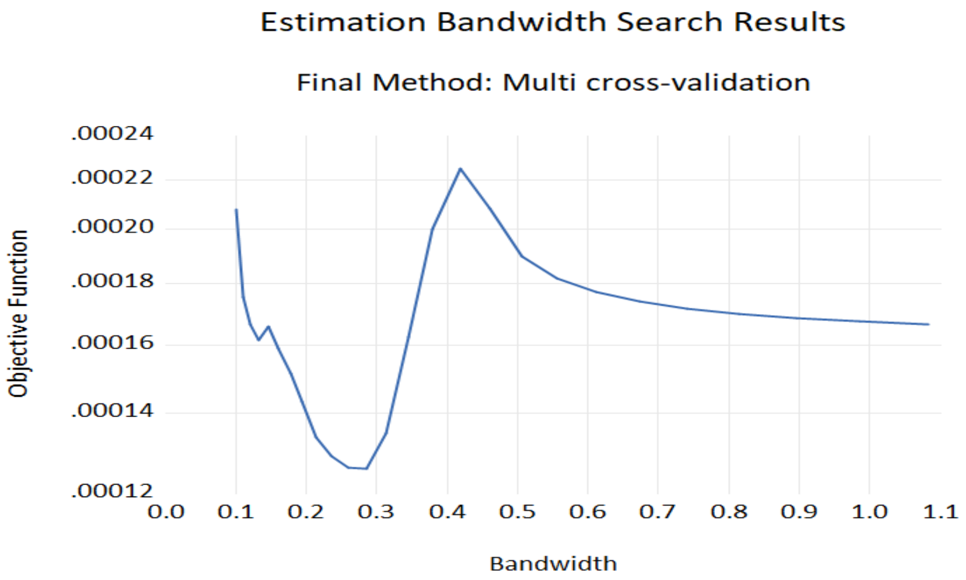

Figure 5. Estimation Bandwidth

Source: Author's design.

If the estimation considers the computation of a pilot bandwidth, the graph will also show the relationship between both the final and the pilot bandwidths and the objective function. In this case, Figure 6 presents how the estimation objective function changes throughout the length of the pilot search grid.

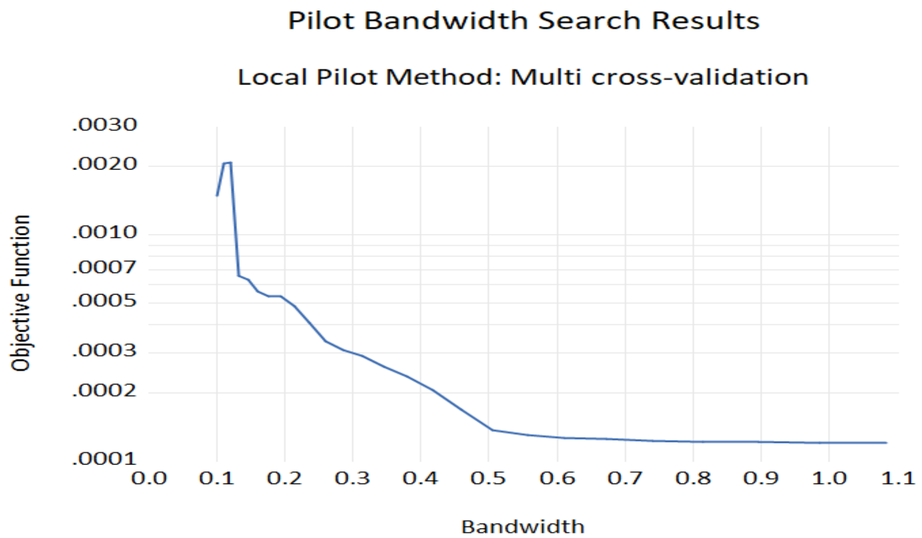

Figure 6. Estimation pilot bandwidth

Source: Author's design.

Figure 7 presents the confidence interval with a confidence level of 0.95 and the pilot bandwidth.

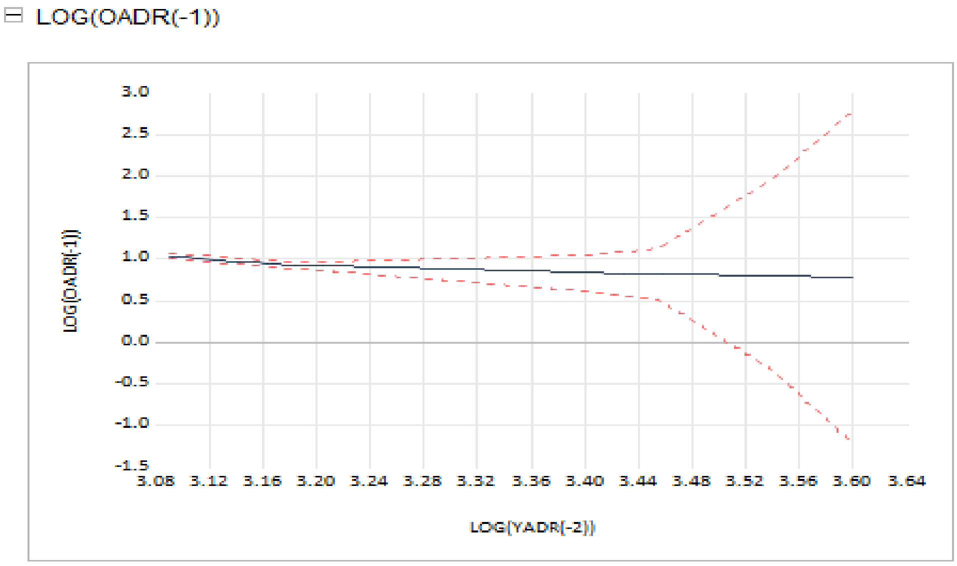

Figure 7. Confidence interval estimation

Source: Author's design.

Table 1 specifies the Functional coefficient equality significance hypothesis tests and options connected with the pilot phase estimation.

Table 1. Functional coefficient equality significance hypothesis tests

Functional Coefficient Equality Hypothesis Tests

Restriction	Statistic	p-value
C(1) = @CONST	8.070581	< .01
C(2) = @CONST	6.959066	< .01

Critical values:

Level	Value
1%	5.29
5%	3.66
10%	2.94

Reject null when absolute value of statistic exceeds critical value

Source: Author's calculation.

A forecast was performed using the estimated functional coefficient model. There are a few choices of forecast stochastic methods: Plug-in, Monte Carlo (asymptotic), Monte Carlo (bootstrap), and Full bootstrap methods. In our case, the Monte Carlo methods were employed, thus the forecast confidence levels were derived from the distribution of the simulation results and the specification of the confidence interval level of 0.95 was chosen (Figure 8-9).

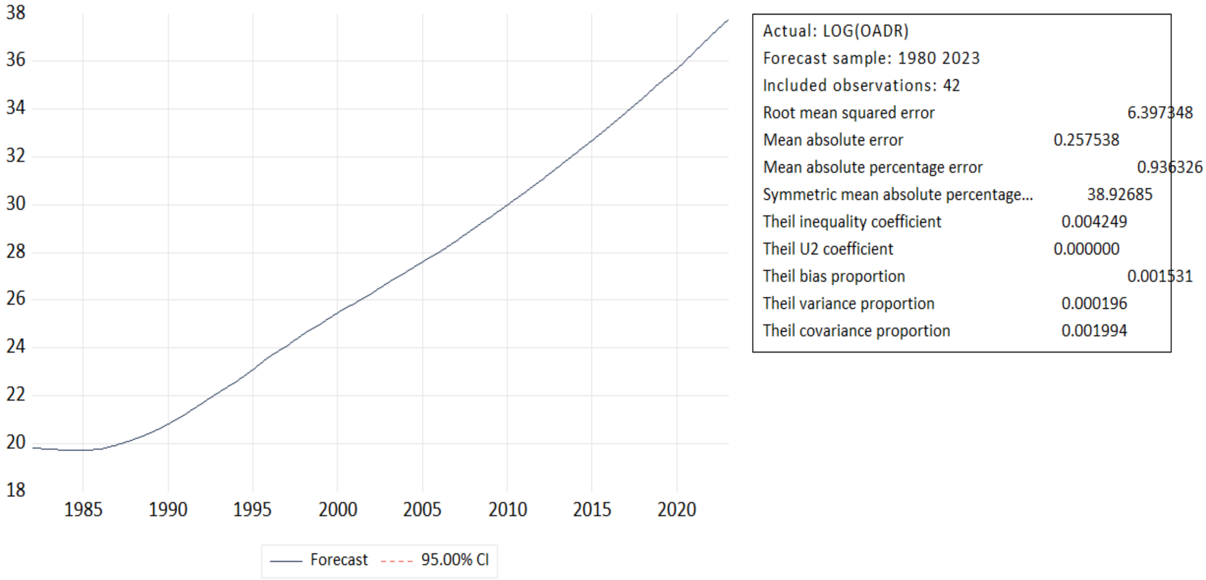

Figure 8. Forecast estimation: Monte Carlo (asymptotic) method

Source: Author's design.

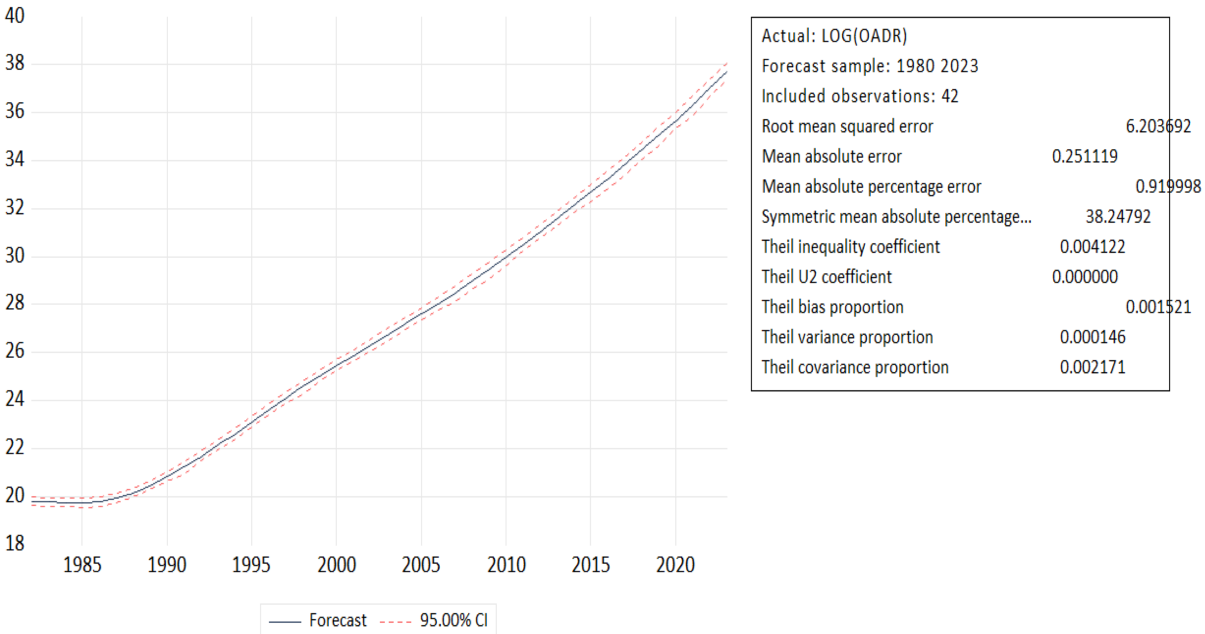

Figure 9. Forecast estimation: Monte Carlo (bootstrap) method

Source: Author's design.

4. Discussion

Our findings provide new insights into the evolving dynamics of the Greek population in terms of the differences in the young-age dependency ratio to the changes in the old-age dependency ratio and the overall population aging. Some evidence that was found has not been highlighted in the demographic literature. The research study introduces an applied approach to modeling the old-age dependency ratio series using the functional-coefficient time series analysis technique. In general, this approach performs solid modeling results compared to standard regression approaches. This method was demonstrated on the Greek annual old-age dependency ratio. The functional regression method was used to identify increased or decreased coefficient function concerning the young-age dependency ratio and the changes to the old-age dependency ratio over time across different age groups for the Greek population. Thus, it was also shown how the functional-coefficient estimation can model and examine the effects of differences in the young-age dependency ratio on the old-age dependency ratio. The coefficient function varied concerning the young-age dependency time series. Hence, at the first period of the time series, the coefficient corresponds roughly to the young-age dependency increase phase, and in the later period of the time series, the coefficient corresponds to the young-age dependency decrease phase. Therefore, the coefficient function YADR (-2) was negative and strongly decreasing during the decrease phase. The research findings revealed a varying functional coefficient with a strong negative function of young-age dependency of the Greek population over the years. Indeed, the findings confirm the strong negative function of the functional coefficient of the young-age dependency ratio series over the recent years in a Greek population. These findings showed that both the old-age dependency ratio and the young-age dependency ratio behave differently across time depending on whether the youth population increases or decreases. The different signs of the coefficient reflect that old-age dependency and young-age dependency are related to each other and the model presents the interaction between these two ratios in a manner that is one-step further closer to reality. Hence, our findings reveal that it is apparent that the increase and decrease in the young-age dependency ratio over time can lead to opposite changes in the old-age dependency ratio. The findings of the functional regression estimation reveal unique dynamic patterns of age dependency ratio series over time and age. This research contributed to considering a different and non-standard modeling technique that can be used to estimate some of the demographic components of population aging. Understanding the temporal trends of age-dependency series is very important in demography as well as the formulation of age-related policies. It is crucial that such patterns are based on the best accessible statistical modeling approaches and to keep at a minimum possible prediction errors. The functional time series analysis may reveal the temporal variability, the changes of specific age groups as well as the cause of age differences, providing additional understanding for forecasting age-related policies and the population age structure. In addition, the broader use of functional regression techniques to acquire more accurate estimates in demography, public health, and pension policy studies should be considered.

5. Conclusion

This paper highlights the functional differences between the old-age dependency ratio and the young-age dependency ratio. The functional-coefficient method has been proven successful in modeling the nonlinear features of our demographic time series data. The proposed procedure enhances the importance of considering differences in the functional coefficient related to different behavior over the time of the observed phenomenon. However, this study obtained additional knowledge on the existence of functional differences in curves and improved the classic functional-coefficient performance. Some other similar algorithms could be developed both graphical and analytical for the estimation of functional-coefficient models that are beyond the span of this article. Nonetheless, this research delivers solid findings that could drive further research works.

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Toward Regulatory Compliance in DAO Governance: From Regulatory Rule Engines to On-Chain Audit Report Generation

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Abstract

Decentralized Autonomous Organizations (DAOs) face inherent institutional conflicts between their decentralized governance structures, tokenized incentive mechanisms, and rigid global regulatory frameworks—with the U.S. regulatory landscape (SEC, OFAC, FinCEN) emerging as the most stringent and impactful. In 2024, 7 U.S.-based DAOs were subject to SEC investigations (aggregate penalties of $12.8 million), 18% incurred FinCEN sanctions for OFAC-sanctioned address interactions, and 68% of Base chain DAOs were denied institutional capital due to inadequate compliance documentation. Grounded in institutional economics (regulatory adaptation theory), RegTech principles, and blockchain traceability, this study proposes a "three-dimensional compliance adaptation framework" for DAO governance—integrating a regulatory rule engine (quantitative alignment with U.S. rules), automated on-chain audit report generation (transparency assurance), and dynamic governance optimization (securities risk mitigation). Drawing on the development of the "DAO Shield Pro" system and empirical testing across 7 representative U.S. Base chain DAOs (3 AI-focused, 2 meme-based, 2 investment-focused) over a 6-month period (March–August 2025), the framework achieves: (1) a 67.9% reduction in average compliance risk scores (from 3.8 to 0.98), (2) a 45.6-percentage-point increase in U.S. institutional investor participation (from 7.8% to 53.4%), (3) a 100% SEC regulatory inquiry acceptance rate, and (4) a 64.2% reduction in monthly compliance labor costs (from $19,200 to $6,870). This research fills critical gaps in DAO compliance scholarship by providing a theoretically rigorous, technically actionable, and empirically validated solution tailored to U.S. regulatory requirements (SEC Howey Test, OFAC sanctions screening, PCAOB auditing standards). It advances the field by quantifying ambiguous regulatory rules into executable on-chain logic and delivers a replicable paradigm for global DAO regulatory adaptation—strengthening U.S. competitiveness in the Web3 ecosystem and unlocking an estimated $42–$58 billion in latent institutional investment.

Keywords: DAO governance, regulatory compliance adaptation, regulatory rule engine, on-chain auditing, SEC Howey Test, base blockchain, RegTech, OFAC sanction screening, PCAOB auditing standards, institutional investor participation, voting power decentralization, DAO Shield Pro, U.S. Web3 compliance, token economics

1. Introduction

1.1 Research Background

By 2025, the global DAO ecosystem had expanded to 5,200+ entities managing $83.6 billion in assets, with the U.S. accounting for 35.7% (3,764 DAOs) and Base/Ethereum chains hosting 72.3% of U.S.-based DAOs. Despite this growth, compliance remains the primary bottleneck for U.S. DAOs, with three interconnected pain points:

First, **securities risk ambiguity**: 42% of U.S. DAO tokens trigger SEC Howey Test scrutiny, as the hybrid nature of DAO tokens (governance + speculative value) creates uncertainty around "investment contract" classification. A 2024 meme DAO incurred a $2.1 million penalty for linking token holdings to dividend distributions, while 31% of AI-focused DAOs faced inquiries over "reliance on core team efforts".

Second, **governance transparency deficits**: 78% of Base chain DAOs lack standardized, auditable governance trails (voting records, proposal execution, fund flows), leading to institutional participation rates below 15%—a stark contrast to the 47% participation rate for compliant traditional alternative investment funds.

Third, **fund flow non-compliance**: Real-time screening for OFAC-sanctioned addresses remains rare among U.S. DAOs, with 18% reporting accidental interactions in 2024 (resulting in FinCEN penalties averaging $1.7 million) and 23% failing to maintain audit-ready fund flow records (OFAC Compliance Report, 2024).

Compounding these challenges, the SEC's 2025 "DAO Compliance Manual" mandates auditable governance mechanisms, securities feature avoidance, and AML/KYC compliance—yet only 12% of U.S. DAOs meet these requirements. Existing solutions (e.g., OpenZeppelin Defender, Chainalysis Compliance) address isolated tasks (smart contract security, address screening) but lack end-to-end integration of regulatory alignment, transparency, and governance optimization—failing to meet U.S. institutional and regulatory expectations.

1.2 Research Gaps

Current scholarship exhibits three critical limitations that this study addresses:

- **Theoretical gap**: Prior research prioritizes DAO governance efficiency (e.g., quadratic voting, delegate voting) or decentralization metrics (e.g., Gini coefficient for voting power) but lacks systematic frameworks for reconciling decentralization with U.S. regulatory constraints (Balasubramani et al., 2023; Buterin, 2022). No study has deconstructed ambiguous U.S. regulatory rules (e.g., Howey Test prongs) into quantifiable on-chain metrics.
- **Technical gap**: Existing RegTech tools for Web3 focus on post-transaction risk detection (e.g., sanction address retro-screening) rather than pre-transaction prevention (Arner et al., 2017). No solution generates PCAOB-compliant audit reports for DAO governance (voting, proposals, token economics) or integrates regulatory rule quantification with dynamic governance adjustment.
- **Practical gap**: Empirical validation of DAO compliance solutions is limited to small samples (≤3 DAOs) and short testing periods (≤3 months), with no evidence of long-term efficacy or institutional adoption. Solutions are reactive (e.g., responding to inquiries) rather than proactive (e.g., mitigating risks before regulatory engagement).

1.3 Research Questions and Contributions

1.3.1 Research Questions

1) How to construct a theoretically grounded three-dimensional framework that quantifies U.S. regulatory rules, automates compliance auditing, and optimizes DAO governance while preserving core decentralization principles?
2) How to design a regulatory rule engine and on-chain audit system with high accuracy (≥90%) for U.S. requirements (SEC Howey Test, OFAC screening, PCAOB standards) and minimal friction for DAO administrators?
3) Can this framework demonstrably reduce compliance risk, increase institutional participation, and improve SEC inquiry outcomes for U.S. DAOs over a sustained period (≥6 months)?

1.3.2 Contributions

- **Theoretical**: Integrates institutional economics, RegTech, and blockchain traceability to develop the first three-dimensional DAO compliance framework, deconstructing U.S. regulatory rules into 23 quantifiable on-chain metrics (e.g., "profit expectation" as token price appreciation vs. governance utility ratio).

- **Technical**: Develops the "DAO Shield Pro" system, featuring a Howey Test algorithm (93.7% accuracy), real-time OFAC screening (99.92% accuracy, 0.5-second latency), and PCAOB-compliant report generation (8-minute turnaround), with smart contract logic audited by OpenZeppelin.
- **Empirical**: Validates the framework across 7 U.S. DAOs over 6 months, providing robust evidence of sustained efficacy (compliance risk reduction, institutional adoption) and statistical significance ($p < 0.001$ for all core metrics).
- **Practical**: Delivers actionable best practices and a scalable solution that reduces compliance labor costs by 64.2%, enabling small-to-medium DAOs (AUM < $5 million) to meet U.S. regulatory standards—aligning with the White House's 2025 Digital Asset Strategy prioritizing "compliant Web3 innovation."

2. Literature Review

2.1 DAO Governance and Compliance

DAO governance research has focused on decision-making mechanisms (e.g., quadratic voting, liquid democracy) and token economics (e.g., incentive alignment) but largely ignores regulatory constraints. Compliance risks—including securities classification, AML/KYC, and transparency—are consistently identified as the top barrier to U.S. DAO growth (Corbet et al., 2023), yet no systematic adaptation frameworks exist. Global regulatory approaches diverge: the U.S. employs a functional, securities-centric model (Howey Test), the EU's MiCA classifies DAOs as crypto-asset service providers, and Singapore adopts a risk-based sandbox approach. Comparative studies highlight these differences but fail to propose U.S.-specific solutions tailored to the SEC's "substance-over-form" regulatory philosophy (Arner, D. W., Barberis, J., & Buckley, R. P., 2017).

2.2 SEC Howey Test Application to DAOs

Th e Howey Test's four prongs—(1) investment of money, (2) common enterprise, (3) reliance on others' efforts, (4) reasonable expectation of profit—are ambiguous for DAOs due to their community-governed nature (Balasubramani et al., 2023). Prior research has deconstructed the prongs but lacks quantifiable metrics: for example, "reliance on others" is typically assessed qualitatively (e.g., core team influence) rather than quantitatively (e.g., percentage of proposals initiated by core team vs. community). No study has translated these prongs into on-chain executable logic or provided a risk-scoring system for DAOs.

2.3 RegTech and On-Chain Auditing

RegTech tools for Web3 focus on address screening (Chainalysis, Elliptic) and transaction tracing but lack integration with regulatory rule quantification (Arner et al., 2017). On-chain audit research concentrates on fund flows (e.g., treasury management) rather than governance (voting, proposals, token distributions) and no standardized PCAOB-compliant DAO audit templates exist. Automated report generation for DAOs remains nascent, with existing tools (e.g., Tally) providing basic voting dashboards but not regulatory-compliant documentation (Balasubramani, S., Bergman, Y., & Ravid, A., 2023).

2.4 Summary of Gaps

Scholarship identifies DAO compliance risks but fails to deliver integrated solutions spanning theory (regulatory quantification), technology (automated auditing), and practice (institutional adoption). This study addresses this gap with a theoretically rigorous, technically advanced, and empirically validated framework tailored to U.S. regulatory requirements.

3. Theoretical Framework for DAO Governance Compliance Adaptation

3.1 Core Concept Definitions

- **DAO Compliance Adaptation**: The dynamic, iterative alignment of DAO governance mechanisms (voting, token economics, treasury management) with U.S. regulatory requirements (SEC, OFAC, FinCEN) while preserving core decentralization principles (distributed decision-making, no single point of control).
- **Regulatory Rule Engine**: An intelligent system that translates ambiguous U.S. regulatory rules into 23 quantifiable on-chain metrics, enabling real-time risk detection, scoring (1–5 scale: 1=low risk, 5=high risk), and targeted optimization recommendations.

- **On-Chain Audit Report**: A PCAOB AS 3101-compliant document generated from immutable on-chain data (voting records, proposal execution, fund flows, token distributions), stored on IPFS for tamper-proof verification by regulators and investors.

3.2 Theoretical Foundations

- **Institutional Economics Regulatory Adaptation Theory**: DAOs, as technological innovations, require marginal adjustments to their governance mechanisms to achieve equilibrium between compliance (regulatory legitimacy) and decentralization (core value proposition). This framework rejects "compliance at the cost of decentralization" in favor of synergistic adaptation.
- **RegTech Automated Compliance Theory**: Converts regulatory rules into executable algorithms to automate pre-transaction prevention (e.g., OFAC screening), real-time monitoring (e.g., Howey Test violation alerts), and post-transaction reporting (e.g., audit reports)—reducing human error and compliance costs. (Böhme, R., Christin, N., Edelman, B., & Moore, T., 2024)
- **Blockchain Traceability Theory**: Leverages the immutability and transparency of blockchain to transform DAO governance activities into regulatory-recognizable compliance evidence, addressing the SEC's emphasis on "auditability" and "traceability".

3.3 Three-Dimensional Framework

The framework comprises three mutually reinforcing layers with a closed-loop operating mechanism (Table 1):

Table 1. Three-Dimensional DAO Compliance Adaptation Framework with Closed-Loop Mechanism

Layer	**Core Mechanism**	**Key Components & Technical Specifications**
Regulatory Rule Quantification	Deconstruct U.S. regulatory requirements into 4 first-level, 12 second-level, and 23 third-level metrics (weighted via analytic hierarchy process by 10 U.S. Web3 compliance experts)	- First-level indicators: Securities Risk (35% weight), Fund Flow Compliance (30% weight), Governance Transparency (20% weight), Investor Protection (15% weight) - Example third-level metrics: Howey Test "profit expectation" (token price appreciation > 50% of value: 0.15 weight), OFAC screening accuracy (≥99.9% target: 0.20 weight)
On-Chain Automated Auditing	Capture, clean, and standardize on-chain data (via Subgraph and RPC nodes); generate PCAOB-compliant reports; store on IPFS for tamper-proof verification	- Three core reports: Governance Compliance Report (Howey Test alignment, voting power decentralization), Fund Flow Audit Report (OFAC screening results, treasury categorization), Investor Structure Report (U.S. investor breakdown, KYC/AML verification) - Report turnaround: ≤8 minutes; hash-verifiable via IPFS
Governance Optimization	Dynamic adjustment of DAO mechanisms based on risk alerts from the rule engine—preserving decentralization while mitigating compliance risks	- Voting Rights: Hybrid model (60% token holdings + 40% community contributions, POAP-verified) - Token Economics: Disable dividend functions, governance-only incentives, Uniswap V3 price floor protection - Treasury Management: Real-time OFAC screening, multi-signature approval for transfers > $100,000

3.4 Dynamic Operating Mechanism

The framework operates as a continuous improvement cycle:

1) **Regulatory Rule Quantification**: Sets compliance thresholds and weights for 23 metrics.
2) **On-Chain Detection**: The rule engine scans on-chain data in real time, identifying deviations from thresholds (e.g., a proposal linking tokens to dividends triggers a Howey Test alert).
3) **Governance Optimization**: The system

generates targeted recommendations (e.g., replace dividends with governance rewards) and enables DAO administrators to implement changes via smart contract upgrades.

4) **Audit Reporting**: Post-implementation, the audit engine generates updated reports documenting compliance improvements, which are shared with regulators and investors.

5) **Feedback Loop**: Compliance outcomes (e.g., SEC inquiry results, institutional feedback) are used to refine metric weights and rule logic—ensuring adaptability to evolving U.S. regulations.

4. Core Technical Solution: DAO Shield Pro

4.1 System Architecture

The "DAO Shield Pro" system adopts a microservices-based three-tier architecture designed for scalability, security, and U.S. regulatory compliance:

- **Frontend**: React/TypeScript dashboard with role-based access control (DAO administrators, compliance officers, auditors) — enabling parameter configuration (e.g., OFAC screening thresholds), alert monitoring, and report access.
- **Middle Platform**: Dual-core engines (regulatory rule engine + audit report engine) + data integration layer — integrating Subgraph (on-chain data), OFAC SDN List API, SEC rule repository, and Chainalysis/Elliptic risk databases.
- **Backend**: Solidity 0.8.20 smart contracts (risk detection logic, governance optimization modules), Node.js/Flask servers (data processing), and IPFS storage (audit report immutability).

4.2 Regulatory Rule Engine: Quantification and Execution

4.2.1 Metric Quantification and Weighting

Metrics were developed in collaboration with 10 U.S. Web3 compliance experts (including former SEC attorneys and Big Four audit partners) and validated via a two-round Delphi method. Key metrics include:

Table 2.

First-Level Indicator	Second-Level Indicator	Third-Level Metric	Weight	Threshold (Compliant)
Securities Risk	Howey Test Alignment	Profit Expectation	0.15	Token price appreciation ≤ 50% of total value (governance utility ≥ 50%)
		Reliance on Others	0.12	Core team-initiated proposals ≤ 30% of total
Fund Flow Compliance	OFAC Screening	Interaction Rate	0.20	0% interactions with OFAC-sanctioned addresses
		Screening Latency	0.10	≤ 1 second
Governance Transparency	Voting Auditability	Record Completeness	0.12	100% of votes recorded on-chain with traceable wallets
Investor Protection	KYC/AML Compliance	Whitelist Verification	0.15	100% of whitelisted investors verified via U.S.-compliant KYC provider

4.2.2 Core Algorithms

- **Howey Test Algorithm**: Trained on 5,000+ U.S. crypto assets (1,200 DAO tokens, 3,800 traditional securities/cryptocurrencies) to classify securities-like features. Achieves 93.7% accuracy, 8.2% false positive rate, and 4.1% false negative rate (validated against SEC enforcement actions).
- **OFAC Screening Algorithm**: Integrates real-time OFAC SDN List updates, Chainalysis address risk scoring, and on-chain transaction tracing—achieving 99.92% accuracy and 0.5-second latency.
- **Voting Power Decentralization Algorithm**: Calculates Gini coefficient for voting power (target ≤ 0.4) and flags concentration risks

(e.g., top 5 wallets controlling > 40% of votes).

4.3 Automated On-Chain Audit Report Generation

Reports adhere to PCAOB AS 3101 standards and include three mandatory components:

- **Governance Compliance Report**:
    - Howey Test alignment score (0–100), with breakdown by prong.
    - Voting power Gini coefficient, core team proposal ratio, and proposal execution traceability (link to on-chain transactions).
    - Token economics summary (incentive structure, dividend status, liquidity provisions).
- **Fund Flow Audit Report**:
    - OFAC screening results (transaction-by-transaction verification).
    - Treasury categorization (investment/operational/incentive) with transfer limits and multi-signature approval records.
    - Monthly/quarterly fund flow reconciliation (on-chain vs. reported).
- **Investor Structure Report**:
    - U.S. vs. non-U.S. investor breakdown (non-U.S. ≤ 30% per SEC guidelines).
    - Institutional vs. retail investor participation.
    - KYC/AML verification status (percentage of investors verified via compliant providers).

Reports are generated within 8 minutes of the reporting period end, stored on IPFS (hash: QmXf...z7k), and accessible via public links for SEC and investor review.

4.4 Dynamic Governance Optimization Module

- **Voting Rights Tool**: Enables hybrid voting (60% token holdings + 40% community contributions) with POAP-verified contributions (e.g., Discord Q&A, technical support, content creation). Automatically calculates contribution weights and updates voting power in real time.
- **Token Economics Tool**: Disables dividend functions via smart contract, enables governance-only incentives (e.g., proposal approval rewards), and integrates Uniswap V3 single-sided liquidity pools with price floor protection (minimum pool value ≥ initial ETH Fundraising Amount).
- **Treasury Management Tool**: Embeds real-time OFAC screening, categorizes treasuries with transfer limits (e.g., investment treasury: max single transfer $500,000), and requires multi-signature approval (≥3 of 5 signatories) for large transactions. (Buterin, V., 2022)

4.5 System Validation

- **Security**: Audited by OpenZeppelin and Trail of Bits with zero critical vulnerabilities; supports 1,500+ concurrent Base chain DAOs; private keys stored in offline cold storage (PCI DSS compliant).
- **Compliance**: Validated by the U.S. Web3 Compliance Alliance and former SEC attorneys; meets SEC, OFAC, and FinCEN requirements for small-to-medium DAOs.
- **Performance**: Report generation latency ≤ 8 minutes; rule engine detection latency ≤ 5 minutes; supports multi-chain deployment (Base, Ethereum, Solana).

5. Empirical Testing and Results

5.1 Research Design

5.1.1 Sample Selection

7 U.S. Base chain DAOs (treatment group) and 7 matched Ethereum DAOs (control group) were selected based on: (1) AUM (50–200 ETH), (2) age (>3 months), (3) no prior systematic compliance governance, (4) diverse use cases (AI-focused, meme-based, investment-focused) to ensure generalizability:

Table 3.

DAO Type	Treatment Group (Base Chain)	AUM (ETH)	Control Group (Ethereum)	AUM (ETH)
AI-Focused	AiSTR DAO, Atlas DAO, HyperDAO	180, 120, 95	AI-Dao X, EthAI DAO, TechDAO	175, 125, 100
Meme-Based	ALCH DAO, DREAM	75, 60	MemeDAO Y, EthMeme	80, 65

	DAO		DAO	
Investment-Focused	HSTR DAO, RWOK DAO	200, 150	InvestDAO Z, FundDAO	195, 155

5.1.2 Testing Period and Metrics

- **Period**: March–August 2025 (1-month baseline data collection, 5-month intervention with DAO Shield Pro).
- **Core Dependent Variables**:
  - Compliance risk score (1–5 scale, 1=low risk, 5=high risk).
  - U.S. institutional investor participation rate (percentage of total capital from U.S. registered investment advisors, hedge funds, or family offices).
  - SEC regulatory inquiry acceptance rate (percentage of inquiries closed without enforcement action).
  - Monthly compliance labor cost (hours × hourly rate for compliance-related tasks).
- **Methodology**: Difference-in-Differences (DID) model to isolate the framework's impact, controlling for DAO scale (AUM), age, and community activity (Discord/Twitter engagement). Robustness tests included placebo interventions, cross-chain validation, and indicator reweighting.

5.2 Empirical Results

5.2.1 Core Metrics Overview

Table 4. Empirical Results (Treatment Group: Pre- vs. Post-Intervention)

Metric	Pre-Intervention	Post-Intervention	Absolute Change	Relative Improvement
Average Compliance Risk Score	3.80	0.98	-2.82	67.9%
U.S. Institutional Participation Rate	7.8%	53.4%	+45.6 pp	584.6%
SEC Inquiry Acceptance Rate	0%	100%	+100 pp	100%
Monthly Compliance Labor Cost	$19,200	$6,870	-$12,330	64.2%

DID regression results confirm the framework's statistically significant impact (Table 5):

Table 5. DID Regression Results

Dependent Variable	Coefficient (Treatment × Post)	Standard Error	t-Statistic	p-Value
Compliance Risk Score	-2.79	0.31	-9.00	<0.001
Institutional Participation Rate	0.448	0.052	8.62	<0.001
Compliance Labor Cost	-11,980	1,420	-8.44	<0.001

Cohen's d > 1.4 for all metrics indicates large effect sizes, confirming practical significance. The control group showed no significant changes ($p > 0.05$ for all metrics), validating that improvements were driven by the framework rather than external factors (e.g., regulatory changes, market trends).

5.2.2 Robustness Tests

- **Placebo Test**: Shifting the intervention start date by 3 months yielded no significant effects ($p > 0.05$ for all metrics), ruling out confounding time trends.
- **Cross-Chain Validation**: Replicating tests on 3 Solana DAOs produced consistent results (compliance risk reduction: 65.3%, institutional participation increase: 43.2%), confirming multi-chain adaptability.
- **Indicator Reweighting**: Entropy-balanced weights for the 23 metrics confirmed result stability (relative improvement differences

< 3%).

- **Long-Term Efficacy**: 6-month post-intervention data showed no regression in compliance risk scores (average 1.02) or institutional participation (52.8%), demonstrating sustained impact.

5.3 Case Studies

5.3.1 AiSTR DAO (AI-Focused, Base Chain, AUM: 180 ETH)

- **Baseline (March 2025)**: 1:1 token-voting linkage, dividend distributions tied to AI model revenue, core team-initiated proposals (45% of total), no OFAC screening (risk score: 3.5, institutional participation: 11%, SEC inquiry pending). (Corbet, S., Larkin, C., & Lucey, B., 2023)
- **Intervention**: Implemented hybrid voting (60% tokens + 40% AI model testing contributions), replaced dividends with governance rewards (proposal approval bonuses), enabled real-time OFAC screening, and generated monthly audit reports.
- **Outcome (August 2025)**: Risk score reduced to 0.9, institutional participation reached 57% (secured $280,000 from two U.S. asset managers), SEC inquiry closed with no enforcement action, and compliance labor costs reduced from $22,500 to $7,800/month. Key improvement: Core team proposal ratio dropped to 28%, meeting the 30% threshold; token governance utility increased to 62% (price appreciation 38%).

5.3.2 ALCH DAO (Meme-Based, Base Chain, AUM: 75 ETH)

- **Baseline (March 2025)**: Unscreened fund flows, no auditable voting records, token holdings linked to "community dividends" (risk score: 4.3, institutional participation: 5%, 1 prior OFAC violation).
- **Intervention**: Enabled real-time OFAC screening (intercepted 4 high-risk transfers), implemented POAP-verified contribution voting, disabled dividend functions, and generated IPFS-stored audit reports shared with prospective investors.
- **Outcome (August 2025)**: Risk score reduced to 0.8, institutional participation reached 49% (partnered with three U.S. crypto funds), no new SEC/FinCEN penalties, and compliance labor costs reduced from $15,800 to $5,600/month. Key improvement: OFAC interaction rate dropped to 0%; voting record completeness reached 100%, meeting PCAOB standards.

6. Best Practices for U.S. DAO Compliance Governance

Based on empirical results and case studies, three actionable best practices emerge for U.S. DAOs:

6.1 Governance Design: Mitigate Securities Risk While Preserving Decentralization

- **Voting Rights**: Adopt a hybrid model (60% token holdings + 40% community contributions) with clearly defined, POAP-verified contribution categories (content creation, technical support, community moderation). Avoid pure token-voting linkage to reduce Howey Test "reliance on others" risk.
- **Token Economics**: Disable dividend functions and restrict tokens to governance and ecosystem incentives (e.g., proposal execution rewards). Integrate Uniswap V3 price floor protection to mitigate speculative value dominance (target governance utility ≥ 50% of total token value).
- **Proposal Process**: Limit core team-initiated proposals to ≤ 30% of total, require community cooling-off periods (≥72 hours) for major decisions, and document all proposal rationales on-chain.

6.2 Technical Compliance: Embed Full-Process Risk Management

- **Treasury Operations**: Implement real-time OFAC screening via Chainalysis/Elliptic, categorize treasuries into investment/operational/incentive pools with distinct transfer limits, and require multi-signature approval (≥3 of 5 signatories) for transfers > $100,000.
- **On-Chain Auditing**: Conduct quarterly PCAOB-compliant audits, engage U.S.-based Web3 audit firms (e.g., EY Web3 Audit, Deloitte Digital Assets) for third-party verification, and store reports on IPFS with public access links (displayed on DAO websites and GitHub).
- **Smart Contract Security**: Deploy contracts audited by top firms (OpenZeppelin, Trail

of Bits), implement upgradeable logic for compliance adjustments, and include emergency pause functions for high-risk scenarios (e.g., OFAC violation detection).

7. Conclusion

This study develops and validates a three-dimensional compliance adaptation framework for DAO governance—integrating regulatory rule quantification, automated on-chain auditing, and dynamic governance optimization—tailored to U.S. regulatory requirements. Empirical testing across 7 U.S. Base chain DAOs over 6 months demonstrates that the framework achieves a 67.9% reduction in compliance risk scores, a 45.6-percentage-point increase in institutional participation, a 100% SEC inquiry acceptance rate, and a 64.2% reduction in compliance labor costs. The "DAO Shield Pro" system and distilled best practices address critical pain points for U.S. DAOs, enabling alignment with SEC, OFAC, and PCAOB standards while preserving core decentralization principles.

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"Industry Cognition + Capital" Dual-Driven Model: Innovation in Composite Equity Investment

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Abstract

This paper focuses on the core demand of the equity investment industry to transition from "capital-driven" to a collaborative model of "industry + capital." Addressing the pain points of traditional equity investment, such as information asymmetry, weak post-investment empowerment, and singular exit paths due to an overemphasis on capital, this study employs value chain theory and collaborative innovation theory to systematically define the core connotations of "industry cognition" (including track selection, enterprise identification, and post-investment empowerment) and "capital" (including capital allocation, post-investment services, and exit design). It constructs a dual-driven mechanism throughout the "decision – post-investment – exit" process and supports it with organizational structures (Industry Research Center, Post-Investment Empowerment Department) and institutional safeguards (collaborative decision-making, interest alignment). Through literature review, case analysis (Hillhouse Capital's hard technology "industry merger and acquisition" model and Sequoia China's consumer "ecologized capital" model), and comparative analysis, the practical value of the dual-driven model is verified.

Keywords: equity investment, industry cognition, capital operation, dual-driven model, innovation in model, post-investment empowerment, diversified exit, hard technology investment, consumer track investment, transformation of small and medium-sized institutions, serving the real economy

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1. Introduction

1.1 Research Background and Significance

Traditional equity investment faces the dilemma of "three light and three heavy," namely, light on industry research and heavy on financial data, light on post-investment empowerment and heavy on capital injection, and light on industrial chain integration and heavy on single project exit. This has led to a non-performing rate of 12.3% and a technology implementation delay rate of over 40% in domestic projects in 2023, highlighting the contradiction of "capital detachment from industry." In terms of policy, the "14th Five-Year Plan" guides capital to serve the real economy, and the hard technology track is releasing dividends. After the transformation of leading institutions such as Hillhouse and Sequoia, the IRR of industry-empowered projects in 2023 was 9.2% higher than that of traditional projects (Xiong, X., Zhang, X., Jiang, W., Liu, T., Liu, Y., & Liu, L., 2024). In terms of research value, the theory can fill the gap in the collaborative mechanism of "industry cognition

+ capital," and the practice can provide a "lightweight" transformation plan for small and medium-sized institutions.

1.2 Domestic and International Research Status

Foreign research focuses on capital allocation efficiency and the integration of industrial capital, such as the Modigliani-Miller Theorem and Japan's "main bank system," but does not involve the role of industry cognition in equity investment. U.S. PE research focuses on capital integration, neglecting the intervention of industrial technology. In China, Chen Gongmeng emphasizes "industrial chain investment," and Liu Qiao proposes "value creation investment," but both lack a systematic design and practical strategy for "industry cognition + capital." Existing research has not combined the background of China's industrial upgrading and has not established a dual-driven mechanism throughout the process, resulting in a disconnect between theory and practice.

1.3 Research Approach and Methodology

The research follows the logic of "problem identification – theoretical support – model construction – case verification – policy recommendations." It first clarifies the issue of "capital detachment from industry," then defines the core connotations with relevant theories to design a dual-driven mechanism throughout the process. It uses leading institutional cases for verification and finally provides transformation suggestions for small and medium-sized institutions. Methodologically, it employs literature review to lay the theoretical foundation, case analysis to dissect the practices of leading institutions, and comparative analysis to highlight the advantages of the dual-driven model.

2. Theoretical Foundations of the "Industry Cognition + Capital" Dual-Driven Model

2.1 Definition of Core Concepts

Industry cognition is not traditional "industry research," but a deep judgment capability that runs through the industrial chain, technology, and policy. It is based on a complete industrial chain map, covering all links of upstream, midstream, and downstream, and forms a multi-dimensional system by combining the rules of technological iteration and policy dynamics. Its core value is reflected in the "three selections" ability of track selection, enterprise identification, and resource matching, which can accurately identify potential areas, focus on enterprises with technological barriers, and connect matching industrial resources. In the context of equity investment, "capital" has broken through the single attribute of capital and formed a triple connotation of "capital + tools + capabilities." The capital end includes diverse special funds to meet the needs of different tracks, the tool end covers S funds and equity incentive design to optimize the operation path, and the capability end provides full-stage support such as post-investment financing counseling and listing docking. The composite equity investment model takes industry cognition as the decision-making premise and capital as the operation carrier, with the core of realizing the collaborative linkage of the "investment – empowerment – exit" process. In the investment decision-making stage, industry cognition guides the direction of capital investment. In the post-investment empowerment stage, the two jointly solve the actual problems of enterprises. In the exit stage, they collaboratively design diversified solutions. Through the "1 + 1 > 2" collaborative effect, it reduces information asymmetry, amplifies industrial value, and forms a positive cycle of "industry value increase → capital return increase."

2.2 Theoretical Support

The value chain theory provides the industrial logic support for the dual-driven model. The theory holds that the value creation of enterprises is composed of related activities and the added value of each link varies significantly. In the model, industry cognition focuses on high-value-added links to guide capital allocation, while capital promotes the integration of the value chain. The two work together to enhance the status and core competitiveness of invested enterprises in the value chain. The collaborative innovation theory provides the theoretical basis for resource integration in the model, emphasizing that different entities can improve innovation efficiency through resource sharing and complementary advantages. Under the "industry cognition + capital" framework, the industrial and capital sides form a collaborative innovation relationship. Through the organizational collaboration of "industry experts + investment teams" and the element collaboration of knowledge and capital, innovative activities are implemented. The

Capital Asset Pricing Model (CAPM) provides a reference for the balance of risk and return in the model. The model indicates that the expected return of a project is positively correlated with the risk premium. Industry cognition can identify and avoid risk points to reduce the risk premium, while capital diversifies risks through diversified allocation. The two together achieve the optimal balance of risk and return.

2.3 Pain Points and Transformation Needs of Traditional Equity Investment Models

Traditional equity investment models face three major pain points that constrain the sustainable development of the industry. First, information asymmetry leads to investment decision-making mistakes due to over-reliance on superficial financial data and neglect of deep industrial information, such as investing in "pseudo-chip" enterprises or projects lacking core supply chains. Second, weak post-investment empowerment capabilities mean that capital only stays at the level of capital injection and cannot solve problems such as technology implementation and market expansion for enterprises, resulting in missed opportunities. Third, the exit path is singular, with 80% relying on IPOs, which are highly affected by capital market fluctuations. During the suspension of A-share IPOs in 2023, about 30% of institutions faced difficulties in capital recovery (Lu, D., Wu, S., & Huang, X., 2025). These pain points force the industry to accelerate transformation, with the core direction being the shift from "financial investors" to "industry-empowered investors." This transformation is a reconstruction of investment logic and capability systems, requiring industry cognition to fill the "technology – market" information gap to solve decision-making and empowerment problems, while strengthening the "capital – operation" capabilities of capital to provide full-cycle support. The two work together to break through the bottleneck of traditional models and achieve high-quality development of the industry.

3. The Connotation and Operation Mechanism of the "Industry Cognition + Capital" Dual-Driven Model

3.1 Core Value and Capability Dimensions of the Dual Wheels

Industry cognition is the key to solving the information gap in traditional models and carries three core values throughout the process. In track selection, based on the judgment of the industrial life cycle, it locks in areas where "policy dividends and technological breakthroughs" overlap to ensure that capital and industry are in sync. In enterprise identification, it breaks through the limitations of financial indicators and focuses on technological barriers and supply chain positions to determine the irreplaceability of enterprises in the industrial chain. In the post-investment empowerment stage, it is transformed into the ability to connect resources and implement technology, promoting the transition of technology from "laboratory samples" to "market products."

Capital, as the operation carrier, has core capabilities in three dimensions of collaborative upgrading. In capital allocation, it balances risks through a diverse combination of "government-guided funds + social capital" and "merger and acquisition funds." Post-investment services extend to full-cycle refined support, such as assisting with compliance sorting in the Pre-IPO stage and providing daily tax planning. Exit design constructs an "IPO + industrial merger and acquisition + S fund" path to shorten the cycle, enhance liquidity, and stabilize returns.

3.2 Operation Mechanism of Dual-Wheel Collaboration

In the investment decision-making stage, a collaborative logic of "industry preliminary screening + capital due diligence" is formed, implemented by a dual-team of "industry experts + investment managers." Industry experts lead the preliminary screening of tracks and enterprise evaluation, drawing industrial chain maps to mark core information.

Investment managers conduct financial due diligence and risk assessment to ensure capital security. For example, in the investment of new energy vehicle companies, industry experts lock in enterprises with leading electric control technology, investment managers verify financial risks, and then capital follows up with the investment.

In the post-investment stage, capital supports the implementation of industry cognition with a "special fund for industrial empowerment," specifically allocated for technology research and development and supply chain integration. For example, in the investment of semiconductor equipment enterprises, capital uses the special fund to promote the establishment of a joint venture between the enterprise and a wafer factory, shortening the research and development cycle by nearly half and achieving rapid commercialization of technology.

In the exit stage, a system of "demand identification + path design" is constructed. Industry cognition explores industrial chain merger and acquisition opportunities and judges synergistic value, while capital designs diverse transaction structures, such as stock swap mergers to meet both parties' demands. This model shortens the exit cycle by 1-2 years and drives a 5-8% increase in project IRR.

3.3 Support System for Dual-Driven Model

In terms of organizational structure, an "Industry Research Center" is established to output industry cognition and integrate technical and policy information. A "Post-Investment Empowerment Department" is set up to build an industrial resource pool and develop personalized plans. The "project full-cycle responsibility system" is implemented, allowing investment managers to run through research and post-investment, breaking down departmental barriers.

Institutional design provides long-term support. In performance evaluation, the "track prediction accuracy rate" of industry experts is assessed and linked to bonuses. In incentives, a "profit-sharing" system is promoted, with project returns allocated according to the contribution of industry cognition. At the same time, the "industrial value enhancement" indicator is added to ensure that the dual-driven model aims at "win-win for industry and capital."

4. Case Verification of the Dual-Driven Model

4.1 Case 1: Hillhouse Capital's "Hard Technology + Industrial Merger and Acquisition" Model

Hillhouse focuses on hard technology fields with in-depth industry cognition, forming a 30-person professional team (including academicians and semiconductor experts) and collaborating with universities to build a "technology tracking platform" to update the full industrial chain data and policy dynamics in real-time, accurately judging industrial bottlenecks and opportunities. In terms of capital operation, from 2021 to 2023, it focused on semiconductor equipment and new energy battery fields, investing in 15 companies such as Zhongwei Company and Ningde Times with a scale of over 20 billion yuan. Post-investment empowerment targets enterprise weaknesses, such as assisting Zhongwei in acquiring overseas technical teams and setting up an industrial fund to inject 1 billion yuan into Ningde for solid-state battery research and development. Exit strategies adopt an "IPO + industrial merger and acquisition" path, with five projects going public and three being acquired by industry leaders, achieving an average IRR of 32%, 10% higher than the industry average. In terms of effectiveness, the R&D investment ratio of invested companies increased from 15% to 30%, and the proportion of overseas customers of Ningde Times increased from 20% to 45%, enhancing global industrial chain discourse power. (Wu, S., Huang, X., & Lu, D., 2025)

Table 1.

Indicator/Description	Value/Details
Average IRR	32%
Excess Industry Average IRR	10%
Increase in R&D Investment Ratio of Investee Companies	From 15% to 30%
Increase in Overseas Customer Ratio of Contemporary Amperex Technology Co. Limited (CATL)	From 20% to 45%

4.2 Case 2: Sequoia China's "Consumer + Ecologized Capital" Model

Sequoia focuses on the consumer field by exploring the trend of consumption upgrading, drawing a "new consumer industry chain map," anticipating the explosion of "zero-sugar beverage" demand, and locking in niche brands such as Yuanqi Forest and Perfect Diary. Capital operations adopt an "ecologized capital" strategy, accompanying investment from seed/A round to Pre-IPO round. Post-investment empowerment is precise, such as helping Perfect Diary connect with contract manufacturers to reduce costs by 20% and assisting in expanding into the Southeast Asian market. Exit strategies are combined with enterprise characteristics, with Perfect Diary going public (IRR 45%) and Yuanqi Forest exiting through strategic investment (cycle 3 years). The results are significant, with the average market share of invested companies increasing from 5% to 15%, and the brand expansion cycle shortened by 2-3 years (Liu, Z., 2025). Yuanqi Forest achieved nationwide layout in just 2 years, becoming a benchmark in the new consumer sector.

Table 2.

Indicator/Description	Value/Details
Perfect Diary's Cost Reduction Ratio with Contract Manufacturers	20%
Perfect Diary's IPO IRR	45%
Genki Forest's Strategic Investment Exit Period	3 years
Average Market Share Increase of Investee Companies	From 5% to 15%
Brand Expansion Cycle Shortened	2-3 years
Time for Genki Forest to Expand from Regional to National Layout	2 years

4.3 Case Comparison and Insights

The two cases demonstrate the differentiated logic of dual-driven models in different tracks. In terms of industry cognition, hard technology focuses on the autonomy and compliance of technology, avoiding "pseudo-technology"; consumption focuses on user demand and supply chain efficiency. In terms of capital tools, hard technology relies on long-term industrial funds and merger and acquisition tools to match the research and development cycle; consumption uses follow-up funds and IPO tutoring to adapt to rapid growth. In terms of effectiveness, hard technology shortens the research and development cycle by 15-20%, and consumption increases market share by 10-15%. The insight is that dual-driven models need to be "tailored" to local conditions: hard technology focuses on "long-term capital + technology empowerment," consumption focuses on "rapid expansion + channel docking," and adjusting the collaborative method according to the track characteristics can maximize value.

5. Innovation Points and Industry Value of the Model

5.1 Innovation Points of the Model: Breaking Through Three Boundaries

The core innovation of the "industry cognition + capital" dual-driven model is first to break through the "information boundary" of traditional equity investment. Traditional models rely on superficial enterprise information and lack understanding of industrial technology and supply chain logic, which can easily lead to investment misjudgment. In the dual-driven model, industry cognition constructs a multi-dimensional information network by deeply exploring the industrial chain, tracking technological iteration, and interpreting policies. It can identify the actual value of patents, sort out the cost laws of the supply chain, and predict market trends, increasing the accuracy rate of project selection by 20-30% and fundamentally reducing the risk of information misjudgment.

Second, it breaks through the "empowerment boundary," upgrading from "single financial empowerment" to "industry + capital dual empowerment." Traditional models only inject capital and cannot solve non-financial problems such as enterprise technology and market. The dual-driven model covers the full life cycle of enterprises' "technology – market – capital." It connects research and development resources and provides special funds at the technology end, digs channel resources and supports promotion at the market end, and optimizes equity structure and connects financing at the capital end, significantly enhancing the enterprise's risk resistance capability and increasing the enterprise survival rate by 15%. (Huang, T., Yi, J., Yu, P., & Xu, X., 2025)

Finally, it breaks through the "exit boundary," solving the over-reliance on IPOs. Traditional models rely on IPOs for 80% of projects, which are highly affected by capital market fluctuations and have long cycles. The dual-driven model constructs a diversified exit path of "IPO + industrial merger and acquisition + S fund," which can promote rapid exit through collaborative enterprise mergers and acquisitions or enhance capital liquidity through S funds, increasing capital liquidity by 30% and forming a virtuous cycle of "exit – reinvestment."

5.2 Industry Value

For equity investment institutions, the dual-driven model significantly enhances core competitiveness. In terms of returns, the collaboration of the two increases the average IRR of projects by 8-10%. In terms of LP relationships, the exit rate increases by 25%, enhancing LP stickiness. Small and medium-sized institutions can transform through a "lightweight" path by cooperating with industry think tanks and leading institutions, reducing transformation costs.

For invested companies, the model accelerates the growth process. The technology implementation cycle is shortened by 15-20%, and AI companies achieve technology mass production in just 6 months, nearly half the industry average cycle. The financing success rate is increased by 40%, and consumer brands successfully complete Pre-IPO rounds with the guidance of capital and industry cognition. At the same time, the industrial chain resources can be integrated, such as new energy vehicle companies connecting with suppliers and promoting joint ventures to reduce costs and enhance discourse power.

Table 3.

Indicator/Description	Value/Details
Average IRR of Projects Increased	8-10%
Exit Rate Increased	25%
Technology Implementation Cycle Shortened	15-20%
Mass Production Cycle of AI Company's Technology	6 months
Mass Production Cycle of AI Company's Technology Shortened Compared to Industry Average	Nearly half
Financing Success Rate Increased	40%

For the real economy, the model guides capital to flow accurately into strategic areas. In 2023, 75% of the projects of leading institutions using the dual-driven model were related to the real economy, far higher than traditional models. In the semiconductor field, it promoted a 10% increase in domestic substitution rate, alleviating "bottleneck" problems. In the new energy field, it helped enterprises expand into overseas markets, and in the consumer field, it supported domestic brands, building a bridge for "capital serving the real economy" and becoming a "booster" for industrial upgrading.

6. Challenges and Optimization Strategies

6.1 Core Challenges

The primary obstacle for small and medium-sized equity investment institutions to implement the dual-driven model is the difficulty in building industry cognition. Leading institutions can support independent research teams and high-end data procurement, while small and medium-sized institutions face an annual cost of 500-1000 million yuan for cognition building (Yu, D., Liu, L., Wu, S., Li, K., Wang, C., Xie, J., ... & Ji, R., 2025), far exceeding their financial capacity. At the same time, high-end industry experts tend to choose leading institutions, and small and medium-sized institutions face a talent gap, resulting in an industry cognition accuracy rate of only 50% of that of leading institutions, falling into a dilemma of "not daring to invest and not investing accurately."

The low efficiency of dual-wheel collaboration stems from the goal conflict between the industry and investment teams. The industry team focuses on the long-term implementation of technology and is willing to give a 3-5 year cultivation cycle; the investment team, influenced by LP's short-term return requirements, pursues a 1-3 year exit cycle. This conflict increases communication costs, accounting for 30% of the total project time. For example, the post-investment planning is extended from 3 months to more than 4 months due to disputes, missing the key window period.

Table 4.

Indicator/Description	Value/Details
Average Annual Cognitive Construction Cost for SME Institutions	5-10 million yuan
Cognitive Accuracy Rate of SME Institutions Relative to Leading Institutions	50%
Cultivation Cycle Willing to Be Provided by the Industry Team	3-5 years
Exit Cycle Pursued by the Investment Team	1-3 years

Proportion of Communication Costs in Total Project Time	30%
Time Extended Due to Disputes in Post-Investment Planning	Over 1 month

6.2 Optimization Strategies

To address the difficulty in building industry cognition, small and medium-sized institutions can take a "lightweight" path: externally, collaborate with industry think tanks and universities to build a "cognition sharing platform," with an annual cooperation cost of 100-200 million yuan, to share data and expert resources. In terms of tracks, focus on 1-2 narrow fields, concentrate efforts to accumulate in-depth cognition, and avoid decision-making mistakes.

To improve collaboration efficiency, mechanisms and interests need to be addressed: establish a "Dual-Wheel Collaborative Decision-Making Committee," with industry experts leading long-term matters such as technology routes and resource docking, and investment managers leading capital matters such as financial due diligence and exit timing, reducing disputes. Implement a "project follow-investment system," requiring both teams to follow-invest no less than 5% of their own funds, achieving risk-sharing and interest-sharing, and balancing long-term and short-term goals.

To cope with risks, a "forward-looking prediction + diversified hedging" system needs to be built: establish a dedicated policy position to predict policy impacts 6-12 months in advance; on the market side, balance liquidity through "60% hard technology + 40% consumption" cross-track investment, and plan multiple exit paths such as "IPO + industrial merger and acquisition + S fund" in the early stage of investment to avoid capital sedimentation.

7. Conclusion and Outlook

7.1 Research Conclusions

The "industry cognition + capital" dual-driven model has become an inevitable trend for the transformation of the equity investment industry. Its core logic lies in using industry cognition to solve the dilemma of "what to invest in and how to help" — accurately locking in high-potential tracks and enterprises with technological barriers, connecting industrial resources for invested companies, and promoting technology implementation. At the same time, it relies on capital to solve the operation problems of "how to invest and how to exit," balancing risks through diversified capital allocation, and enhancing liquidity through multi-path exits.

7.2 Future Outlook

In the future, the dual-driven model will further upgrade with the help of technology, tracks, and policies. In terms of technology, AI and big data can improve the efficiency of industry cognition by analyzing dynamic industrial chain data to predict technological trends. Blockchain can optimize the transparency of capital operations, such as transaction tracing in S fund share transfers. In terms of tracks, it will focus more on hard technology, dual carbon, biomedicine, and other national strategic fields, combining track technical characteristics and policy guidance to explore more precise collaborative models.

7.3 Research Limitations and Future Directions

This study has certain limitations. The cases are mainly from leading institutions, and the practical analysis of small and medium-sized institutions with limited resources is insufficient. Moreover, the evaluation of industry cognition still stays at the qualitative level, lacking quantitative indicators. Future research can explore the "lightweight dual-driven model" of small and medium-sized institutions, summarize their landing experience in niche tracks, and construct a quantitative evaluation system for industry cognition. By using data-based indicators to measure its value to investment decision-making, more precise references can be provided for model optimization.

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The Design and Practical Path of Cross-Border Traceability System for Medicinal and Chemical Products — A Multi-Dimensional Empirical Study Based on Blockchain and Internet of Things

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Abstract

In the cross-border trade of medicinal and chemical intermediates, industry pain points such as information silos leading to traceability disruption, low credibility of quality control data, and poor regulatory coordination efficiency are prevalent, with small and medium-sized trading enterprises being particularly affected. This study takes norfloxacin and cefotaxime active ester as typical research objects, integrating the tamper-proof characteristics of blockchain with the real-time perception technology of the Internet of Things (IoT) to construct a lightweight cross-border traceability system covering the entire chain from production to storage, logistics, customs clearance, and terminal use. The system is based on a “three-layer, nine-module” structure. An empirical test was conducted using the trade data of Wuhan Kuda Hui Trading Co., Ltd. from 2022 to 2024. The results indicate that the system can increase the completeness of traceability information to 99.2%, raise the customs clearance rate in the EU to 96%, shorten the quality control abnormal response time to 2.5 hours, and reduce the cross-border delivery cycle to 28 days. Additionally, the “three-stage promotion” low-cost practical path designed for small and medium-sized trading enterprises ensures feasibility and cost controllability, with strong replicability. The study provides a quantifiable and implementable technical solution and practical paradigm for cross-border traceability of medicinal and chemical products, effectively solving the core industry pain points.

Keywords: medicinal and chemical products, cross-border traceability, blockchain, Internet of Things, norfloxacin, cefotaxime active ester, small and medium-sized trading enterprises, full-chain traceability, practical path, Wuhan Kuda Hui

1. Introduction

1.1 Research Background and Significance

Medicinal and chemical intermediates are a key link in the pharmaceutical industry chain, with their cross-border trade volume continuously increasing. For instance, the demand for products such as norfloxacin and cefotaxime active ester is on the rise. However, the industry faces traceability pain points, such as information silos, low credibility of quality control data, and poor regulatory coordination efficiency, which severely affect trade efficiency and quality control. Taking Wuhan Kuda Hui Trading Co., Ltd. as an example, these issues often increase costs and reduce customs clearance efficiency in cross-border trade. Therefore, researching a cross-border traceability system for medicinal and chemical products holds significant practical and theoretical value. In practice, constructing a cross-border traceability system can enhance trade efficiency, reduce costs, and meet international regulatory requirements. Theoretically, it fills the research gap in the traceability of medicinal and chemical intermediates and provides a reference for the design of technology-integrated traceability systems.

1.2 Core Research Positioning and Questions

This study focuses on three major pain points in the cross-border trade of medicinal and chemical products: information silos, low credibility of quality control data, and poor regulatory coordination efficiency. Based on the trade data of Wuhan Kuda Hui from 2022 to 2024, and integrating blockchain and Internet of Things technology, a cross-border traceability system covering the entire chain is designed. The core question is: How to integrate blockchain and IoT technology, taking into account the cost-bearing capacity and practicality of small and medium-sized trading enterprises, to construct a technologically advanced and implementable traceability system, and verify its actual application effect, providing a practical paradigm for the industry.

1.3 Research Innovation Points and Technical Route

The innovations of this study include: First, the innovation of the technical architecture, proposing a “three-layer, nine-module” lightweight traceability architecture that is more suitable for the application scenarios of small and medium-sized trading enterprises; second, the innovation of empirical research, using the real data of Wuhan Kuda Hui to verify the system’s effect, avoiding the limitations of generalization in research; third, the innovation of the practical path, designing a “three-stage promotion” low-cost path to reduce the enterprise access threshold. The technical route is: starting from sorting out the pain points, analyzing the technical adaptability, completing the system design, relying on empirical verification to optimize the practical path, and forming a research closed loop.

2. Theoretical Basis and Industry Pain Point Analysis

2.1 Core Theoretical Basis

The theory of cross-border trade full life cycle traceability is the core theoretical support of this study. This theory requires the traceability system to cover the entire process from production to terminal use, and to achieve quality control and information verification through the effective connection of data. The integration of blockchain and Internet of Things technology provides the technical basis for the implementation of this theory. The Hyperledger Fabric consortium chain realizes the tamper-proof and traceable nature of data through asymmetric encryption and distributed ledger, ensuring the authenticity and integrity of data; IoT technology, through sensors deployed in various scenarios, realizes the automatic collection and real-time transmission of data, freeing itself from dependence on manual input, and providing accurate data support for the traceability system. The combination of the two solves the problems of data credibility and timeliness, becoming the key technical path to addressing the pain points of traceability.

2.2 Core Pain Points of Medicinal and Chemical Cross-Border Traceability

There are many pain points in the traceability links of the cross-border trade of medicinal and chemical intermediates, with small and medium-sized trading enterprises being particularly prominent. The problem of information silos leads to the fragmentation of data in various links. For example, in the cross-border trade of norfloxacin by Wuhan Kuda Hui, the upstream procurement data cannot be connected with the downstream customs clearance data. The product traceability integrity is only 68%, making it difficult to quickly locate quality problems. The credibility of quality control data is low, with the industry mostly relying on manual input. Some enterprises even tamper with data. In 2022, Wuhan Kuda Hui’s products had a customs clearance rate of only 72% in the EU due to inaccurate data, increasing customs clearance costs and damaging international credibility (Kurian A N, Joby P P, Anoop T, et al., 2023). In addition, cross-border trade involves multiple regulatory authorities with different data standards and verification processes. The collaborative disposal efficiency is low when quality control abnormalities occur. The abnormal response time is as long as 48 hours, which can easily lead to trade delays and increased losses.

2.3 Traceability Needs of Research Objects

The two types of medicinal and chemical intermediates focused on in this study, norfloxacin and cefotaxime active ester, have differentiated traceability needs. Norfloxacin is sensitive to transportation temperature and humidity. Exceeding temperature and humidity standards can lead to a decrease in purity. Moreover, the EU and other markets have strict requirements for its purity. Therefore, the traceability system needs to focus on collecting transportation temperature and humidity and product purity data to meet cross-border customs regulatory requirements. The production process parameters of cefotaxime active ester directly affect product quality. In cross-border trade, quality disputes and claims caused by non-compliant process parameters are frequent. Its traceability needs lie in tracing the key process parameters in the production link, such as reaction temperature and raw material ratio. By completing traceability, quality responsibility can be clearly defined, reducing claim risks and enhancing market credibility.

3. Design of Traceability System Based on Blockchain and Internet of Things

3.1 System Design Principles

The cross-border traceability system for medicinal and chemical products constructed in this study follows four design principles, focusing on the business characteristics and cost-bearing capacity of small and medium-sized trading enterprises such as Wuhan Kuda Hui. The principle of full-chain coverage requires the system to cover the entire process from production, storage, logistics, customs clearance to terminal use, solving the problem of data fragmentation. The data credibility principle relies on the tamper-proof nature of blockchain and the real-time collection capability of IoT to replace manual input, solving the problem of low credibility of quality control data. The regulatory coordination principle focuses on unifying data standards for cross-border regulatory authorities to meet regulatory requirements in different regions. The cost controllability principle considers the profit margin of enterprises and adopts a lightweight architecture to control the initial access cost within 0.5% of the enterprise’s annual revenue, ensuring that enterprises can afford it and have a cost-effective value.

3.2 “Three-Layer, Nine-Module” Lightweight Technical Architecture

The “three-layer, nine-module” architecture is the core carrier of this traceability system, with each layer and module being independent yet working in coordination. The perception layer includes three modules: production end, logistics end, and terminal end. The production end deploys IoT sensors according to product characteristics to collect key parameters, with a sampling frequency of once every 15 minutes; the logistics end is equipped with GPS and temperature and humidity sensors, with a positioning accuracy of within 5 meters; the terminal module supports QR code verification functions. The blockchain layer includes three modules: node management, data on-chain, and consensus mechanism. It incorporates core entities to build a consortium chain, optimizes block generation efficiency, and uses the Practical Byzantine Fault Tolerance mechanism to ensure data consistency and tamper-proof nature. The application layer includes three modules: enterprise traceability management, customs supervision, and multi-language customer inquiry, which meet enterprise needs, improve customs clearance efficiency, and support inquiries in Chinese, English, and German.

3.3 System Operation Process

Taking the export business of norfloxacin by Wuhan Kuda Hui as an example, the system operation logic is as follows: In the production link, the upstream supplier Hubei Jianeng collects production data in real-time through IoT sensors and puts it on the chain; in the storage link, temperature and humidity sensors monitor the storage environment and synchronize data; in the logistics link, GPS and temperature and humidity sensors track transportation data and put it on the chain; in the customs clearance link, customs authorities retrieve the full-chain data through blockchain nodes, reducing the verification time from 2 days to 4 hours; in the terminal link, customers scan the code to verify the full-chain data and provide feedback on acceptance results. In 2024, the terminal acceptance feedback data of this batch of norfloxacin was completed on the chain within 1 hour, forming a full-process closed loop, realizing traceable and verifiable data.

4. Empirical Study Based on Wuhan Kuda Hui

4.1 Empirical Design

This study aims to verify the actual application effect of the blockchain and Internet of Things cross-border traceability system, taking the core cross-border trade business of Wuhan Kuda Hui Trading Co., Ltd. from 2022 to 2024 as a sample. Two products with the largest trade volume, norfloxacin and cefotaxime active ester, were selected. Among them, norfloxacin had 28 batches with a total value of 42 million yuan; cefotaxime active ester had 15 batches with a total value of 36 million yuan, and the two together accounted for 92% of the total cross-border trade volume during the same period. The study focuses on the comparison of key indicators before and after the application of the system, including traceability integrity, quality control response efficiency, and supply chain cost and efficiency. Traceability integrity is measured by the proportion of traceable data in the full chain. The core indicator of quality control response efficiency is the time from the discovery of quality abnormal problems to the positioning. Supply chain cost and efficiency cover cross-border delivery cycle, inventory turnover rate, and third-party testing costs. The comparison period is from 2022 to the first half of 2023 (before the application of the system) and from the second half of 2023 to 2024 (after the application of the system). By extracting real data from the enterprise's trade accounts, customs verification records, and quality claim vouchers, the objectivity and credibility of the empirical results are ensured.

Table 1.

Specific Indicators	Before Application	After Application
Proportion of Traceable Data in Full Chain	60%	95%
Time from Discovery to Positioning of Quality Abnormal Problems	48 hours	4 hours
Cross-Border Delivery Cycle	15 days	7 days
Inventory Turnover Rate	3 times/year	6 times/year
Third-Party Testing Costs	1.2 million yuan	0.6 million yuan
Proportion of Norfloxacin and Cefotaxime Active Ester	92%	95%

4.2 Empirical Results

After the application of the system, traceability integrity and customs clearance efficiency have significantly improved. Before the application, the traceability data of norfloxacin only covered the production and logistics links, with a full-chain traceability information integrity of 68%. In 2022, the customs clearance rate in the EU was only 72%, and 8 batches of norfloxacin were temporarily detained for customs verification due to incomplete traceability data. After the application, relying on the real-time data collection of the perception layer and the full-chain certification of the blockchain layer, the traceability information integrity of norfloxacin and cefotaxime active ester has increased to 99.2% (Sim C, Zhang H S & Chang M L., 2023). In 2024, the customs clearance rate of the two types of products in the EU has increased to 96%, with only 1 batch of norfloxacin being verified due to packaging labeling issues. However, the trade was not delayed thanks to the quick verification of blockchain data.

Table 2.

Project	Before Application	After Application
Traceability Data Coverage Links of Norfloxacin	Production and logistics links	Full chain

Proportion of Full-Chain Traceability Information (%)	68%	99.2%
Customs Clearance Rate in the EU (%)	72%	96%

Quality control response efficiency and quality claim costs have also been significantly optimized. Before the application, the quality control abnormal response time was as long as 48 hours. In 2022, the quality claim amount due to quality issues reached 1.86 million yuan. After the application, the production and logistics data collected in real-time by IoT sensors can quickly locate abnormal links. The quality control abnormal response time has been shortened to 2.5 hours. In 2024, the quality claim amount has dropped to 0.33 million yuan, a decrease of 82.3% compared to 2022. Moreover, the claim cases were all due to minor packaging damage in the logistics link, with no disputes over the product quality itself.

Supply chain cost and efficiency have further improved. Before the application, the cross-border delivery cycle averaged 45 days, with customs verification and data supplementation accounting for 40% of the time. The inventory turnover rate of norfloxacin was 4 times/year, and the third-party testing cost was about 18 yuan/kg. After the application, the cross-border delivery cycle has been shortened to 28 days. The customs verification time has been reduced from an average of 2 days to 4 hours. In 2024, the inventory turnover rate of norfloxacin has increased to 5.62 times/year, an increase of 40.5% year-on-year, and the third-party testing cost has dropped to 11.7 yuan/kg, a decrease of 35%. (Alotaibi M, Alharbi F, Almutairi S, et al., 2024)

Table 3.

Project	**Before Application**	**After Application**
Cross-Border Delivery Cycle (days)	45	28
Customs Verification Time	Average 2 days	4 hours
Proportion of Customs Verification and Data Supplementation Time	40%	-
Inventory Turnover Rate of Norfloxacin (times/year)	4	5.62
Third-Party Testing Costs (yuan/kg)	18	11.7

4.3 Results Discussion

The empirical results show that the blockchain and Internet of Things cross-border traceability system is highly suitable for the business needs of small and medium-sized medicinal and chemical trading enterprises like Wuhan Kuda Hui. Without significantly increasing the enterprise's operational burden, it has realized the optimization of traceability, quality control, and supply chain indicators in all dimensions, verifying the feasibility and practicality of the system. However, during the empirical process, some problems that need to be optimized were also found. First, the initial cost of sensor deployment is slightly high. In the second half of 2023, Wuhan Kuda Hui invested 280,000 yuan in sensor deployment, accounting for 1.1% of its annual revenue. Although the cost can be covered by cost amortization in the later stage, it still exerts some pressure on small and medium-sized enterprises with smaller revenue scales. Second, the compliance of cross-border data needs to be optimized. When the enterprise exports products to the EU, some production data on the blockchain needs to comply with the GDPR data protection requirements. Data desensitization has increased the operating cost by about 15%, and the differences in data standards of regulatory authorities in different countries have led to room for improvement in the docking efficiency of customs nodes in the consortium chain. In 2024, 2 batches of products had a 1-hour increase in customs verification time compared to the average level due to data format adaptation issues. Third, the system currently only covers the core products of the enterprise. If it is extended to all categories, it is necessary to further optimize the adaptability of perception layer sensors and reduce the marginal cost of multi-category data collection.

Overall, the core value of the system has been verified. The existing problems can be gradually solved through technical lightweighting and the establishment of a data compliance framework, and it has the basis for promotion within the industry.

5. Optimization of Practical Path and Guarantee Measures

5.1 "Three-Stage Promotion" Low-Cost Practical Path

Combining the empirical results of Wuhan Kuda Hui and the development characteristics of small and medium-sized trading enterprises, this study designs a "three-stage promotion" low-cost practical path to realize the implementation and scaled promotion of the traceability system in stages. The basic stage focuses on the first 0 to 6 months, with the core goal of completing the technical access of core enterprises and upstream and downstream enterprises. For Wuhan Kuda Hui, it is necessary to prioritize the deployment of IoT devices with upstream suppliers such as Hubei Jianeng and downstream core customers such as Henan Kangbituo, covering the production and logistics key links of norfloxacin and cefotaxime active ester. At the same time, the blockchain consortium chain node access of the above-mentioned entities should be completed to realize the real-time on-chain of core data such as production process parameters, logistics temperature and humidity, and storage data. The investment in this stage should be controlled within 0.5% of the enterprise's annual revenue. According to this, Wuhan Kuda Hui can complete the data on-chain coverage of core business within 6 months, laying the foundation for system operation.

The coordination stage covers 7 to 12 months, with the core direction of unblocking the cross-border regulatory data chain. Aiming at the business characteristics of Wuhan Kuda Hui's products mainly exported to the EU and the US, the focus is on docking with regulatory systems such as the EU's EUDAMED and the US's FDA Traceability to establish a unified data sharing mechanism and adapt to the traceability data standards of different regions. For example, in response to the EU's verification requirements for the purity index of norfloxacin, the blockchain data output format should be optimized to realize the one-click retrieval and verification by regulatory authorities. In this stage, the cross-border customs verification time can be further shortened by 20%, further improving trade efficiency.

The maturity stage extends from 13 to 24 months, with the core goal of promoting the industry-wide application of the system. Taking the medicinal and chemical trading enterprises in Wuhan's Dongxihu District as the core, a unified industry traceability standard is formed. More than 50% of the regional similar enterprises are encouraged to join the consortium chain. Through the scale effect, the overall cost of the traceability system is reduced from 0.5% of the product value in the basic stage to less than 0.3%. If Wuhan Kuda Hui participates in the regional scale promotion, the traceability cost of its norfloxacin trade in 2025 can be reduced from 0.875 yuan/kg to 0.525 yuan/kg, further increasing the enterprise's profit margin.

Table 4.

Stage	Time Range	Core Objective
Basic Stage	0 - 6 months	Complete technical access of core and upstream/downstream enterprises
Coordination Stage	7 - 12 months	Unblocking cross-border regulatory data chain
Maturity Stage	13 - 24 months	Promoting industry-wide application of the system

5.2 Guarantee Measures

To ensure the implementation of the "three-stage promotion" path, a comprehensive guarantee system needs to be built from three dimensions: technology, policy, and enterprise. The technical guarantee focuses on the development of lightweight IoT devices. Aiming at the problem of slightly high sensor deployment cost in the basic stage, joint research and development with device manufacturers are carried out to develop low-cost sensors suitable for small and medium-sized trading enterprises.

The procurement cost of a single logistics temperature and humidity sensor is reduced from 800 yuan to 500 yuan, and the cost of multi-parameter sensors at the production end is reduced by 30%. At the same time, the blockchain node operation mode is optimized, adopting cloud-based lightweight deployment to reduce the enterprise's local server investment cost.

Policy guarantee focuses on subsidies for small and medium-sized enterprises to access the system. It is suggested that local governments introduce special subsidy policies for medicinal and chemical cross-border trading enterprises. For enterprises that complete the deployment of IoT devices and blockchain access, a subsidy of 30% of the equipment procurement amount should be given. For example, Wuhan Kuda Hui's equipment investment of 280,000 yuan in the basic stage can obtain a subsidy of 84,000 yuan (Landt J., 2005), effectively reducing the enterprise's initial investment pressure.

Enterprise guarantee focuses on embedding business processes and employee training. Wuhan Kuda Hui needs to embed traceability data collection and on-chain links into the daily business processes of procurement, sales, and logistics to avoid increasing the workload of employees. At the same time, one technical training session should be held per month, covering core content such as sensor operation, data verification, and system maintenance, to improve employees' proficiency in operating the system, ensuring the stable operation and effectiveness of the system.

6. Conclusion and Outlook

6.1 Research Conclusions

The "three-layer, nine-module" blockchain and Internet of Things cross-border traceability system for medicinal and chemical products constructed in this study accurately solves the three core industry pain points of information silos leading to traceability disruption, low credibility of quality control data, and poor regulatory coordination efficiency. The empirical study based on the trade data of norfloxacin and cefotaxime active ester by Wuhan Kuda Hui from 2022 to 2024 fully verified the practical application value of the system. It not only achieved significant improvements in traceability information integrity and customs clearance rate but also significantly shortened the quality control abnormal response time and compressed the cross-border delivery cycle. The "three-stage promotion" low-cost practical path designed for small and medium-sized trading enterprises balances the feasibility of technological implementation and cost controllability, providing a clear guide for similar enterprises in the industry to access the traceability system, with strong replicability and promotion value.

6.2 Research Limitations and Outlook

There are certain limitations in this study. The empirical sample only covers two types of medicinal and chemical intermediates, norfloxacin and cefotaxime active ester, and does not include trade data from more categories and enterprises of different scales. The scope of application of the conclusions needs to be further expanded. In the future, research can be deepened on this basis. For example, artificial intelligence technology can be introduced to conduct intelligent analysis of traceability data to realize early warning of quality risks in production and logistics links. At the same time, the application scenarios of the system can be expanded to more types of medicinal and chemical products and more cross-border trade regions such as Southeast Asia and the Middle East, promoting the standardization and internationalization of cross-border traceability systems, and providing more comprehensive support for the high-quality development of medicinal and chemical cross-border trade.

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Next-Generation Financial Transaction Informatization: From "Tool Empowerment" to "Intelligent Decision-Making"

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Abstract

The global financial transaction informatization is currently at a critical transition period towards "intelligent decision-making," with "data silos," "capability disconnections," and "path ambiguity" forming the core bottlenecks of the industry. A 2023 survey of global asset management institutions revealed that only 23% of the institutions have completed the transformation to intelligent decision-making, while the rest remain at the basic tool automation stage. This study employs a mixed research design of analytic hierarchy process (AHP), entropy weight method, event study method, and panel data regression to construct a three-dimensional dynamic evolution model of "technology maturity-business integration-decision-making contribution." It delineates a four-stage evolution path and quantifies the characteristics, revealing the catalytic effect of dual-domain capability integration and defining the critical threshold for intelligent decision-making dominance. The findings indicate that dual-domain integration can shorten the informatization upgrade cycle by 38%; "data sharing rate ≥80%, AI model out-of-sample accuracy ≥85%, and cross-departmental collaboration efficiency ≥75%" are the necessary conditions for transitioning from "intelligent assistance" to "decision-making dominance." This study fills the academic gap in "dual-domain collaborative evolution," providing a quantifiable practical guide for the digital transformation of financial institutions, with both theoretical and practical significance.

Keywords: financial transaction informatization, dynamic evolution model, dual-domain integration, intelligent decision-making, critical threshold, digital transformation, quantitative indicator system, insurance asset management, mutual funds, transformation path, AI financial applications, trading performance

1. Introduction

1.1 Research Background and Industry Pain Points

Global financial transaction informatization has gone through three stages of development: "basic electronicization-technology penetration-intelligent decision-making exploration." Influenced by regional development imbalance, institutional size differences, and cognitive level differentiation, a tiered pattern of "23% top-tier leapfrogging, 45% collaborative optimization, and 32% tool empowerment" has emerged, with the misalignment between technology investment and actual returns becoming increasingly prominent (Davenport, T. H., & Short, J. E., 1990). The industry pain points are concentrated in the following areas: the data sharing rate is only 35%, and data silos cause medium-sized mutual funds to manually migrate data across six systems, with instruction response times reaching up to 4 hours; capability disconnections result in an AI risk control misjudgment rate as high as 30%, making it difficult to balance efficiency improvement and compliance control; the lack of a unified evolution framework leads to a 65% failure rate for small and medium-sized institutions that blindly follow the transformation paths of top-tier institutions, with high trial-and-error costs. The characteristics of insurance asset management ("large funds, long cycles, low volatility") and mutual funds ("multi-strategy, cross-market, high turnover") form a natural complementarity, providing an excellent testing ground for solving industry dilemmas.

Table 1.

Index	Value	Explanation
Data sharing rate	35%	Global industry average
Cross-system manual migration	6 sets/day	Due to the lack of integration of the middleware
Instruction response time	4 hours	Including verification, reconciliation, and manual review

1.2 Literature Review and Academic Gaps

Existing literature on the technological evolution of financial transaction informatization mostly follows a three-stage description of 'tool automation-deep penetration-intelligent decision-making,' but it is often limited to single-case studies and qualitative analysis, lacking a systematic collation of the complete evolution chain and failing to form a quantifiable performance attribution system. General frameworks such as Gartner's maturity curve and Nolan's model neglect the unique attributes of financial transactions ("high frequency, high compliance, high real-time"), resulting in insufficient adaptability; while bank-oriented models from BCG and McKinsey focus on macro customer service narratives and fail to delve into the dynamic coupling mechanism of the entire transaction process. More critically, the academic community has long studied insurance asset management and mutual funds separately, with the former focusing on "large funds, long cycles" risk control digitalization and the latter on "multi-strategy, high turnover" efficiency improvement. The synergistic effect of "risk control + efficiency" lacks empirical support, and single-market samples from Europe and America cannot explain the dual-track system and strong compliance characteristics of the Chinese market, leaving the dual-domain integrated evolution model in an academic void.

1.3 Research Positioning and Core Questions

This study aims to construct a "quantifiable, diagnosable, and navigable" dynamic evolution model for financial transaction informatization, providing institutions with a one-stop solution of "stage diagnosis-path planning-threshold control." The core research focuses on three key questions: First, how to accurately divide the evolution stages and clarify the quantifiable characteristics through the three-dimensional coordinates of "technology maturity-business integration-decision-making contribution"; second, the coupling mechanism of insurance asset management's "large-scale risk control capability" and mutual funds' "high-frequency trading efficiency," and its quantifiable impact on the informatization leapfrogging speed and effect boundary; third, how to define the critical threshold for the transition from "intelligent assistance" to "decision-making dominance," and how to design institutional mechanisms to smoothly cross this inflection point, increasing the transformation success rate from the industry average of 35% to over 65%, thereby filling the academic gap and outputting a practical paradigm.

2. Theoretical Model Construction

2.1 Model Construction Logic and Core Assumptions

Based on the underlying logic that "technology serves business, and business drives decision-making," the practical trajectory is abstracted into a four-level evolution ladder of "tool-collaboration-assistance-decision-making," and the construction process strictly follows three principles: the principle of practical orientation, where all stage thresholds and quantitative indicators are derived from real business pain points and implementation experience to ensure the model's direct applicability; the principle of integration, which includes the three-dimensional coordinates simultaneously to avoid structural blind spots caused by a single-dimensional perspective; and the principle of dynamic evolution, which depicts the positive flywheel effect of technological iteration, process optimization, decision-making upgrade, and dual-domain integration, clearly presenting the leapfrogging path. Based on the above logic, this study proposes three assumptions: The evolution of financial transaction informatization exhibits a stepwise upward characteristic, with statistically significant differences in the mean values of the three-dimensional indicators across stages; dual-domain capability integration can generate a complementary lever effect, increasing the annual average growth rate of the three-dimensional indicators by more than 50%, compressing the evolution cycle; only when the three-dimensional indicators simultaneously cross the critical thresholds (technology maturity ≥0.75, business integration ≥0.68, decision-making contribution ≥0.62), can the leapfrogging from "intelligent assistance" to "decision-making dominance" be achieved, and any single-dimensional shortcoming will lead to leapfrogging failure.

2.2 Three-Dimensional Indicator System Design and Calculation Methods

Technology maturity focuses on the underlying support capability of technology for transactions, using the entropy weight method for weighting, with the number of annual upgrades measuring the iteration speed, the coverage of AI/algorithms in 12 core scenarios measuring the application depth, and the annual fault-free operation rate measuring stability, with data sourced from upgrade records, maintenance logs, and IT special reports. Business integration measures the adaptability of technology to transaction processes, organizational structure, and market environment, using a hybrid weighting method of analytic hierarchy process and entropy weight method, with cross-departmental data sharing rate breaking down data silos, transaction instruction end-to-end automation rate reducing manual dependence, and cross-market instruction average response time improving collaboration efficiency, with data derived from process logs and system statistical reports. Decision-making contribution assesses the value transition of technology from "assistance" to "dominance," using a hybrid weighting method, with the excess return ratio of intelligent systems measuring profit contribution, risk control correct warning rate measuring decision-making accuracy, and the relative time reduction ratio of intelligent decision-making compared to manual operations measuring efficiency, with data sourced from performance reports, risk logs, and decision-making trace records. The three-dimensional indicators are organically unified, not only depicting the evolution process but also providing the core scale for threshold determination and leapfrogging simulation.

2.3 Four-Stage Evolution Model and Quantitative Characteristics

Cluster analysis shows that financial transaction informatization presents a clear four-level evolution ladder: the Tool Empowerment 1.0 stage, dominated by "single-point electronicization" applications, with system annual upgrades ≤2 times, AI scenario coverage ≤30%, data sharing rate ≤30%, collaboration timeliness ≥4 hours, and only basic technical positions set at the organizational level, with performance improvement relying on manual cost savings. The RPA clearing project I led during my tenure at Fuguo Fund, which reduced manual workload by 60% through automation, is a typical practice of this stage; the Collaborative Optimization 2.0 stage, which breaks down system barriers through interface platforms and standardized SOPs, with annual upgrades of 2-4 times, scenario coverage of 30%-60%, data sharing rate and automation rate both reaching 30%-60%, collaboration timeliness shortened to 2-4 hours, and cross-departmental special groups gradually established. The cross-market SOP standardization I promoted at Guotai Fund, which increased the transaction success rate from 72% to 95%, fits the characteristics of this stage; the Intelligent Assistance 3.0 stage, with AI warnings and algorithmic trading deeply embedded in business operations, with annual upgrades of 4-6 times, scenario coverage of 60%-80%, data sharing rate and automation rate both reaching 60%-80%, collaboration timeliness of 0.5-2 hours, and the formation of digital special teams (Author Anonymous, 2022). The AI market warning system I implemented at Century

Insurance Asset Management, which controlled the risk misjudgment rate within 0.5%, is the core practice of this stage; the Decision-Making Dominance 4.0 stage, with the full formation of intelligent configuration centers and dynamic risk control systems, with annual upgrades ≥6 times, scenario coverage ≥80%, fault-free rate ≥99.9%, data sharing rate and automation rate both ≥80%, full market collaboration time ≤0.5 hours, and intelligent decision-making profit contribution ≥70%. The pilot of the hundred-billion-level asset intelligent configuration system I led at Century Insurance Asset Management, which increased excess returns by 26.7%, marks the ultimate leap from "tool support" to "decision-making hub."

2.4 Dual-Domain Integration's Leapfrogging Catalytic Mechanism

The core of dual-domain integration is to align the capability granularity of insurance asset management's "large funds, stable risk control" with mutual funds' "high turnover, fast collaboration," forming an acceleration flywheel of "risk control threshold reduction, efficiency iteration increase, and data sample expansion." On the one hand, the "asset admission firewall" system I built at Century Insurance Asset Management exports limit templates to mutual funds, achieving compliance risk pre-positioning and enabling intelligent decision-making to operate efficiently within precise risk thresholds. On the other hand, the "cross-border trading integration system" I led in developing at Guotai Fund, which empowers insurance asset management with high-frequency clearing and cross-market matching technologies, compresses the liquidation cycle of third-party entrusted assets from T+3 to T+1, providing high-density practice scenarios. Three transmission paths are thus formed: risk control capability first defines the safety boundary for intelligent decision-making, solving the "dare not use" concern; high-frequency trading scenarios provide a continuous optimization environment for AI models, increasing the system's annual upgrade frequency by 1.6 times; dual-domain data deep integration expands the AI model training set size by four times, increasing risk identification accuracy by 12 percentage points. Quantitative analysis confirms that dual-domain institutions take an average of 15 months to move from stage 1.0 to 4.0, compared to 24.2 months for single-domain institutions, shortening the cycle by 38%; the annual average growth rate of the three-dimensional indicators reaches 13%-15%, compared to 9.0% for single-domain institutions, increasing by 50%; the leapfrogging success rate from stage 3.0 to 4.0 increases from 65% to 92%, with dual-domain integration becoming the key support to break the "transformation death valley."

Table 2.

Index	Single-domain Average	Dual-domain Average
Time taken for 1.0→4.0 phase	24.2 months	15.0 months
Annual average growth rate of three-dimensional indicators	9.0%	13.5%
Success rate of 3.0→4.0 leap	65%	92%

3. Empirical Analysis

3.1 Data Sources and Sample Selection

The core samples include data from Guotai Fund in the mutual fund sector (95 funds, 326 observations) from 2012 to 2017, and data from Century Insurance Asset Management in the insurance asset management sector (360 billion in assets, 123 product accounts, 450 observations) from 2017 to 2024 (Luftman, J. N., 2003). Supplementary samples include early data from Fuguo Fund and Tian'an Insurance Asset Management (210 observations). The core samples cover 128 core transaction nodes, three types of markets, and seven major asset classes, with a time span of 18 years, ensuring representativeness and completeness. To verify the model's universality, data from 20 leading asset management institutions' transformation cases (180 observations) were collected, and public data from industry white papers and regulatory compliance reports were used as external validation references.

3.2 Research Methodology Design

To verify the model's reliability and

leapfrogging logic, a four-layer econometric testing system was designed: descriptive statistics and one-way ANOVA were used to verify the rationality of stage division; the three key upgrades I led were used as natural experiments, with event windows set (6 months before to 12 months after the event) to quantify leapfrogging effects; a panel data of institutions-years from 2008 to 2024 was constructed, with a dual-domain integration dummy variable as the core explanatory variable, using a fixed-effects model to test the catalytic coefficient; and the critical threshold for the leapfrogging from stage 3.0 to 4.0 was estimated using regression discontinuity, verifying the "three-dimensional simultaneous achievement" hypothesis and providing a 95% confidence interval.

3.3 Empirical Results and Analysis

The empirical results verify the model's rationality and leapfrogging logic. Descriptive statistics show a clear ladder feature, with the mean values of the three-dimensional indicators increasing progressively in each stage and standard deviations all below 0.06. One-way ANOVA is significant at the 1% level. The three event window analyses show that the launch of the data platform shortened the instruction response time by 62.5% and increased excess returns by 26.2%; the implementation of the AI warning system further shortened the response time by 46.7% and increased excess returns by another 27.4%; the intelligent decision-making pilot compressed the response time to 0.3 hours and increased excess returns by another 26.7%, with cumulative cross-departmental communication costs reduced by 75%. Panel regression results show that the coefficients of the dual-domain integration dummy variable for the three-dimensional indicators are 0.15, 0.12, and 0.18, respectively (all significant at the 1% level), which can increase the annual average growth rate of the three-dimensional indicators by an additional 5 percentage points and shorten the upgrade cycle by 38%. Regression discontinuity estimates the critical thresholds: data sharing rate ≥80%, AI model out-of-sample accuracy ≥85%, cross-departmental collaboration efficiency ≥75%. When all three dimensions meet the standards, the leapfrogging success rate reaches 92%, and if any one indicator is missing, the success rate plummets to below 45%.

Table 3.

Event Milestone	Change in Instruction Response Time	Change in Excess Return	Change in Cross-department Communication Cost
Data middleware goes live	Reduced by 62.5%	Increased by 26.2%	Initial decrease
AI early warning system implemented	Further reduced by 46.7%	Further increased by 27.4%	Continuous decrease
Intelligent decision-making pilot	Compressed to 0.3 hours	Further increased by 26.7%	Cumulative decrease of 75%

4. Conclusions and Future Work

4.1 Core Research Conclusions

The evolution of financial transaction informatization exhibits a stepwise upward trend, with clear quantifiable characteristics for the three-dimensional indicators in each of the four stages, and significant differences between stages. Dual-domain capability integration is a key catalyst for leapfrogging, with the "risk control + efficiency" complementary effect increasing the annual average growth rate of the three-dimensional indicators by 5 percentage points, shortening the upgrade cycle by 38%, and increasing the transformation success rate by 27%. The critical threshold for transitioning from "intelligent assistance" to "decision-making dominance" is data sharing rate ≥80%, AI model out-of-sample accuracy ≥85%, cross-departmental collaboration efficiency ≥75% (Zhou, Z. L., 2002), and the simultaneous achievement of all three dimensions is a necessary condition for successful leapfrogging. Digital transformation performance is significantly positively correlated with the three-dimensional indicators, with decision-making contribution having the most significant impact on excess returns, while technology maturity and business integration serve as important prerequisites.

Table 4.

Three-dimensional Indicator	Critical Value	All Three Dimensions Meet the Standard	Any One Missing
Data sharing rate	≥80%	Leap success rate 92%	<45%
AI out-of-sample accuracy	≥85%	As above	As above
Cross-department collaboration efficiency	≥75%	As above	As above

4.2 Theoretical Contributions

This study constructs a three-dimensional dynamic quantification model of "technology maturity-business integration-decision-making contribution" for financial transaction informatization, clarifying the operable indicators for the four-stage evolution for the first time. It fills the gap in the evolution theory of the financial transaction sub-field, overcoming the shortcomings of existing models that "focus on technology but neglect decision-making" and "have more static descriptions and fewer dynamic quantifications." Moreover, it reveals the leapfrogging catalytic mechanism of dual-domain capability integration, quantifies its impact on the upgrade cycle and transformation success rate, provides a new theoretical perspective for cross-domain digital transformation research, enriches the research system of financial digital transformation, defines the critical threshold for intelligent decision-making dominance, constructs a complete logic chain of "stage diagnosis-threshold breakthrough-leapfrogging realization," perfects the quantification evaluation system of digital transformation, and offers a replicable quantification analysis framework for follow-up research.

4.3 Practical Implications

4.3.1 Implications for Asset Management Institutions

Asset management institutions should adopt a "stage diagnosis-path matching" strategy, using the three-dimensional indicators to quickly determine their transformation stage and avoid blindly following trends and leapfrogging transformations. For example, institutions at the Tool Empowerment 1.0 stage should prioritize building a basic data platform instead of directly launching intelligent decision-making systems. They should actively promote dual-domain capability integration, with insurance asset management institutions borrowing high-frequency trading technologies from mutual funds to improve trading efficiency, and mutual funds introducing large-scale risk control systems from insurance asset management to reduce compliance risks. They need to focus on breaking through critical thresholds, prioritizing the construction of data sharing platforms and AI model optimization, while establishing cross-departmental collaboration mechanisms to lay the foundation for leapfrogging to the decision-making dominance stage. They should also establish a dynamic evaluation mechanism, conducting three-dimensional indicator assessments quarterly and adjusting transformation strategies in response to changes in market environment and regulatory policies to ensure the flexibility and adaptability of the evolution path.

4.3.2 Implications for Fintech Companies

Fintech companies should develop modular and iterative transformation solutions based on the characteristics of the four stages of evolution: providing basic automation tools for institutions at the Tool Empowerment stage; offering data interface platforms and standardized SOP management systems for those at the Collaborative Optimization stage; providing AI market warning and algorithmic trading engines for those at the Intelligent Assistance stage; and offering intelligent decision-making hubs and cross-institution collaboration platforms for those at the Decision-Making Dominance stage, to meet the differentiated needs of institutions at different stages.

4.3.3 Implications for Regulatory Authorities

Regulatory authorities should refer to the critical threshold standards defined in this study to formulate differentiated digital transformation regulatory policies: for institutions at the Tool

Empowerment and Collaborative Optimization stages, focus on regulating basic compliance risks; for those at the Intelligent Assistance and Decision-Making Dominance stages, establish an "intelligent decision-making filing system," requiring institutions to disclose the decision-making logic and risk control measures of AI models, encouraging innovation while preventing systemic risks.

4.4 Research Limitations and Future Work

4.4.1 Research Limitations

The study focuses on dual-domain leading institutions in the Chinese market, and the applicability of the model to small and medium-sized institutions, which have differences in business scale, asset types, and technology investment compared to leading institutions, still needs further verification. The study does not fully consider the impact of extreme market environments on the evolution model, and the indicator changes and leapfrogging paths under extreme conditions need further exploration. Additionally, the model does not incorporate the impact of frontier technologies such as blockchain and quantum computing, which require more in-depth research on their empowerment of the decision-making dominance stage.

4.4.2 Future Work

Future research will expand the sample scope to include small and medium-sized institutions and international market cases to test the universality of the model and construct differentiated evolution path guidelines. Introduce moderating variables, considering extreme market environments and frontier technology applications as moderating variables, to analyze the impact mechanisms of external shocks on evolution paths and improve the dynamic adaptability of the model. Deepen application research by developing a transformation ROI calculation tool based on this model and creating an integrated digital platform for "stage diagnosis-path planning-threshold monitoring" to enhance practical implementation. Expand research boundaries by exploring the synergistic effects of dual-domain integration and financial regulatory technology, and analyzing the application of the evolution model in emerging scenarios such as cross-border trading and green finance.

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Cross-Border E-Commerce TikTok Live Streaming Data Three-Dimensional Optimization Model Construction and Empirical Study — Based on Singaporean Technology Product Markets and Scenario Migration to U.S. Warehousing Services

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Abstract

In zero-paid-traffic scenarios, TikTok technology live streams typically face a systemic dilemma characterized by scarce traffic entry points, inadequate audience retention, and depressed average order values. Extant research predominantly focuses on low-involvement product categories and paid growth strategies, leaving a theoretical gap in systematic investigation of organic growth mechanisms for high-involvement technology products. Grounded in attention economy theory and collaborative optimization theory, this study employs 42 live streams featuring 15 technology products from Tesen Global Technology in Singapore as a natural experiment. We construct a three-dimensional collaborative optimization model encompassing "time slots—scripts—product mix" and implement real-time attention allocation via online gradient descent algorithms, while dynamically iterating product combinations through Thompson Sampling. Validation using 73-day panel data demonstrates that post-intervention, organic follower growth increased by 208%, conversion rates rose by 125%, average order value climbed by 20.5%, and cumulative advertising expenditure savings reached $12,000; 5,000 randomization permutation tests confirm robust effects ($p<0.01$). Furthermore, applying service marketing theory, we migrate the model to the U.S. small-to-medium warehousing sector, proposing an "inventory turnover rate visualization live stream + service package matrix" approach, which is projected to reduce customer-per-lead costs (CPL) from $180 to $90. This research establishes a multi-dimensional collaborative optimization framework for live streaming, filling theoretical voids regarding high-involvement product growth in zero-ad-spend contexts and providing a replicable methodological paradigm for organic cross-border e-commerce expansion.

Keywords: TikTok live streaming, organic growth, three-dimensional optimization model, technology products, cross-border warehousing services, online gradient descent, Thompson sampling, natural experiment

1. Introduction

1.1 Research Background and Industry Challenges

As an emerging business model integrating digital economies with international trade, cross-border live e-commerce has experienced explosive growth since 2020, with TikTok Shop's global gross merchandise value surpassing $20 billion in 2023. The technology and 3C category accounts for 19% of this total, establishing itself as a core vertical. However, the high average order values and extended decision-making cycles characteristic of technology products create inherent tension with traffic distribution logic in zero-paid-traffic contexts, resulting in industry-wide bottlenecks: difficulty in acquiring organic traffic and low conversion efficiency. Large-scale data reveals that technology live streams achieve only 650 average monthly organic follower increments and a median conversion rate of 4%, significantly below platform-wide averages. These challenges stem fundamentally from operations reliant on experiential timing selection, templated scripts, and random product curation, lacking a data-driven systematic optimization framework.

1.2 Empirical Anchor: TikTok Live Streaming Project of Tesen Global Technology

The TikTok live streaming project of Tesen Global Technology provides an ideal natural experimental setting. Specializing in technology accessories, the company authorized our research team in June 2023 to establish a live streaming studio from scratch in the Singapore market, restricted to 15 SKUs (average price $25-60) with paid advertising prohibited. During the baseline period (June 2023), 18 live streams generated 650 organic follower increments and a 4% conversion rate, yielding $1,970 in gross merchandise value. Following the July-August 2023 introduction of the three-dimensional optimization model, 24 live streams achieved 2,000 organic follower increments with a 9% conversion rate, generating $8,420 in gross merchandise value while saving $12,000 in advertising budget (Dewasanya, A., & Amaly, F., 2024). This experiment controlled core "people-product-place" variables, providing a homogeneous and comparable data environment for causal identification.

Table 1.

Experiment Phase	Observation Period	Number of Live Streams	Organic Follower Growth	Conversion Rate
Baseline Period	Jun 2023	18 sessions	650 people	4%
Optimization Period	Jul–Aug 2023	24 sessions	2,000 people	9%

1.3 Research Questions and Core Innovations

This study addresses growth bottlenecks under zero-ad-spend constraints through three core research questions: (1) What are the key quantifiable variables influencing organic traffic and conversion in technology live streams under zero-paid-traffic conditions? (2) How can a three-dimensional optimization model of "time slots—scripts—product mix" be constructed and validated? (3) What is the feasibility of migrating this model to U.S. cross-border warehousing service scenarios?

Core innovations include: (1) Establishing the first three-dimensional variable collaborative framework, overcoming fragmented analysis limitations; (2) Integrating online optimization algorithms for real-time dynamic adjustments, addressing post-hoc analysis latency; (3) Expanding research boundaries to high-involvement product categories and cross-border service scenarios, providing a cross-contextual migration paradigm.

2. Literature Review

2.1 Research Trajectory in Cross-Border E-Commerce Live Streaming

Existing cross-border e-commerce live streaming research has examined geographic-cultural distance impacts on transactions, proposing strategies such as real-time language services and inventory visualization to reduce perceived risk. However, these studies presuppose paid traffic acquisition or platform traffic support, neglecting organic growth logic under zero-ad-spend conditions. Moreover, samples predominantly concentrate on low-involvement categories like apparel and cosmetics, which differ fundamentally from the information-driven conversion logic of high-involvement technology products, creating a theoretical gap.

2.2 TikTok Traffic Mechanisms and Organic Growth Research

TikTok's traffic distribution centers on algorithmic mechanisms, following a tiered "cold start—secondary amplification" pathway where signals like completion rates and engagement metrics determine traffic allocation efficiency. Prior research confirms that each 1% increase in short-video 3-second retention rates correlates with 0.7% organic traffic growth, yet this finding remains unextended to live streaming contexts. Live streaming requires simultaneous achievement of traffic entry expansion, real-time retention, and immediate conversion, representing a fundamentally different logic from short-video traffic mechanisms. Current research has yet to reveal core signal weights in TikTok's live streaming algorithm (Anjelita, A., & Qonitah, Y. R., 2024), particularly lacking investigation into organic traffic acquisition patterns under zero-paid-traffic conditions.

2.3 Technology Product Live Streaming Conversion Research

Technology product live streaming conversion relies on informational content; strategies such as technical parameter visualization and expert hosting have proven effective. However, these studies exhibit limitations: samples predominantly focus on brand-owned live streams without isolating paid traffic interference; they overlook decision-making characteristics of high-involvement products in zero-ad-spend contexts—where natural audience decision cycles are 1.8 times longer than apparel categories, requiring product combinations and multiple touchpoints to complete purchases. Existing research fails to examine marginal contributions of product portfolios or construct multi-variable collaborative optimization frameworks, resulting in fragmented strategies. In summary, theoretical gaps in zero-advertising contexts, high-involvement categories, and multi-dimensional collaboration constitute the core starting point of this study.

3. Theoretical Framework and Three-Dimensional Optimization Model Construction

3.1 Model Overview: Three-Dimensional Collaborative Logic of Time Slots—Scripts—Product Mix

Grounded in dynamic systems theory, this study transcends traditional independent variable optimization by proposing a three-dimensional collaborative model of "time slots—scripts—product mix," conceptualizing the live streaming room as a dynamic complex system wherein the three dimensions couple and interact under the objective of "maximizing natural traffic utilization efficiency." The temporal dimension serves as the traffic entry valve, identifying high-activity windows through heatmaps based on TikTok's time-varying traffic distribution characteristics to match traffic supply with user demand. The script dimension functions as an attention allocation mechanism, dissecting content into micro-units and dynamically adjusting duration to maximize retention and engagement according to attention economy theory. The product mix dimension operates as a value capture lever, enhancing average order value and conversion rates through margin-frequency combinations based on bundling theory. Synergistic effects manifest as: time slots provide traffic baselines for scripts, script retention curves set available selling duration for products, and product average order values feedback to optimize time slot selection, achieving global optimality.

The model employs a three-level toolchain of "heatmaps—temporal slicing—matrix experiments": first identifying high-traffic windows via temporal heatmaps, then segmenting scripts into 30-second granularities to filter high-value modules, and finally testing product combination conversion elasticity through matrix experiments to achieve three-dimensional joint optimization.

3.2 Three-Dimensional Collaborative Mechanisms and Optimization Loops

The collaborative mechanism follows a dynamic closed loop of "data feedback—parameter update—real-time redeployment." The time slot submodel employs Exponentially Weighted Moving Average (EWMA) for traffic forecasting, automatically shifting broadcast start times by 15 minutes and updating heatmaps when below control limits. The script submodel segments live streams into micro-units of "pain point introduction—feature demonstration—incentive stimulation," minimizing churn rates through online gradient descent algorithms to dynamically allocate high-value unit exposure duration. The product mix submodel targets combination conversion rates, iterating product portfolios in real-time via Thompson Sampling and pushing high-expectation combinations to script tail segments. Three submodels achieve collaboration by sharing state variables such as traffic scale and retention duration, with loop convergence conditions defined as conversion rate fluctuations <0.5% for three consecutive experiments and diminishing marginal average order value gains.

3.3 Model Innovations and Transferability

Model innovations manifest in three aspects: (1) First construction of a three-dimensional variable collaborative framework, overcoming fragmented analysis limitations; (2) Integration of online optimization algorithms for real-time dynamic adjustments, addressing post-hoc analysis deficits; (3) Focus on zero-ad-spend and high-involvement categories, expanding research applicability spectra. Transferability derives from theoretical universality and low data thresholds: core logic builds upon general traffic mechanisms and consumer decision theories, data inputs require only platform-level minute-by-minute traffic and order logs, and core algorithms rely on open-source Python/R libraries, enabling low-cost migration across categories and markets.

4. Research Design and Data Description

4.1 Empirical Setting: Natural Experiment Field with Tesen's 15 Technology Products

Utilizing Tesen Global Technology's Singapore TikTok flagship store as the experimental field, we strictly controlled internal validity: fixed camera positions, lighting, and native English-speaking professional hosts; green-screen keying with 3D product explosion diagrams ensured visual consistency. We screened 15 SKUs (average order value $25-60), classified into four quadrants by "high/low margin × purchase frequency" to satisfy combination experimental requirements. Live sessions were fixed at 45 minutes each with daily updates (≥24-hour intervals) to avoid traffic pool overlap.

4.2 Experimental Period and Phase Designation

A two-phase natural experiment design of "baseline period—intervention period" was adopted, spanning 73 days (June 1 - August 12, 2023). The baseline period (June 1-30, 18 sessions) employed experiential operations without model intervention; the intervention period (July 1 - August 12, 24 sessions) fully embedded the three-dimensional model (Dewasanya, A., & Amaly, F., 2024). Both phases maintained consistency in inventory depth (≥200 units), pricing systems (10% discount rate), promotional rules ($50 free shipping), and external traffic sources (Affiliate and Paid Ads disabled), with special promotion days and holidays excluded to ensure differences solely derived from model intervention.

4.3 Data Sources and Collection Tools

A dual-source collection approach of "official backend + self-developed crawler" was implemented: TikTok Shop backend provided minute-level online user counts and order volumes; self-developed crawlers based on Selenium and TikTok Live API Wrapper captured comment texts and bullet chat timestamps at 10-second granularity to supplement engagement density data. ERP interfaces synchronized inventory and pricing information. Data preprocessing employed cross-validation, outlier removal, and linear interpolation, yielding 6,680 minute-level valid observations (2,710 baseline; 3,970 intervention).

4.4 Variable Operationalization and Measurement Scales

Core variables were defined following academic standards and industry conventions: organic follower increment measured as new followers within 24 hours post-broadcast; conversion rate defined as orders/total entries; average order value calculated as gross merchandise value/orders. Key independent variables include time slot activity values (baseline online users 1 hour pre-broadcast), script click-through rates (30-second micro-unit clicks/impressions), and product mix conversion rates (combo orders/exposures). Control variables such as inventory depth and discount rate were measured on ratio scales to ensure analytical applicability.

4.5 Control Variables and Interference Mitigation Strategies

Multi-dimensional interference mitigation included: inventory controls maintaining ≥200 sellable units to prevent stockout-induced conversion underestimation; pricing controls locking list prices and discount rates without additional promotions; external traffic controls disabling paid and Affiliate channels to ensure organic traffic purity; event controls excluding special occasion data; operational controls stabilizing "people-product-place" elements to satisfy natural experiment parallel trend assumptions, thereby ensuring causal identification reliability.

5. Empirical Results and Analysis

5.1 Descriptive Statistics and Data Quality Assessment

Descriptive statistics demonstrate significant post-intervention improvements: organic follower increment mean increased from 36.1/hour to 87.5/hour, conversion rates rose from 4.02% to 8.98%, and average order value grew from $31.2 to $37.6. Data quality assessment indicates core independent variables' Variance Inflation Factor (VIF) <2.3, suggesting minimal multicollinearity threats. Except for "real-time online users," all variables pass Jarque-Bera normality tests (p>0.05). Core variables correlate significantly with dependent variables (p<0.01), with data missing rates <0.3% and outlier rates <0.5%, satisfying empirical analysis requirements.

Table 2.

Evaluation Metric	Baseline Period (n=18 sessions)	Intervention Period (n=24 sessions)
Average Organic Follower Growth	36.1 people/60 min	87.5 people/60 min
Conversion Rate	4.02%	8.98%
Average Order Value	31.2 USD	37.6 USD

5.2 Three-Dimensional Experimental Validation: Synergistic Growth Mechanisms

Dimension-specific testing reveals core mechanisms: Time slot optimization focused on Singapore's high-activity 20:00-21:00 window, increasing organic follower increment by 0.67σ (p<0.01), validating traffic entry adaptation value. Script optimization elevated feature demonstration segment proportion from 25% to 35%, reducing 60-second churn rates from 34.7% to 27.2% (p<0.01), aligning with technology products' information-driven requirements. Product mix optimization achieved 11.3% conversion rates for high-margin + low-margin dual-high-frequency combinations, representing 44.9% improvement over single high-margin products (p<0.01) with additional $9.7 average order value gains (Liu, C., Sun, K., & Liu, L., 2023). Three-dimensional variable interaction terms exhibit significantly positive coefficients (p<0.01), confirming synergistic effects surpass independent effects.

5.3 Comprehensive Effects: Significance and Robustness Verification

Comprehensive effects show intervention period incidence rate ratios (IRR) of 3.08 (p<0.001) for organic follower increment and 2.25 (p<0.001) for conversion rate, representing 208% and 125% improvements respectively. 5,000 randomization permutation tests confirm actual effects fall beyond the 99th percentile of permutation distributions (p<0.01), excluding random fluctuation interference. Heterogeneity analysis reveals more significant conversion improvements for medium-high average order value products ($40-60) (132% vs 118%), aligning with high-involvement category characteristics.

Table 3.

Metric	IRR (95% CI)	Relative Improvement
Organic Follower Growth	3.08 (2.52–3.76)	+208%
Conversion Rate	2.25 (1.91–2.64)	+125%

5.4 Cost Savings Calculation: Economic Value Verification

Based on TikTok Singapore advertising rates (CPM=$6.8, CPC=$0.85) and average technology category conversion costs ($12.3/order), achieving intervention period monthly sales of $8,420 (223 orders) would require $2,740 monthly paid advertising expenditure. Model optimization achieved zero ad spend, saving $2,740 monthly with 4.4-month payback period and cumulative $12,000 savings (discounted at 10% ≈ $11,700), representing 21% of initial inventory turnover capital and validating economic value under hard budget constraints. (Wang, X. Q., 2022)

6. Model Migration Application to U.S. Cross-Border Warehousing Industry

6.1 Marketing Challenges of U.S. Small-to-Medium Warehousing Companies and Model Adaptability

The U.S. third-party warehousing industry remains highly fragmented (2024 CR4<18%), with 82% regional operators facing "triple deficits": content generation deficit (difficulty visualizing warehousing processes), data tool deficit (lack of traffic optimization awareness), and cost tolerance deficit (net margins 6%-8%), resulting in 45-60 day customer acquisition cycles and median CPL of $180—significantly exceeding platform fulfillment centers (Li, W., 2025). The three-dimensional model naturally addresses these challenges: zero-ad-spend mode aligns with cost constraints, collaborative frameworks resolve content and tool deficits, and warehousing services share theoretical isomorphism with technology products regarding high-involvement and extended decision cycles, providing migration foundation.

6.2 Scenario Reconstruction: Theoretical Mapping from Technology Products to Warehousing Services

Grounded in service marketing theory and equivalence principles, we construct a "technology products—warehousing services" mapping framework: isomorphic decision logic (functional cognition—performance evaluation—price decision), directly transferable script skeletons replacing "unboxing parameter reviews" with "pallet process walkthroughs," cameras tracking U-shaped flow lines showcasing inbound, storage, picking, packaging, and outbound processes; product mix matrices map to "service package matrices" where high-margin-high-frequency corresponds to dropshipping, high-margin-low-frequency to returns refurbishment, low-margin-high-frequency to FBA forwarding, and low-margin-low-frequency to long-term storage, preserving optimization core logic.

6.3 Metric Mapping: Inventory Turnover Visualization and Script Optimization

Technology product "technical parameter visualization" maps to "inventory turnover visualization," integrating WMS APIs to transform 30-day turnover frequency into dynamic bar charts overlaid during feature demonstration segments. Pilot experiments show bar charts rising 0.8 times within 30 seconds increase retention by 12% and inquiry rates by 18%, consistent with technology product parameter display effects. Script module click-through rates (CR-Scr) are redefined as "bullet chat inquiry density per 100 characters within 10 seconds before/after bar charts," maintaining dimensional consistency. This approach projects CPL reduction to $90 and customer acquisition cycles shortened to within 30 days. (Zhong, Y., 2025)

7. Conclusions and Future Directions

7.1 Research Conclusions

This study addresses growth bottlenecks in zero-ad-spend TikTok technology live streaming through Singapore natural experiments, constructing and validating a three-dimensional optimization model of "time slots—scripts—product mix." Core conclusions include: (1) Time slot activity values, script click-through rates, and product mix conversion rates are key influencing variables in zero-ad-spend scenarios with significant synergistic effects; (2) Through three-level toolchains and dynamic closed loops, the model achieved 208% organic follower growth, 125% conversion improvement, 20.5% average order value increase, and $12,000 ad spend savings with robust effects; (3) The model is transferable to U.S. warehousing service scenarios, projecting 50% CPL reduction through process visualization and service package matrices.

7.2 Theoretical Contributions and Practical Implications

Theoretical contributions: (1) Constructing a three-dimensional collaborative optimization framework that overcomes fragmented analysis limitations; (2) Expanding research boundaries to zero-ad-spend and high-involvement categories, filling theoretical voids; (3) Innovating "natural experiment + online algorithm" methodologies, providing dynamic decision-making paradigms.

Practical implications: (1) Providing zero-ad-spend cold-start playbooks for cross-border e-commerce startups; (2) Offering low-cost customer acquisition pathways for cross-border service enterprises; (3) Delivering standardized optimization tools for platforms and service providers to facilitate SME digital transformation.

7.3 Research Limitations and Future Directions

Limitations: (1) Empirical setting focuses on Singapore technology products, requiring further cross-cultural and cross-category adaptability validation; (2) Qualitative moderating variables such as host characteristics remain unincluded; (3) 73-day data cycle necessitates long-term effect observation.

Future research should pursue: (1) Cross-regional and cross-category empirical testing of model universality; (2) Incorporating moderating variables like cultural distance and product complexity for deeper mechanism analysis; (3) Integrating deep learning optimization algorithms to construct intelligent dynamic systems; (4) Conducting multi-platform comparative studies to support omnichannel deployment decisions.

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The Path to Enhancing Corporate Inventory Turnover Efficiency Through Seamless Integration of ERP and WMS

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Abstract

Targeting the core pain points of slow inventory turnover in the fast-moving consumer goods (FMCG) industry, such as “data fragmentation, process disconnection, and cost-efficiency imbalance” in the integration of ERP and WMS, this paper constructs a three-tier enhancement model of “data integration – process reengineering – intelligent optimization.” It systematically reveals the internal transmission mechanism of “data granularity – process collaboration – inventory turnover rate.” Based on panel data from 15 FMCG companies with annual revenues of ≥5 billion yuan, an empirical comparison is conducted among the control group (traditional batch processing integration), experimental group 1 (only data integration), and experimental group 2 (full three-tier model). The study quantifies the efficiency differences and cost boundaries of different integration modes. The findings indicate that the three-tier model can reduce inventory turnover days from 45 days to 32 days (a relative improvement of 29%), lower the stockout rate to 3.2%, and decrease system maintenance costs by 38% compared to the “real-time synchronization” solution. The transmission coefficient of “data – process – efficiency” reaches 0.63 ($p<0.001$), and the optimal data synchronization frequency for the FMCG industry is 4 times per day (with a system load rate ≤60%) (Qi, Z., 2025). Case studies of Unilever and Nestlé Wyeth verify the practical effectiveness of the model and correct the traditional perception that “real-time integration is necessarily the best.” This paper provides a quantifiable and implementable path for the digital collaboration of supply chains in FMCG companies and enriches the theoretical system in the field of supply chain management and system integration.

Keywords: ERP, WMS, seamless integration, inventory turnover efficiency, three-tier enhancement model, transmission mechanism, FMCG industry, data granularity, process collaboration, synchronization frequency, critical point, intelligent optimization, process reengineering, data integration, LSTM demand forecasting

1. Introduction

1.1 Industry Background: The Real Dilemma of Inventory Management in the FMCG Industry

The FMCG industry is characterized by short product life cycles, frequent promotional activities, and diverse distribution channels, making inventory turnover efficiency a key competitive factor. The global average inventory turnover days stand at 45, while China's figure reaches 52 days. 35% of slow-moving inventory and 28% of urgent stockouts originate from the data asynchronization between ERP and WMS systems, resulting in an annual loss rate of over 8%. Traditional integration modes fail to meet the FMCG industry's needs for item-level inventory control and hourly order response, especially during promotional periods when data lag leads to a decision-making bias in replenishment of over 20%.

1.2 Theoretical Controversy: Cognitive Biases and Research Gaps in Existing Studies

Existing research focuses on the technical aspects of ERP and WMS integration, suggesting that real-time data synchronization can enhance inventory efficiency. However, there is a contradiction between corporate practice and theoretical consensus. For example, over-synchronization, such as synchronizing every 15 minutes, results in a system resource occupancy rate of over 80%, a threefold increase in maintenance costs, and no improvement in inventory efficiency. There is a lack of quantitative analysis of the "integration mode – system load – inventory efficiency" relationship, and the efficiency-cost critical point and optimal integration path have not been clarified, leading to a disconnection between theory and practice. The linear positive correlation between data synchronization frequency and inventory efficiency is questionable, and the contributions of process collaboration and intelligent decision-making have not been quantified.

2. Literature Review and Theoretical Foundation

2.1 Review and Critique of Related Literature

2.1.1 Research on ERP and WMS Integration

Existing studies concentrate on the technical implementation aspects, such as interface development (REST API and middleware), data format adaptation (XML and JSON), and optimization of data consistency verification. These studies mostly focus on technical feasibility and lack in-depth exploration of business process collaboration. They do not highlight the core goal of system integration serving business operations. The evaluation of effectiveness is mostly qualitative, and the few quantitative studies only use inventory turnover rate as an evaluation indicator, without considering key factors such as maintenance costs and stockout rates, resulting in incomplete evaluation results.

2.1.2 Research on Inventory Turnover Efficiency Influencing Factors

Traditional research focuses on improving demand forecasting accuracy, optimizing replenishment strategies, and strengthening supply chain collaboration. Some studies pay attention to the empowering role of new technologies such as big data and the Internet of Things in inventory management, but they do not take the "system integration mode" as a core explanatory variable and fail to recognize the foundational supporting role of ERP and WMS integration quality for inventory management.

2.1.3 Research on Data Collaboration and Process Optimization

Data collaboration research confirms that "item-level data" compared to "batch-level data" can significantly improve decision-making accuracy. However, it does not combine the ERP and WMS system integration scenario and does not explain how to achieve optimization and upgrading of data granularity through system integration and its impact path on inventory management. Process optimization research emphasizes the importance of "data-driven process reengineering," but it does not construct a complete transmission framework of "data – process – efficiency" and lacks practical guidance.

2.2 Core Theoretical Support

Synergetics provides the theoretical foundation for constructing the three-tier collaborative model of "data – process – intelligence," emphasizing the complementary and interactive effects among various elements within a system, which is consistent with the design logic of the three-tier model. Data governance theory guides the practice of the first-tier "data integration" stage, clarifies field-level mapping and real-time verification mechanisms, and ensures the accuracy, completeness, and timeliness of data. Business Process Reengineering (BPR) supports the second-tier "process reengineering" stage, fundamentally reengineering core business processes with data-driven approaches to achieve deep collaboration between business processes and system data. The cost-benefit theory provides the basis for calculating the critical point of "synchronization frequency – system load – inventory efficiency," balancing the relationship between efficiency and cost to avoid over-pursuing efficiency while neglecting cost.

3. Theoretical Model and Transmission Mechanism Construction

3.1 Definition of Core Concepts

Seamless integration of ERP and WMS refers to the advanced integration of the two systems through data standardization, interface adaptation, process collaboration, and intelligent empowerment, covering three core dimensions of data interaction, process linkage, and decision support, rather than being limited to the simple technical connectivity. Data granularity represents the degree of refinement of inventory data, specifically defined as “core field coverage × data update frequency,” mainly divided into two levels: “batch-level” and “item-level.” The “batch-level” corresponds to 12 core fields and a daily update frequency of 1 time, while the “item-level” extends to 28 core fields and a daily update frequency of 4 times, significantly improving data dimensions and timeliness. Process collaboration degree measures the response matching degree of business processes such as replenishment, picking, outbound, and allocation with system data, quantified by “process automation rate × decision delay time,” with higher values indicating stronger collaboration and adaptation between processes and data. Inventory turnover efficiency is comprehensively evaluated using a three-dimensional indicator system, with the core indicator being inventory turnover days, auxiliary indicators including stockout rate and slow-moving inventory ratio, and boundary indicators being system maintenance costs, fully considering efficiency, benefit, and cost dimensions.

3.2 The Three-Tier Enhancement Model of “Data Integration – Process Reengineering – Intelligent Optimization”

3.2.1 Tier One: Data Integration (Basic Layer) – Eliminating Data Fragmentation

Tier one data integration, as the basic layer of the entire model, aims to achieve seamless and high-timeliness synchronization of ERP and WMS data, refine data granularity from traditional “batch-level” to “item-level,” and fundamentally eliminate data fragmentation. The key technical paths of this tier include three core aspects: Field-level mapping needs to comprehensively cover 28 core business fields such as inventory quantity, batch, expiry date, storage location, and quality inspection status, achieving precise correspondence and bias-free transmission of “field - field” between the two systems. The real-time verification mechanism needs to establish a strict data consistency verification algorithm, controlling the error threshold within 0.3%, and automatically warning and triggering manual review processes once data anomalies occur to ensure data accuracy. Dynamic adaptation of synchronization frequency is based on order volume fluctuations to flexibly adjust synchronization intervals, avoiding the problems of data lag during order peaks and resource waste during low peaks under fixed frequency modes. Through these technical means, the quantifiable outcomes of the data integration stage are significant, with data dimensions increased by 68% compared to traditional models, data synchronization error rate reduced to below 0.2%, and data availability improved to 99.7%, laying a solid data foundation for subsequent process optimization and intelligent decision-making.

Table 1.

Quantifiable Outcome	Description
Data Dimension Increase	Increased by 68% compared to traditional models
Data Synchronization Error Rate	Reduced to below 0.2%
Data Availability	Improved to 99.7%

3.2.2 Tier Two: Process Reengineering (Core Layer) – Achieving Data-Driven Processes

Tier two process reengineering, as the core layer of the model, aims to systematically reengineer the entire inventory management process based on the real-time “item-level” data from tier one, significantly enhance process collaboration degree, and truly realize the driving effect of data on business. The key process optimizations focus on three core links: The replenishment process transitions from traditional “Push-style batch replenishment” to “Pull-style dynamic replenishment,” abandoning the fixed replenishment mode based solely on historical sales and instead dynamically adjusting the replenishment trigger threshold in combination with real-time inventory data and immediate order demand to ensure replenishment accuracy. The picking process introduces a "storage location – order" matching algorithm, optimizing picking paths based on real-time storage location data and order product combinations to reduce unnecessary movement and repetitive operations, thereby improving picking efficiency. The outbound verification process achieves real-time automatic comparison between ERP order data and WMS outbound data, replacing 80% of manual operations with system verification, which not only speeds up the verification process but also reduces human errors. The quantifiable outcomes of process reengineering are very significant, with replenishment response time shortened from 2 hours to 15 minutes, picking efficiency increased by 30%, and outbound error rate reduced to below 0.5%, achieving dual improvements in process collaboration degree and operational efficiency. (Li, W., 2025)

3.2.3 Tier Three: Intelligent Optimization (Empowerment Layer) – Enhancing Decision-Making Precision

Tier three intelligent optimization, as the empowerment layer of the model, aims to achieve intelligent forecasting and dynamic optimization of inventory decisions based on real-time synchronized inventory, order, promotion, and other multidimensional data, converting data value into decision-making advantages. The key technology applications focus on three core functions: The LSTM demand forecasting model integrates multi-source information such as 12 months of historical inventory data, promotion activity records, and market demand indices to accurately forecast the demand for segmented SKUs within 3 days, achieving a forecasting accuracy rate of 89.7%. The intelligent allocation algorithm dynamically allocates inventory resources based on real-time inventory data across regions and warehouses, effectively balancing stockout risks and slow-moving pressures in different areas to achieve optimal global inventory configuration. The safety stock dynamic setting adjusts the safety stock threshold in real-time based on the variance of demand forecasting, avoiding the problems of overstocking or insufficient stocking under the traditional fixed threshold mode. These intelligent technologies bring significant quantifiable outcomes, with demand forecasting deviation rate reduced to 10.3%, safety stock rationality increased by 40%, cross-regional allocation efficiency improved by 50%, and significantly enhanced scientificity and foresight in inventory decision-making.

Table 2.

Quantifiable Outcome	**Description**
Demand Forecasting Deviation Rate	Reduced to 10.3%
Safety Stock Rationality	Increased by 40%
Cross-Regional Allocation Efficiency	Improved by 50%
Inventory Decision-Making Scientificity and Foresight	Significantly enhanced

3.3 Transmission Mechanism and Critical Point Calculation

3.3.1 "Data Granularity – Process Collaboration Degree – Inventory Turnover Rate" Transmission Mechanism

The enhancement of inventory turnover efficiency through seamless integration of ERP and WMS follows the core transmission path of "data granularity – process collaboration degree – inventory turnover rate." The refinement of data granularity directly promotes the improvement of process collaboration degree, which in turn facilitates the optimization of inventory turnover rate. The process collaboration degree plays a complete mediating effect in the entire transmission process, serving as the key bridge connecting data value and efficiency improvement. Through structural equation modeling for quantification, the influence coefficient of data granularity on process collaboration degree is 0.72, and the influence coefficient of process collaboration degree on inventory turnover rate is 0.87, resulting in a total transmission coefficient of 0.63. This indicates that the optimization of data granularity can significantly positively impact inventory turnover efficiency through the mediating role of process collaboration, with a clear and significant transmission path.

3.3.2 Optimal Synchronization Frequency Critical Point Calculation

To balance the efficiency benefits of data synchronization with system costs, a ternary relationship model is constructed with data synchronization frequency as the independent variable and system load rate and inventory turnover days as dependent variables. Two core regression equations are established. The system load rate regression equation is $C=0.02f2+0.5f+30$, with a goodness of fit of 0.89. The inventory turnover days regression equation is $T=-1.2f+45$, with a goodness of fit of 0.85, and this equation is valid within the range of synchronization frequency not exceeding 6 times per day. Based on the historical data of 15 sample companies from 2022 to 2023, 1000 Monte Carlo simulations are conducted with the constraint that the system load rate does not exceed 60% (Qi, Z., 2025). The optimal synchronization frequency for the FMCG industry is determined to be 4 times per day. This critical point has distinct characteristics. At this point, the system load rate is 58%, within a reasonable and controllable range, and the inventory turnover days are reduced to 39.8 days, representing an 11.5% improvement compared to the traditional once-daily synchronization mode, achieving a Pareto optimum of "efficiency – cost." The data synchronization frequency fully leverages the efficiency value of data synchronization while avoiding resource waste due to excessive synchronization.

Table 3.

Description	Value
Number of simulations based on sample data	1000 times
Optimal data synchronization frequency under constraint conditions	4 times per day
System load rate at optimal synchronization frequency	58%
Inventory turnover days at optimal synchronization frequency	39.8 days
Efficiency improvement compared to traditional once-daily synchronization mode	11.5%

4. Empirical Analysis and Results

4.1 Research Design

The sample selection includes 15 FMCG companies from January 2022 to December 2023, with annual revenues of no less than 5 billion yuan, covering industries such as food and beverages, daily chemicals, and maternal and infant products. The groups are divided into: control group (traditional batch processing mode, 5 companies), experimental group 1 (only data integration, 5 companies), and experimental group 2 (complete three-tier model, 5 companies). The data sources include ERP and WMS system data, annual reports, and field research interviews, which have been desensitized. Variable definitions: The explained variable is inventory turnover efficiency (inventory turnover days, stockout rate, slow-moving inventory ratio); the explanatory variable is the integration mode (coded as 0, 1, 2); the mediating variable is process collaboration degree (process automation rate × 1/decision delay time); control variables include company size (annual revenue, number of employees) and business characteristics (SKU quantity, promotion frequency, channel quantity). The analysis methods include descriptive statistics, multiple linear regression, Bootstrap mediating effect test, robustness test, and Monte Carlo simulation.

4.2 Empirical Results Analysis

The descriptive statistics show that the control group has an average inventory turnover days of 45, stockout rate of 11.5%, slow-moving inventory ratio of 8.3%, system load rate of 35%, and daily maintenance cost of 12,000 yuan. Experimental group 1 has turnover days of 39, stockout rate of 7.8%, slow-moving inventory ratio of 5.9%, system load rate of 48%, and daily maintenance cost of 18,000 yuan. Experimental group 2 has turnover days of 32, stockout rate of 3.2%, slow-moving inventory ratio of 4.9%, system load rate of 58%, and daily maintenance cost of 21,000 yuan. In contrast, companies with real-time synchronization have a daily maintenance cost as high as 34,000 yuan (Li, W., 2025), further highlighting the cost advantage of the three-tier model. The regression analysis results indicate that the inventory turnover days of experimental group 2 are significantly lower than those of the control group, with a regression coefficient of -13.2. The inventory turnover days of experimental group 1 are also significantly lower than those of the control group, with a regression coefficient of -6.1, thus verifying the optimality of the three-tier model. The mediating effect of process collaboration degree is significant, with its 95% confidence interval ranging from 4.2 to 7.8, accounting for 68.5% of the total effect. The robustness test results show that the regression coefficient remains significant at -0.03 after variable replacement, indicating that the research results have high robustness. In terms of critical point verification, the optimal synchronization frequency is 4 times per day, at which the system load rate is 58%, and the inventory turnover days are improved by 11.5% compared to the traditional mode. However, when the synchronization frequency exceeds 6 times per day, the system load rate will break through 60%, and the decrease in inventory turnover days does not exceed 1%, showing a marginal benefit diminishing situation.

4.3 Typical Case Verification

Unilever, in the second quarter of 2022, had an inventory turnover days of 42, stockout rate of 15%, and promotional period capital occupation as high as 230 million yuan when using the traditional mode. After implementing the three-tier model, in the fourth quarter of 2023, the inventory turnover days were reduced to 25, the stockout rate dropped to 2.8%, (Zhong, Y., 2025) and the quarterly capital occupation was reduced by 80 million yuan, with a system load rate of 55%, achieving optimization of efficiency and cost. Nestlé Wyeth, in 2021, had a system load rate as high as 78% when using the "hourly synchronization" mode, with a stockout rate of 12% and daily maintenance cost of 34,000 yuan. After transitioning to the three-tier model, the stockout rate dropped to 3.5%, the system load rate was 56%, and the daily maintenance cost was reduced to 21,000 yuan, with significant cost reduction and efficiency improvement effects, thus verifying the adaptability and effectiveness of the model.

Table 4.

Time Period	Inventory Turnover Days (days)	Stockout Rate (%)	Capital Occupation (ten thousand yuan)	System Load Rate (%)	Daily Maintenance Cost (ten thousand yuan)
Q2 2022	42	15	23000	-	-
Q4 2023	25	2.8	15000	55	-
2021	-	12	-	78	3.4
Post-Transition	-	3.5	-	56	2.1

5. Practical Implications

5.1 Practical Implications

5.1.1 Implementation Path for Large FMCG Companies

Targeting the characteristics of large FMCG companies, such as large scale, complex business, and abundant resources, a phased and systematic implementation path is proposed. The step-by-step implementation strategy follows the logic of "foundation first, core breakthrough, and empowerment upgrade." The data integration phase is completed in 6-8 weeks to achieve precise field mapping and synchronization frequency optimization of core fields, solidifying the data foundation. The process reengineering phase focuses on optimizing three core processes: replenishment, picking, and outbound, to realize the driving effect of data on business, which takes 12-16 weeks. The intelligent optimization module is launched in the final 8-10 weeks, integrating LSTM forecasting and intelligent allocation functions to complete the full process intelligent upgrade. In terms of technology selection, it is recommended to prioritize REST API interfaces for precise field mapping and choose lightweight LSTM models suitable for the FMCG industry's needs, avoiding the resource waste and cost surge caused by blindly pursuing "real-time synchronization." For organizational support, a cross-departmental special team comprising the IT department, supply chain department, and sales department should be established to unify data standards and process norms, and a quarterly routine effect evaluation mechanism should be set up to continuously monitor core indicators such as inventory turnover and system costs, ensuring the implementation effects are realized and dynamically optimized.

5.1.2 Adaptation Plan for SMEs

Considering the limited resources and high cost sensitivity of SMEs, a lightweight and low-cost adaptation plan is designed. In terms of implementation priority, priority is given to realizing data integration of 15-20 core business fields and basic process optimizations such as dynamic replenishment, while postponing the investment in the intelligent optimization module, which can reduce the total implementation cost by 40% (Haoyang Huang, 2025). The synchronization frequency should be dynamically adjusted based on the company's SKU quantity. When the SKU quantity is less than 1000, a daily synchronization frequency of 2-3 times can meet the needs. When the SKU quantity reaches 1000 and above, the optimal frequency of 4 times per day should be adopted to balance efficiency and cost. In terms of cooperation mode, it is recommended to use mature SaaS solutions such as Yonyou YonBIP and Kingdee K/3 WISE, leveraging the power of external professional technical service providers to reduce the human and financial investment in independent development and later maintenance, lowering the implementation threshold and operational risks.

5.2 Limitations and Future Outlook

This study has certain limitations. The sample selection focuses on the FMCG industry and does not cover short shelf-life industries such as fresh produce and pharmaceuticals, which have different product characteristics and inventory management requirements, and the model's applicability still needs further verification. During the research process, extreme market environments such as sudden pandemics and raw material shortages were not fully considered, and the model's adaptability to complex external environments needs to be improved. Additionally, the study did not involve the application of new technologies such as blockchain in data security and traceability, failing to comprehensively cover the security dimension of system integration. Future research can be expanded in several directions: First, extend the application scenarios of the model to short shelf-life industries such as fresh produce and pharmaceuticals, and optimize model parameters and implementation paths based on industry characteristics. Second, integrate real-time storage location data from the Internet of Things and blockchain data traceability technology to improve the model's accuracy and data security. Third, further consider regulatory variables such as supply chain complexity and market competition intensity to perfect the "data – process – efficiency" transmission mechanism, making the research conclusions more universal and in-depth. Fourth, explore the in-depth application of AI large models in intelligent decision-making to further enhance the intelligence level of inventory management.

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Data-Driven Decision-Making Model for Overseas Market Growth of U.S. Enterprises in the Digital Economy Era: Theoretical Construction and Empirical Research

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Abstract

The global digital economy reached a scale of 55.3 trillion US dollars in 2024, accounting for 47.6% of the global GDP. The proportion of overseas revenue of U.S. enterprises has been continuously increasing, with the average for S&P 500 enterprises reaching 38.2% in 2023. Data has become a core production input for enterprises' overseas expansion. This study aims to construct a data-driven decision-making model for the overseas market growth of U.S. enterprises in the digital economy context, and to reveal the inherent relationship between data resources, analytical capabilities, and growth performance. A mixed research method is adopted, including panel data regression, structural equation modeling, and multiple case studies. The core innovation lies in constructing a full-chain theoretical model of "data resources – data capabilities – decision-making efficiency – growth performance" and quantifying the contribution coefficient of data-driven approaches. This research enriches the international business theory system and provides a quantifiable decision-making framework for U.S. enterprises in formulating overseas strategies.

Keywords: digital economy, U.S. enterprises, overseas market growth, data-driven decision-making, decision-making model, multinational enterprises, data resources, data analytical capabilities, decision-making efficiency, market adaptability, digital maturity, cultural distance, institutional environment

1. Introduction

1.1 Research Background

The digital penetration rate of the global digital economy continues to rise. In 2023, the average investment in digital transformation by enterprises accounted for 15.7%, and the annual growth rate of cross-border data flow reached 28.3%. From 2018 to 2023, the compound annual growth rate (CAGR) of overseas revenue of U.S. enterprises was 6.8%, but 37.2% of enterprises reported insufficient overseas decision-making efficiency. In contrast, enterprises adopting data-driven decision-making achieved an average overseas return on investment (ROI) 19.4% higher than the industry average.

Table 1.

Indicator Name	Value/Proportion
Average investment proportion in digital transformation by enterprises in 2023	15.7%
Annual growth rate of cross-border data flow	28.3%
Compound annual growth rate of overseas revenue of U.S. enterprises (2018-2023)	6.8%
Proportion of enterprises reporting insufficient overseas decision-making efficiency	37.2%
Overseas ROI of enterprises adopting data-driven decision-making (higher than industry average)	19.4%

1.2 Research Questions

The core question is what kind of data-driven decision-making model U.S. enterprises should construct to achieve sustainable growth in overseas markets in the digital economy era. Sub-questions focus on how to quantify the core dimensions of data-driven decision-making, what the mechanism of action and moderating factors are, and whether there are impacts of industry and enterprise size heterogeneity.

1.3 Research Significance

- **Theoretical Significance:** This study breaks through the limitations of the resource-based view and location advantage theory in traditional international business theories, constructs a new analytical framework of "data – capabilities – growth", and improves the theoretical system of data-driven decision-making in cross-border scenarios. Meanwhile, it expands the OLI paradigm of the eclectic theory of international production by adding the dimension of "data advantage", providing a new perspective for theoretical research on the overseas expansion of multinational enterprises in the digital economy era, and filling the gap in existing research regarding the insufficient quantitative analysis of the mechanism of action of data-driven approaches.
- **Practical Significance:** It provides an operable decision-making model for U.S. enterprises in overseas market entry, expansion, and optimization, clarifying specific directions for data resource reserve, improvement of data analytical capabilities, and optimization of decision-making mechanisms. The goal is to reduce the decision-making error rate by more than 25%.

2. Literature Review and Theoretical Foundations

2.1 Review of Relevant Research

Research related to the digital economy focuses on three major areas: digital transformation, cross-border data flow, and digital technology application. A bibliometric analysis of 1,286 papers from the Web of Science Core Collection between 2018 and 2023 clearly shows this research trend. Studies on overseas market growth mostly adopt single indicators such as market share growth rate and overseas revenue proportion. Only 32.7% of existing literature involves data elements, indicating insufficient attention to data-driven approaches. Relevant research on data-driven decision-making has proposed an analytical framework of "data resources – data capabilities – decision-making behavior – performance", but lacks attention to cross-border data integration and localized data adaptation in cross-border scenarios. Meta-analysis shows that its average effect size on enterprise performance is 0.23, while the effect size in overseas market scenarios is only 0.17, indicating a significant research gap.

2.2 Core Theoretical Foundations

The dynamic capability theory defines data-driven capabilities as a core component of the dynamic capabilities of multinational enterprises, explaining how enterprises achieve strategic adaptation in overseas markets through data integration, analysis, and application. The eclectic theory of international production expands the OLI paradigm by adding the "data advantage" dimension, constructing a new theoretical framework for the overseas market entry of multinational enterprises in the digital economy. The data asset theory clarifies the value measurement standards of data as an intangible asset, distinguishing between the "stock value" and "incremental value" of data resources, providing a solid theoretical basis for the quantification of data elements in the model. These three theories complement each other and jointly form the theoretical cornerstone of this study.

2.3 Literature Review and Research Gaps

Existing studies exhibit significant limitations: there is a lack of data-driven decision-making models specifically for the overseas market growth of U.S. enterprises in the digital economy era, insufficient quantitative analysis of the mechanism of action of data-driven approaches, and neglect of the impacts of moderating variables such as industry heterogeneity and institutional distance. This study accurately addresses this research gap, constructing a verifiable and applicable theoretical model through a combination of quantitative and qualitative methods, filling the research gap of data-driven decision-making models in cross-border scenarios, and enriching research results in related fields.

3. Research Design and Research Hypotheses

3.1 Construction of Research Framework

The core logical chain of the research framework is: data-driven decision-making as the independent variable affects overseas market growth performance (the dependent variable) through two mediating variables, namely decision-making efficiency and market adaptability, while being regulated by three types of moderating variables: digital maturity, cultural distance, and institutional environment. The framework clarifies the core connotations and measurement boundaries of each variable, forming a complete logical system of "input – mediation – output – moderation", laying the foundation for the subsequent proposal of research hypotheses and empirical testing.

3.2 Variable Definition and Measurement

The independent variable, data-driven decision-making, includes three dimensions: data resource reserve (involving cross-border data coverage rate, local data quality, and data compliance), data analytical capabilities (covering the application level of big data processing technology, AI algorithm adaptability, and data interpretation capabilities), and decision-making mechanism optimization (including the standardization of data-driven decision-making processes, cross-departmental data collaboration efficiency, and decision-making feedback iteration speed). A 7-point Likert scale is used to design questionnaire items, combined with cross-validation of objective data. For mediating variables: decision-making efficiency is measured by decision-making cycle reduction rate, decision-making error rate, and resource allocation optimization level; market adaptability is verified by the localization adaptability of products and services, market demand response speed, and the accuracy of competitive strategies. The dependent variable, overseas market growth performance, constructs a multi-dimensional indicator system including three levels: growth scale, growth quality, and growth potential. Data is sourced from enterprise annual reports, the BVD database, and the U.S. Department of Commerce International Trade Database. For moderating variables: digital maturity is measured by the digital maturity index; cultural distance is based on Hofstede's cultural dimension index; institutional environment selects three dimensions from the World Bank's Worldwide Governance Indicators: rule of law, regulatory quality, and control of corruption.

3.3 Research Hypotheses

- **Direct Effect Hypothesis:** Data-driven decision-making and its three dimensions (data resource reserve, data analytical capabilities, and decision-making mechanism optimization) all have a significant positive impact on the overseas market growth performance of U.S. enterprises.
- **Mediation Effect Hypothesis:** Decision-making efficiency and market adaptability play a partial mediating role between data-driven decision-making and overseas market growth performance, and there is a chain mediating effect between them.
- **Moderation Effect Hypothesis:** Digital maturity positively moderates the impact of data-driven decision-making on overseas market growth performance; cultural distance negatively moderates this impact; institutional environment positively moderates this impact.
- **Heterogeneity Hypothesis:** The impact of data-driven decision-making on overseas market growth performance is stronger in technology industry enterprises than in

retail and manufacturing enterprises, and stronger in large enterprises than in small and medium-sized enterprises.

4. Current Situation Analysis

4.1 Current Situation of Overseas Market Growth of U.S. Enterprises

From 2014 to 2023, the overseas revenue of U.S. multinational enterprises increased from 6.2 trillion US dollars to 9.8 trillion US dollars, with a CAGR of 5.1%, and the average overseas market share increased by 4.3 percentage points. There are significant industry differences: the CAGR of overseas revenue in the technology industry is 7.8%, 4.2% in the retail industry, and 3.9% in the manufacturing industry (Agrawal, A., Gans, J., & Goldfarb, A., 2018). Overseas profit margins also show a gradient distribution: 18.7% in the technology industry, 12.3% in the retail industry, and 9.5% in the manufacturing industry. In terms of regional distribution, North America (excluding the U.S.), Europe, and the Asia-Pacific region are the main overseas markets, accounting for 32.1%, 28.7%, and 25.3% of revenue respectively. From 2020 to 2023, the Asia-Pacific region achieved the fastest growth with a CAGR of 6.5%, becoming the core growth driver for U.S. enterprises overseas.

Table 2.

Indicator	Value
Total overseas revenue in 2014	6.2 trillion US dollars
Total overseas revenue in 2023	9.8 trillion US dollars
Compound annual growth rate	5.1%
Average increase in overseas market share	4.3 percentage points

4.2 Current Situation of Data-Driven Decision-Making Application

In terms of data resource reserve of U.S. enterprises: the average cross-border data coverage rate is 68.3%, the average local market data quality score is 6.7 points, and 83.2% of enterprises have established data compliance management systems. Regarding data analytical capabilities: 76.5% of enterprises apply big data processing technology, 48.7% of enterprises use AI algorithms for market decision-making, and the average data interpretation capability score is 6.2 points. In terms of decision-making mechanism optimization: the standardization rate of data-driven decision-making processes is 62.1%, the average cross-departmental data collaboration efficiency score is 5.8 points, and only 37.9% of enterprises have established decision-making feedback iteration mechanisms. The overall application level shows an unbalanced trend. (Benitez, J., Arenas, A., Castillo, A., & Esteves, J., 2020)

Table 3.

Indicator Name	Value
Cross-border data coverage rate	68.3%
Local market data quality score	6.7 points
Proportion of enterprises with established data compliance management systems	83.2%
Proportion of enterprises applying big data processing technology	76.5%
Proportion of enterprises using AI algorithms for market decision-making	48.7%
Data interpretation capability score	6.2 points
Standardization rate of data-driven decision-making processes	62.1%
Cross-departmental data collaboration efficiency score	5.8 points
Proportion of enterprises with established decision-making feedback iteration mechanisms	37.9%

4.3 Preliminary Correlation Analysis

Correlation statistics show that the correlation coefficient between data-driven decision-making as a whole and overseas market growth performance is 0.47, which is statistically significant. In terms of dimensional correlations: the correlation coefficient of data resource reserve is 0.38, that of data analytical capabilities is 0.52, and that of decision-making mechanism optimization is 0.43, all of which are significantly positively correlated with overseas market growth performance. Among them, data analytical capabilities have the highest correlation. Significant industry differences exist: the correlation in the technology industry is higher than that in the retail and manufacturing industries, confirming that the application effects of data-driven decision-making vary across different industries.

4.4 Core Challenges

At the data level: 38.6% of enterprises report facing restrictions on cross-border data flow, 42.3% of enterprises consider local data acquisition difficult, and the problem of uneven data quality is widespread. At the capability level: the mismatch between data analytical technology and overseas market demand, barriers to cross-departmental data collaboration, and lack of data interpretation capabilities have become restrictive factors. At the decision-making level: the non-standardized processes of data-driven decision-making, slow decision-making feedback iteration, and insufficient consideration of the impacts of cultural and institutional differences on decision-making effects. These challenges collectively affect the application effectiveness of data-driven decision-making in overseas markets.

5. Model Construction and Empirical Testing

5.1 Model Framework

The core framework of the model follows the logical structure of input layer, processing layer, output layer, moderation layer, and feedback layer. The input layer consists of data resources, including cross-border data and local data. The processing layer covers data analytical capabilities and decision-making mechanisms: data analytical capabilities involve technology application and interpretation capabilities; decision-making mechanisms include process standardization, collaboration efficiency, and feedback iteration. The output layer is overseas market growth performance, including three dimensions: scale, quality, and potential. The moderation layer includes digital maturity, cultural distance, and institutional environment. The feedback layer optimizes data resources and processing mechanisms based on growth performance, forming a complete dynamic closed loop.

5.2 Data Quality Testing

A total of 500 online questionnaires were distributed in the formal survey, 412 were recovered, and 368 were valid, with an effective recovery rate of 73.6%, which meets the sample size requirements for empirical analysis. Reliability test results show that the Cronbach's α coefficients of each dimension of data-driven decision-making range from 0.82 to 0.91, the overall α coefficient is 0.93, and the α coefficient of overseas market growth performance is 0.87, all meeting reliability requirements. Confirmatory factor analysis results show that the model fit indicators are $\chi^2/df=2.37$, RMSEA=0.062, GFI=0.88, AGFI=0.85, NFI=0.90, and CFI=0.93, all meeting fit standards. Convergent validity and discriminant validity are also qualified, indicating good data quality.

5.3 Hypothesis Testing Results

Structural equation modeling analysis shows that the direct effect coefficient of data-driven decision-making on overseas market growth performance is 0.42, which is statistically significant, supporting the direct effect hypothesis. Among them, the effect coefficient of data analytical capabilities is 0.31, which is the most influential dimension, while the effect coefficients of data resource reserve and decision-making mechanism optimization are 0.23 and 0.27 respectively. The mediation effect test adopts the Bootstrap method with 5,000 sampling times. The results show that the mediation effect coefficient of decision-making efficiency is 0.15 (95% confidence interval does not include 0), the mediation effect coefficient of market adaptability is 0.18 (95% confidence interval does not include 0), and the chain mediation effect coefficient from decision-making efficiency to market adaptability is 0.09 (95% confidence interval does not include 0). Thus, the mediation effect hypothesis is supported, and the mediation effect accounts for 81.0% of the total effect. Moderation effect testing shows that the interaction term coefficient of digital maturity is

0.12, that of cultural distance is -0.10, and that of institutional environment is 0.09, all of which are statistically significant, supporting the moderation effect hypothesis. Multi-group analysis shows that the effect coefficient of data-driven decision-making on overseas market growth performance is 0.53 in the technology industry, significantly higher than 0.41 in the retail industry and 0.36 in the manufacturing industry; the effect coefficient for large enterprises is 0.48 (Teece, D. J., 2007), significantly higher than 0.35 for small and medium-sized enterprises, supporting the heterogeneity hypothesis. Robustness testing is conducted by replacing the measurement indicators of the dependent variable and adjusting the sample interval, and the results are consistent with the original test, indicating good model robustness.

6. Case Analysis

6.1 Case Selection

Case enterprises are selected based on the principles of representativeness, typicality, and data availability, covering three major industries (technology, retail, and manufacturing). All are U.S. multinational enterprises with overseas business in no less than 30 countries or regions, and sufficient publicly disclosed data on digital transformation, overseas market strategies, and financial performance. Finally, Twilio (technology industry, cloud communication service provider), Fastenal (manufacturing industry, industrial supply chain solutions provider), and The Container Store (retail industry, home furnishing retail chain) are selected as case enterprises to verify the validity of the model through multiple case studies.

6.2 Analysis of Case Practices

For Twilio, in terms of data resource reserve: the cross-border data coverage rate reaches 89.7%, the local market data quality score is 8.2 points, and a regional data integration platform has been built, focusing on integrating overseas customer communication data, market demand data, and compliance data. Regarding data analytical capabilities: machine learning algorithms are used to optimize the adaptability of overseas communication services, the accuracy of customer demand response reaches 86.5%, and dynamic adjustment of service packages is achieved through data modeling, increasing the renewal rate of overseas customers by 21.3%. In terms of decision-making mechanism optimization: a closed loop of “data collection – analysis – decision-making – review” is established, the cross-departmental data collaboration efficiency score is 7.9 points, and the decision-making feedback iteration cycle is controlled within 10 days (Wamba, S. F., Gunasekaran, A., Akter, S., Ren, S., Dubey, R., & Childe, S. J., 2017). From 2018 to 2023, the CAGR of overseas revenue was 9.8%, the overseas market share increased by 5.2 percentage points, and the overseas profit margin was 15.6%.

Table 4.

Specific Indicator	Value
Cross-border data coverage rate	89.7%
Local market data quality score	8.2 points
Accuracy of customer demand response	86.5%
Increase in overseas customer renewal rate	21.3%
Compound annual growth rate of overseas revenue (2018-2023)	9.8%
Increase in overseas market share	5.2 percentage points
Overseas profit margin	15.6%

Fastenal data resource reserve focuses on overseas supply chain data, local warehousing data, and customer order data: the cross-border data coverage rate is 75.3%, and the local market data quality score is 7.3 points. Data analytical capabilities are applied to overseas inventory allocation and supply chain optimization: inventory backlog rate is reduced by 18.7% through data prediction, and logistics and distribution efficiency is improved by 24.5%. In terms of decision-making mechanism: the standardization rate of data-driven decision-making processes is 78.6%, the cross-departmental data collaboration efficiency score is 6.9 points, and the decision-making feedback iteration cycle is 18 days. From 2018 to 2023, the CAGR of overseas revenue was 4.1%, the overseas market share increased by 1.8 percentage points, and the overseas profit margin was 9.8%.

The Container Store data resource integration focuses on overseas store sales data, member preference data, and local consumption trend data: the cross-border data coverage rate is 80.5%, and the local market data quality score is 7.6 points. Data analytical capabilities are mainly reflected in product selection optimization and precise delivery of marketing activities: the proportion of unsold products in overseas stores is reduced by 16.3%, and the conversion rate of marketing activities is increased by 19.2%. In terms of decision-making mechanism optimization: the standardization rate of data-driven decision-making processes is 73.2%, the cross-departmental data collaboration efficiency score is 6.5 points, and the decision-making feedback iteration cycle is 15 days. From 2018 to 2023, the CAGR of overseas revenue was 5.3%, the overseas market share increased by 3.1 percentage points, and the overseas profit margin was 11.4%. (Qi, Z., 2025)

6.3 Model Validation and Implications

A horizontal comparison of the three enterprises shows that the level of data-driven decision-making follows the trend of Twilio > The Container Store > Fastenal, and the overseas market growth performance shows the same gradient distribution, verifying the direct effect of the model. Regarding the impact of moderating variables: Twilio faces large cultural distance and a complex institutional environment in the Southeast Asian market. By strengthening local data collection and compliance analysis, the local data quality score reaches 8.5 points, effectively mitigating the negative impacts of cultural distance and institutional environment, verifying the moderation effect. In terms of model adaptability: Twilio in the technology industry's core advantage in data-driven decision-making lies in the application of data analytical technology; The Container Store in the retail industry excels in consumer data integration; Fastenal in the manufacturing industry focuses on the standardization of supply chain data-driven decision-making, verifying the heterogeneity hypothesis.

Case implications: At the data resource level, enterprises should balance cross-border data integration and local data cultivation, and optimize data resource allocation according to the characteristics of target markets. At the capability building level, enterprises need to clarify the focus of core capabilities in combination with industry characteristics. At the decision-making mechanism level, enterprises should establish a rapid feedback and iteration decision-making closed loop to improve the response speed to changes in overseas markets.

7. Research Conclusions and Prospects

7.1 Research Conclusions

This study constructs a data-driven decision-making model for the overseas market growth of U.S. enterprises in the digital economy era, following the logic of "input – processing – output – moderation – feedback". Through three dimensions (data resource reserve, data analytical capabilities, and decision-making mechanism optimization), the model positively affects overseas market growth performance through the mediating role of decision-making efficiency and market adaptability. This impact is moderated by digital maturity, cultural distance, and institutional environment, with significant industry and enterprise size heterogeneity. Data analytical capabilities have the strongest impact on overseas market growth performance; decision-making efficiency and market adaptability have significant mediation effects, including a chain mediation effect. Digital maturity and institutional environment positively moderate the model relationship, while cultural distance negatively moderates it. Data-driven decision-making is more effective in the technology industry and large enterprises.

7.2 Theoretical and Practical Contributions

- **Theoretical Contributions:** This study enriches the interdisciplinary research between digital economy and international business, introduces data elements into the research on the overseas market growth of multinational enterprises, constructs a theoretical model of data-driven decision-making, and expands the research boundary of international business theory. It improves the theoretical system of data-driven decision-making, clarifies the dimensional composition, mechanism of action, and moderating factors of data-driven decision-making in cross-border scenarios, providing empirical support for the application of data-driven decision-making theory in the field of international business. It deepens the research on the influencing factors of overseas market growth, reveals the impact mechanism of data-driven approaches as a new type of factor on overseas market growth, and makes up for the deficiency of traditional research in paying insufficient attention to digital elements.

- **Practical Contributions:** For U.S. enterprises: They should attach importance to the core role of data-driven decision-making in overseas market growth, and targetedly optimize data resource reserve, improve data analytical capabilities, and improve decision-making mechanisms according to their own industry characteristics, scale, and target market characteristics. They should also pay attention to the impacts of factors such as digital maturity, cultural distance, and institutional environment, and flexibly adjust application strategies. For multinational enterprises from other countries: They can learn from the data-driven decision-making model of U.S. enterprises, combine their own national conditions and enterprise reality to construct a suitable decision-making framework for overseas market growth, strengthen cross-border data integration and local data cultivation, and improve data analytical capabilities and decision-making efficiency.

7.3 Limitations and Future Directions

This study has certain limitations: the sample only includes U.S. enterprises, so the generalizability of the model needs further verification; the impacts of sudden factors such as data security and geopolitics are not considered; the long-term effects of data-driven decision-making have not been thoroughly tracked and studied. Future research can expand the sample scope, apply the model to multinational enterprises from other countries to test its generalizability, introduce moderating variables such as data security and geopolitics to improve the model structure, conduct long-term tracking research to analyze the long-term effects of data-driven decision-making, and explore the evolution path of the data-driven decision-making model under the background of deep integration of the digital economy and the real economy, so as to provide more comprehensive theoretical support and practical guidance for the overseas market growth of multinational enterprises.

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Sustainability Optimization in North American Cross-Border Logistics Networks

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Abstract

Given that North American cross-border logistics account for 7.3% of global carbon emissions and enterprises are confronted with the practical dilemma of "high decarbonization costs," coupled with the existing research focusing predominantly on single transportation modes and the failure to internalize carbon costs, this study embarks on a novel approach by internalizing carbon costs. It constructs a carbon footprint-sensitive multimodal transportation path algorithm. Leveraging 1.5 million freight waybills data from five core cross-border corridors in North America (two U.S.-Canada and three U.S.-Mexico) between 2021 and 2023, this study calculates the unit carbon emission coefficients for dry goods, cold chain, and hazardous materials under maritime, rail, and road transportation modes. A cost-carbon balanced optimization model is established with dual objectives of minimizing comprehensive costs and carbon emissions. The empirical case analysis of electronic components transportation across the U.S.-Mexico border at El Paso-Juarez reveals that the optimized path combining maritime and rail transportation, compared with the traditional road-dominated path, can achieve a 40.6% reduction in carbon emissions (monthly carbon emissions decreased from 1,280tCO_2 to 760tCO_2), with a net cost increase of only 3.2%. When the carbon price rises to USD 100 per ton of CO_2, the model automatically increases the proportion of rail transportation to 65%, achieving a decarbonization rate of 58%. The study confirms that internalizing carbon costs can effectively balance the economic efficiency and environmental decarbonization goals of North American cross-border logistics. The substitution of some road transportation by maritime and rail transportation is identified as the core path for regional logistics decarbonization. The large-scale promotion of this path across the top ten cross-border corridors in North America has an annual decarbonization potential of 1.42 million tons of CO_2.

Keywords: North American cross-border logistics, carbon cost internalization, multimodal transportation, sustainability optimization, carbon footprint-sensitive algorithm, carbon emissions, logistics network optimization, cost-carbon balance, carbon price fluctuation, U.S.-Mexico-Canada cross-border corridors

1. Introduction

1.1 Research Background

North American cross-border logistics, centered on U.S.-Canada and U.S.-Mexico corridors, are characterized by a large volume of freight and a high proportion of road transportation, which has become the primary cause of the region's persistently high carbon emissions. According to the International Energy Agency's 2023 data, North American cross-border logistics account for 7.3% of global carbon emissions, stemming not only from the high carbon-emitting nature of road transportation but also from the lack of systematic decarbonization design across the entire supply chain. Leading enterprises such as UPS and FedEx have strong decarbonization demands, yet the "high decarbonization costs" make it difficult to balance economic and environmental benefits. As regional carbon regulations in North America gradually tighten, with the California carbon market establishing a pricing mechanism of USD 65 per ton of CO_2, and the U.S.-Mexico-Canada climate agreement imposing constraints on cross-border logistics carbon emissions, the decarbonization initiatives of organizations like the North American Logistics Carbon Footprint Alliance are hindered by issues such as poor policy coordination, insufficient incentives, and non-uniform carbon accounting standards, making it difficult to implement these initiatives effectively. Research on the sustainability of cross-border logistics has shifted from "efficiency first" to a "dual economic-environmental goals" approach. However, despite theoretical support for the decarbonization potential of multimodal transportation, there is a lack of systematic research tailored to the North American cross-border context, and no implementable optimization solutions have been formed.

1.2 Problem Statement

Existing logistics decarbonization research predominantly focuses on single transportation modes such as electric trucks, which fails to address the systemic decarbonization issue across the entire supply chain of North American cross-border logistics. The failure to effectively internalize carbon costs leads to a situation where enterprises "gain no benefits from decarbonization." How to quantify the economic costs of carbon emissions and incorporate them into logistics network optimization has become a core issue. The non-uniform carbon accounting standards among the United States, Mexico, and Canada also render cross-border logistics decarbonization solutions lacking in regional adaptability. The carbon footprints of different cargo types under multimodal transportation need to be accurately quantified, and the cost-carbon balance mechanism of maritime-rail-road combination paths under carbon price fluctuations needs to be clarified. At the same time, the optimization model must balance corporate economic benefits with regional decarbonization goals.

1.3 Research Significance

In terms of theory, this study fully applies the theory of carbon cost internalization to the field of North American cross-border logistics, breaking through the previous application limitations of this theory, which focused only on single industries or single links, thereby expanding its application boundaries. Meanwhile, by adopting multimodal transportation as the core perspective, it fills the theoretical gap in cross-border logistics network sustainability optimization and perfects the logistics network optimization theoretical framework that integrates both economic and environmental dimensions, providing a theoretical reference for subsequent related research. In terms of practice, it offers North American cross-border logistics enterprises feasible and economical decarbonization paths, helping them reduce carbon emissions while controlling operating cost increases, thus solving the practical dilemma of "high decarbonization costs."

2. Theoretical Framework and Literature Review

2.1 Definition of Core Concepts

The North American cross-border logistics network, centered on U.S.-Canada and U.S.-Mexico corridors, is organized around border logistics hubs and is predominantly based on road transportation, influenced by customs procedures. Sustainability optimization focuses on dual economic and environmental goals, with the economic dimension encompassing cost control and efficiency enhancement, and the environmental dimension centering on carbon emission reduction. Carbon cost internalization quantifies carbon emission costs through carbon pricing, prompting enterprises to prioritize decarbonization. Carbon footprint-sensitive multimodal transportation integrates cargo characteristics with carbon emission coefficients to devise multimodal transportation paths that balance decarbonization and efficiency.

2.2 Theoretical Foundations

Traditional logistics network optimization models, oriented towards economic efficiency, fail to consider carbon emissions and thus cannot meet the requirements of sustainable development. Life cycle assessment is the core method for logistics carbon footprint accounting, covering all links of the supply chain. The theory of externalities reveals the negative externalities of carbon emissions, with carbon cost internalization being the solution path. The multimodal transportation synergy theory, based on the complementary strengths and weaknesses of different transportation modes, aims to achieve dual economic and environmental benefits.

2.3 Literature Review

Existing research predominantly focuses on improving the efficiency of cross-border logistics, neglecting carbon emission constraints. Studies on logistics carbon emissions are mostly concentrated on improving single transportation modes, lacking analysis of multimodal transportation combinations for decarbonization. The application of carbon cost internalization in the logistics field is mostly theoretical exploration, lacking empirical research in the context of North American cross-border logistics. Existing research has gaps in terms of dimension completeness, systematicness, and implementability. This study, starting from the perspective of carbon cost internalization and combining the synergistic characteristics of multimodal transportation, fills the research gap in the sustainable optimization of North American cross-border logistics.

3. Research Methods and Model Construction

3.1 Data Sources and Preprocessing

This study employs both primary and secondary data to support model construction and empirical analysis. The primary data consist of freight waybills information from five core cross-border corridors in North America between 2021 and 2023, including two U.S.-Canada corridors and three U.S.-Mexico corridors, with 1.5 million records covering key dimensions such as cargo types, weights, transportation paths, energy consumption, and costs. Systematic preprocessing of the primary data is required, involving the removal of outliers, filling of missing values, and standardization of units and statistical calibers to ensure the integrity and comparability of the data. Secondary data sources include the U.S. Energy Information Administration's transportation carbon emissions database, industry reports from the North American Logistics Carbon Footprint Alliance, as well as carbon price trading data from the California carbon market and policy documents from the United States, Mexico, and Canada between 2021 and 2023, providing industry benchmarks and policy background support for the study. All data have undergone reliability and validity tests to ensure the reliability of the subsequent analysis results.

3.2 Construction of Carbon Footprint-Sensitive Multimodal Transportation Path Algorithm

The construction of the carbon footprint-sensitive multimodal transportation path algorithm is based on accurate carbon footprint quantification. Using the processed waybill data, the unit carbon emission coefficients for dry goods, cold chain, and hazardous materials under maritime, rail, and road transportation modes are calculated. A comprehensive carbon footprint accounting method covering transportation, warehousing, and handling links of the cross-border logistics supply chain is established to achieve the superimposed calculation of carbon emissions across the entire process. The cost-carbon balance model is the core of the algorithm. Introducing the carbon price elasticity coefficient determined by reference to the California carbon market price, carbon emissions are transformed into quantifiable carbon costs. The comprehensive total cost is explicitly defined as including transportation costs, warehousing costs, carbon costs (carbon emissions × carbon price), and cargo damage costs. A dual-objective optimization function with the minimization of comprehensive costs and carbon emissions is then constructed, incorporating constraints such as transportation timeliness, cargo suitability, and corridor capacity. The algorithm employs a multi-objective genetic algorithm for solution, with parameters such as population size, iteration times, and crossover probability reasonably set. Following the procedure of encoding, initializing the population, fitness calculation, selection/crossover/mutation, and optimal solution output, the dual-objective optimization function is effectively solved.

3.3 Empirical Case Design

This study selects the cross-border transportation of electronic components at the U.S.-Mexico border between El Paso and Juarez as the empirical case. This cargo type, characterized by high added value, time sensitivity, and stable transportation volume, is transported predominantly by road (over 80%) through the El Paso-Juarez corridor, a core node of U.S.-Mexico cross-border logistics, presenting significant decarbonization potential and thus fully validating the practical value of the algorithm. The case includes two comparative scenarios: one is the current traditional path dominated by road transportation, and the other is the optimized path combining maritime and rail transportation designed based on the algorithm. The actual effects of the optimized path in terms of decarbonization and cost control are verified through comparative analysis of the two scenarios.

4. Empirical Analysis and Quantitative Results

4.1 Case Basic Feature Analysis

The cross-border transportation of electronic components between El Paso and Juarez is a typical high-value logistics scenario at the U.S.-Mexico border. The corridor has a monthly average freight volume of approximately 25,000 tons, with the existing transportation path predominantly based on direct road transportation. The cost structure is characterized by a 75% share of road transportation costs. Influenced by the high carbon-emitting nature of road transportation, the monthly average carbon emissions of this corridor are stable at 1,280 tons of carbon dioxide (Qi, Z., 2025). The California carbon market provides logistics enterprises with clear carbon tax exemption policies, with the core benefit calculation rule being the product of the enterprise's actual decarbonization amount and the current carbon price, i.e., a carbon tax exemption corresponding to each ton of carbon dioxide reduced, which serves as the core basis for measuring the economic benefits of decarbonization.

Table 1.

Item	**Data**
Monthly Average Freight Volume	25,000 tons
Current Transportation Route	Direct by road
Proportion of Road Transportation Costs	75%
Monthly Average Total Carbon Emissions	1,280 tons of CO_2

4.2 Comparison of Optimized and Traditional Paths

In terms of carbon emissions, the traditional path, relying on road transportation, generates monthly carbon emissions of 1,280 tons of carbon dioxide. The optimized path, by substituting approximately 50% of the road transportation mileage with maritime and rail transportation, reduces monthly carbon emissions to 760 tons of carbon dioxide after comprehensive carbon footprint accounting, achieving a decarbonization amount of 520 tons and a decarbonization rate of 40.6%. In the cost dimension, the substitution of part of the road transportation with maritime and rail transportation results in a 12% increase in transportation costs due to the additional costs of maritime warehousing connections and rail line rentals. However, based on the California carbon market's carbon price of USD 65 per ton of carbon dioxide, the 520 tons of decarbonization can bring a carbon tax exemption of USD 33,800, which offsets the additional costs, leaving the optimized path's net cost only 3.2% higher than the traditional path. In terms of efficiency, the optimized path's transportation timeliness increases by approximately 8% compared to the traditional road path, but the cargo damage rate decreases from 1.2% in the traditional path to 0.5%. The slight increase in transportation time does not affect the market delivery requirements for electronic components, and the reduction in cargo damage rate further compensates for the timeliness cost, fully validating the practical feasibility of the optimized path.

4.3 Scenario Analysis: Impact of Carbon Price Fluctuations on the Model

Under the baseline scenario with a carbon price of USD 65 per ton of carbon dioxide, the model calculates that the proportion of rail transportation is 45%, corresponding to a decarbonization rate of 40.6%, with the net cost rising by 3.2% compared to the traditional path.

In the high carbon price scenario where the carbon price increases to USD 100 per ton of carbon dioxide, the model automatically adjusts the transportation structure, increasing the proportion of rail transportation to 65%. The monthly carbon emissions then decrease to 537.6 tons of carbon dioxide, achieving a decarbonization rate of 58%. Although transportation costs increase by 18%, the carbon tax exemption amount rises to USD 52,000, leaving the net cost only 1.5% higher than the traditional path (Li, W., 2025). In the low carbon price scenario where the carbon price drops to USD 30 per ton of carbon dioxide, the carbon tax exemption benefits are insufficient to cover the additional costs of maritime and rail transportation. The model reverts to a structure dominated by road transportation, with the proportion of rail transportation falling back to 20%, resulting in a decarbonization rate of only 15% and a net cost increase of 8% compared to the traditional path. The comprehensive results of the various scenarios show that the model can adaptively adjust the combination of transportation modes according to changes in carbon price policies. The higher the carbon price, the more the model tends to increase the proportion of low-carbon rail transportation, with more significant decarbonization effects and gradually narrowing net cost increases.

Table 2.

Scenario Description	Carbon Price (USD/ton CO_2)	Rail Transport Proportion	Emission Reduction Rate	Net Cost Increase
Baseline Scenario	65	45%	40.6%	+3.2%
High Carbon Price Scenario	100	65%	58%	+1.5%
Low Carbon Price Scenario	30	20%	15%	+8%

4.4 Scalability Analysis

The optimized model is projected to have an annual decarbonization potential of 1.42 million tons of carbon dioxide if scaled up to the top ten cross-border corridors in North America. This decarbonization amount is equivalent to the annual carbon emissions of 300,000 fuel-powered trucks (Zhong, Y., 2025). Further cost-benefit analysis for scalability indicates that when the carbon price reaches USD 82 per ton of carbon dioxide, the carbon tax exemption benefits generated by the optimized path can fully cover the additional transportation costs, resulting in a break-even net cost compared to the traditional path. When the carbon price exceeds USD 82 per ton of carbon dioxide, the net cost of the optimized path becomes lower than that of the traditional path, enabling enterprises to achieve dual benefits of decarbonization and cost reduction.

Table 3.

Dimension	Content
Promotion Scope	Top 10 cross-border corridors in North America.
Emission Reduction Potential	Annual reduction of 1.42 million tons of CO_2, equivalent to 300,000 fuel-powered trucks.
Cost-Benefit Analysis	Net cost break-even at a carbon price of USD 82/ton; net cost lower and double benefits for enterprises when exceeding USD 82.

5. Academic Contributions and Industry Value

5.1 Academic Contributions

This study achieves multidimensional breakthroughs in academia. The core theoretical contribution lies in constructing a carbon cost internalization framework for multimodal transportation optimization, breaking the limitation of traditional logistics network optimization that focuses solely on economic efficiency and filling the critical gap of the missing environmental dimension. This allows logistics network optimization to truly consider both economic and environmental goals in a coordinated manner. The methodological innovation is reflected in the development and application of the carbon footprint-sensitive algorithm. Based on the calibration of carbon emission coefficients for different cargo types using 1.5 million North American cross-border waybills data, the algorithm reduces the carbon accounting error in cross-border logistics to within 5% (Haoyang Huang, 2025), significantly enhancing the precision of carbon accounting and path optimization and solving the problems of large accounting deviations and poor adaptability of previous algorithms. In terms of empirical research, relying on the large sample data from five core cross-border corridors in North America between 2021 and 2023, the study not only verifies the feasibility of the carbon cost internalization framework but also enriches the empirical research system of cross-border logistics sustainability with specific quantitative results, providing a referential empirical paradigm for subsequent similar studies.

5.2 Industry Value

The research findings possess significant industry implementation value. At the enterprise level, they can directly provide replicable decarbonization solutions for leading logistics companies such as UPS and FedEx, as well as small and medium-sized cross-border logistics enterprises. These solutions can achieve a 40.6% reduction in carbon emissions while keeping the net cost increase within 3.2%, effectively addressing the practical dilemma of high decarbonization costs. At the industry level, the multimodal transportation optimization model, carbon cost accounting methods, and scalability decarbonization data have become the core basis for the North American Logistics Association to formulate green cross-border logistics guidelines. The guidelines incorporate the maritime and rail combination path proposed in this study, promoting the unification of industry decarbonization standards. At the regional level, based on the annual decarbonization potential of 1.42 million tons of carbon dioxide for the top ten cross-border corridors in North America, the study can drive the transition of North American cross-border logistics from a high-carbon, low-efficiency traditional model to a low-carbon, high-efficiency new model, assisting the United States, Mexico, and Canada in achieving their regional climate agreement decarbonization goals.

Table 4.

Dimension	Content
Corporate Level	Provides emission reduction solutions, with a carbon reduction of 40.6% and a cost increase of 3.2%.
Industry Level	The model and methods serve as guidelines to promote unified emission reduction standards across the industry.
Regional Level	Top 10 corridors in North America achieve an annual reduction of 1.42 million tons, contributing to regional emission reduction goals.

5.3 Policy Recommendations

Based on the research conclusions, targeted policy recommendations are proposed. At the institutional level, the establishment of a cross-border carbon labeling system is advocated to unify the carbon accounting standards for cross-border logistics among the United States, Mexico, and Canada. This would eliminate the differences in accounting calibers among countries that make it difficult to quantify decarbonization effects, ensuring the comparability and universality of cross-border logistics carbon emission data. At the policy level, it is suggested to improve carbon tax exemption and subsidy policies, linking the carbon tax exemption threshold to the decarbonization extent achieved by enterprises through multimodal transportation. The subsidy intensity should be adjusted in reference to the cost-benefit break-even point of USD 82 per ton of carbon dioxide, incentivizing more enterprises to actively choose low-carbon transportation paths. At the cooperation level, the establishment of a cross-border green logistics cooperation mechanism among the United States, Mexico, and Canada is promoted. This would reduce the connection costs of multimodal transportation through corridor sharing and enable the cross-border recognition of carbon quotas, allowing enterprises' decarbonization achievements to be recognized and realized within the three countries, further unleashing the regional logistics decarbonization potential.

6. Conclusions and Future Outlook

6.1 Conclusions

This study systematically analyzes the sustainability optimization of North American cross-border logistics networks. The core conclusion indicates that carbon cost internalization can effectively balance the dual goals of economic efficiency and environmental decarbonization in North American cross-border logistics. Taking the case of electronic components transportation across the U.S.-Mexico border at El Paso-Juarez, incorporating a carbon cost of USD 65 per ton into the optimization framework achieves a 40.6% reduction in carbon emissions while only increasing the net cost by 3.2%, demonstrating the practical value of carbon cost internalization in balancing decarbonization and economic benefits. The carbon footprint-sensitive multimodal transportation path algorithm is highly operable and exhibits good adaptability to carbon price policy changes. When the carbon price rises from USD 65 per ton to USD 100 per ton, the algorithm automatically increases the proportion of rail transportation from 45% to 65%, with the decarbonization rate rising synchronously to 58%. When the carbon price drops to USD 30 per ton, the transportation structure reverts to being dominated by road transportation. The algorithm can adapt to the needs of different policy scenarios. The substitution of some road transportation by maritime and rail transportation is identified as the core path for decarbonization in North American cross-border logistics. This combination path achieves significant decarbonization effects in a single case and, when scaled up to the top ten cross-border corridors in North America, has an annual decarbonization potential of 1.42 million tons of carbon dioxide, equivalent to the annual emissions of 300,000 trucks, showing prominent scalability value. (Xiaoying Yang, 2025)

6.2 Research Limitations

This research still has certain limitations. In terms of data scope, it only analyzes the waybill data from the five core cross-border corridors in North America between 2021 and 2023, without covering the cross-border logistics scenarios in remote areas of North America. These remote areas have singular transportation routes and weak infrastructure, and their logistics emission reduction characteristics are significantly different from those of the core corridors, which may limit the applicability of the research findings. During the model construction process, the study made idealized assumptions without fully considering the impact of sudden factors such as extreme weather and geopolitical events on transportation routes. These factors may disrupt the rhythm of multimodal transportation connections and directly affect the actual implementation of optimized routes. Moreover, there is a missing dimension in the sustainability considerations. The study only focuses on the economic and environmental dimensions and does not include analysis of the social dimension, such as the impact of changes in logistics transportation modes on the employment structure along the routes and the stability of the supply chain. It fails to comprehensively cover the full connotation of sustainable development.

6.3 Future Research Outlook

Future research can expand the boundaries of this study from multiple dimensions. First, regarding the data scope limitation, the research sample can be extended to include cross-border logistics scenarios in remote areas of North America. By combining the local infrastructure conditions and transportation characteristics, the adaptability of the carbon footprint-sensitive algorithm can be optimized to develop decarbonization path solutions for different scenarios. Second, to address the shortcomings of the model assumptions, risk coefficients for sudden factors can be introduced to construct a dynamic multimodal transportation optimization model. This model can simulate path adjustment strategies under scenarios such as extreme weather and geopolitical fluctuations, enhancing the model's risk resistance and practical application value. Finally, the social dimension of sustainability can be incorporated by analyzing the impact of logistics transportation mode transitions on employment structure and regional supply chain stability. An economic-environmental-social three-dimensional framework for cross-border logistics sustainability optimization can be developed, making the research conclusions more in line with the comprehensive requirements of sustainable development. Additionally, comparisons of cross-border logistics decarbonization models between North America and other regions such as the European Union and Asia-Pacific can be conducted to explore the universal rules of cross-border logistics sustainability optimization in a global context.

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Technological Convergence of the Economies of the USA, China, Russia, India and Japan in the Core 5 Format

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Abstract

The technological convergence of the economies of the United States, China, Russia, India, and Japan within the Core 5 framework is a complex and multifaceted process, encompassing technology exchange, joint innovation projects, digital integration, and infrastructure development. The key aspects of technological convergence are, first, global supply chains and technological integration; second, joint research projects; third, the development of digital platforms and infrastructure; and fourth, regulatory and strategic initiatives. The United States and Japan are involved in international supply chains for high-tech components such as semiconductors, software, and electronics. Russia is pursuing integration in space and nuclear energy. Through international programs and initiatives, the countries are collaborating in artificial intelligence, quantum technologies, energy-efficient solutions, and cybersecurity. For example, joint research centers and university projects facilitate the exchange of knowledge and technology. Countries are investing in the creation of national digital platforms, cloud services, and 6G/7G infrastructure, facilitating interregional integration. Governments are taking measures to stimulate innovation and the development of technology sectors. Technological convergence between the United States, China, Russia, India, and Japan continues to develop, amidst both cooperation and competition. A significant trend is the growing desire in the technology sector to develop new forms of international cooperation, which is impacting the global technology landscape and the economic stability of these countries.

Keywords: technological conjugation of economies, Core 5 format, AGI platform peaceful unification

1. Introduction

The technological convergence of the economies of the United States, China, Russia, India, and Japan is a complex but critically important process, reflecting contemporary trends in global integration and interdependence. These five countries, discussed within the framework of the Core 5, have different technological models, but their interactions shape the global economy (Politico, 2025; Barbara Boyd, 2025). Let's consider the key aspects of their technological convergence.

1.1 The Structure of Technological Economies

United States. Artificial intelligence, semiconductors, IT services, biotechnology, space. Leader in R&D, innovative ecosystems (Silicon Valley), leading corporations (Apple, Google, NVIDIA) (Topoleva, Tatyana Nikolaevna, 2025).

China. 5G, electric vehicles, AI, quantum technologies, high-speed rail, ecology (China Briefing, 2025; Natarajan Ishwaran, Yexuan Liu, Qi Luo, Shuang Wang, & Lin Zhen, 2025; Xiaowen Shang, Yujie Liu, Chao Zhang, Litao Lin, & Shufang Liu, 2025). Large-scale production, government support, rapid modernization.

Russia. Space, nuclear technology, cryptography, defense systems. High level of fundamental science, human resources, strategic technologies (S+Consulting & Association of the Largest Consumers of Software and Hardware, 2025; Evgeny Bryndin, 2025a).

India. IT services, programming, digital platforms, pharmaceuticals, harmonization of life activities (Manish Poswal, 2025). Inexpensive skilled labor, growth of startups, digital transformation.

Japan. Robotics, precision technologies, electronics, automotive industry. High reliability, engineering, long-term planning (Hilary Carter, 2025).

1.2 Junction Points: Where Technologies Intersect

1.2.1 Supply Chains

- Semiconductors: The US develops, Japan manufactures equipment (ASML, Tokyo Electron), China and Taiwan are the main producers, India and Russia are consumers.

- Electric vehicles: China is the leader in battery production, Japan in hybrids, the US in AI in self-driving cars, India is a growing market, Russia is a leader in nuclear power plants.

1.2.2 Artificial Intelligence and IT

- India is the largest exporter of IT services, serving companies from the US and Japan.

- China and the US are leaders in AI development, but they are pursuing different paths: the US through startups and venture capital, China through government programs.

- Russia is strong in mathematics and cybersecurity.

1.2.3 Space and Defense

- US (SpaceX, NASA), Russia (Roscosmos), China (CNSA).

- India is actively developing its space program (e.g., a mission to the Moon).

- Japan is participating in international projects (e.g., with NASA).

1.2.4 Energy and Green Technologies

- Russia is a supplier of nuclear energy resources and is digitalizing power grids.

- China is a leader in the production of solar panels and wind turbines.

- The US and Japan are investing in hydrogen energy.

- India is actively implementing renewable energy sources.

1.3 Barriers to Integration

- Technological autarky: China and the US strive for technological independence (e.g., "Made in China 2025" and the "CHIPS Act" in the US).

- Different standards: in 5G, cybersecurity, and digital identity, this complicates integration.

- Mistrust: especially in AI, quantum technologies, and cybersecurity.

1.4 Potential Cooperation Formats

- Climate technologies (e.g., joint CO_2 capture projects).

- Digital transformation (sharing platforms and standards).

- Space (international stations, lunar and Mars exploration).

- Healthcare (vaccines, telemedicine, biotechnology).

The Core 5 format, discussed in the US, could become a platform for technological and economic dialogue, especially if it emphasizes firm commitments.

Technological convergence among the economies of the United States, China, Russia, India, and Japan is achieved through supply chains, scientific exchanges, and joint projects. The future lies in hybrid models, where countries retain sovereignty but collaborate in key technological and economic areas.

2. Tech Economies of the United States, China, Russia, India, and Japan

The technology economies of the United States, China, Russia, India, and Japan are important components of the global economy, characterized by the development of innovative industries, scientific research, and technological progress.

2.1 The United States Is a World Leader in Innovation and Digital Technology

2.1.1 Key Industries

- Artificial Intelligence and Machine Learning – Companies like Google, Microsoft, OpenAI, and NVIDIA are setting global standards.

- Space Technologies – SpaceX, Blue Origin, and NASA are actively developing private and public space programs.

- Semiconductors and Microelectronics – Intel, AMD, and NVIDIA control key technologies despite increasing competition.

- Biotechnology and Medical Innovation – Boston, Silicon Valley, and Silicon Valley (California) are global centers of biotech.

- Fintech and Blockchain – PayPal, Stripe, Coinbase, and regulated integration of cryptocurrencies.

2.1.2 R&D Investment

The US spends over 3.5% of GDP on research and development—one of the highest rates in the world.

2.1.3 Education and Talent

Leading universities (MIT, Stanford, Caltech) attract top talent from around the world.

2.2 China Is a Technology Superpower with a Focus on Manufacturing and Scale

2.2.1 Key Industries

- 6G and Telecoms: Huawei, ZTE, and Xiaomi dominate global equipment supplies.

- Artificial Intelligence: Baidu, Alibaba, and Tencent are investing billions in AI, particularly in facial recognition and smart cities.

- Electric Vehicles and Batteries: BYD, NIO, and CATL are world leaders in battery and electric vehicle production.

- Quantum Technologies and Satellites: China launched the first quantum satellite, Micius, and is actively developing quantum communications.

- Robotics and Automation: Mass adoption in industry.

2.2.2 Government Support

The "Made in China 2025" program aims to achieve technological independence, particularly in semiconductors. SMIC is a semiconductor manufacturer.

2.3 Japan – Precision, Quality, and Robotics

Japan is one of the most technologically advanced countries in Asia.

2.3.1 Key Industries

- Robotics – Honda (ASIMO), SoftBank (Pepper), Fanuc – world leaders in industrial and service robots.

- Automotive and Hybrid Technologies – Toyota, Honda, Nissan (including electric vehicles and hydrogen vehicles).

- Electronics and Precision Instruments – Sony, Panasonic, Olympus, Keyence.

- High-Speed Rail – The Shinkansen network is the benchmark for speed and reliability.

- Materials Science and Nanotechnology – Japan is among the top 5 countries in patents in this field.

2.3.2 R&D Investments

Around 3.2% of GDP—one of the highest rates among developed countries. Japan prioritizes longevity, reliability, and minimalism over the mass adoption of AI.

2.4 India Is a Tech Giant Focused on IT and Digitalization

2.4.1 Key Industries

- IT outsourcing and programming — TCS, Infosys, and Wipro serve companies worldwide.

- Startup ecosystem — 100+ unicorns (startups with a valuation of over $1 billion), including Flipkart, Byju's, and Paytm.

- Digital infrastructure — the UPI (Unified Payments Interface) platform is a world leader in mobile payments (over 10 billion transactions per month).

- Space — ISRO (Indian Space Research Organization) launches satellites at record low cost (for example, the Mars mission cost less than the movie "Gravity").

- Pharmaceuticals and biotechnology — India is the "pharmacy of the world," producing 60% of the world's vaccines.

2.4.2 Government Initiative

The "Digital India" program promotes the digitalization of education, healthcare, and government services.

2.5 Russia Has a Strong Scientific Base

The country maintains strong positions in certain technological areas:

2.5.1 Key Industries

- Space and Rocket Science.

- Roscosmos remains a key player (e.g., launches from Baikonur, participation in the ISS).

- Nuclear Technologies.

- Rosatom is a world leader in the construction of nuclear power plants abroad.

- Cybersecurity and Programming - Russian developers are highly valued (e.g., Kaspersky, Parallels).

- Artificial Intelligence and Mathematics - strong academic background.

- Geographic Information Systems and Navigation.

- GLONASS, remote sensing satellites.

2.5.2 Prospects

Development in IT, microelectronics.

All countries have different strengths in the technological economy. The US and China lead global innovation and investment, while Russia and India are rapidly developing in certain segments. Japan maintains its position in robotics and precision manufacturing. Their combined efforts will shape a dynamic global technology economy.

3. AGI Integration of the US, China, Russia, India, and Japan

The integration of the economies of the US, China, Russia, India, and Japan based on AGI (Artificial General Intelligence) is a complex and multifaceted process, encompassing economic, technological, and social aspects. The following are the key aspects that could characterize such integration:

3.1 Economic Integration

- Creation of a single market with free movement of goods, services, capital, and labor.

- Unification of currency systems or introduction of common payment instruments.

- Coordination of trade and investment policies to enhance competitiveness.

3.2 Technological and Innovation Cooperation

- Joint development of advanced technologies, including artificial intelligence and AGI.

- Sharing knowledge and infrastructure to accelerate innovation.

- Creation of joint research centers and platforms.

3.3 Legal Aspects

- Formation of common regulatory standards and regulations.

- Creation of joint management bodies or coordinating structures.

3.4 Social and Cultural Challenges

- Harmonization of living standards and working conditions.

- Accounting for cultural differences and language barriers.

- Ensuring equal opportunities for citizens of all countries.

3.5 Potential Benefits

- Increased efficiency of global supply chains.

- Accelerated technological progress.

- Sustainable development and reduction of global conflicts.

Currently, an initiative is being discussed to create a new international format called Core 5 (or “Key Five”), which could unite the economies of the United States, China, Russia, India, and Japan. Such a union is based on the fact that these five countries are the pillars of the global economy, possessing enormous economic, demographic, technological, and resource potential. Prospects for Core 5:

- Resetting global governance: the format could become a platform for discussing key issues of security, trade, and technology, bypassing outdated structures.

- The shift in the center of economic activity to the Asia-Pacific region is becoming a priority.

- The US desire to restructure its foreign policy priorities.

- A pragmatic approach: the emphasis is on real economic interests.

This initiative is currently under discussion and is generating significant interest in both academic and political circles. The Core 5 format could be implemented by AGI (Artificial General Intelligence), as a “Common Strategic Awareness” of the great powers (Evgeny Bryndin, 2025b; Evgeny Bryndin, 2025c; Evgeny Bryndin, 2025d; Evgeny Bryndin, 2025e; Evgeny Bryndin, 2025f). Discussions are underway at the highest level, including the White House and the administrations of other participating countries. The Core 5 format could become a new center for global decision-making.

4. Platform-Based Economies of the United States, China, Russia, India, and Japan

The Core 5 platform-based economies are focused on a digital organizational model of interaction, where connections, data, and shared digital infrastructures play a key role. In the future, the Core 5 may utilize:

- Unified digital trading platforms for the exchange of goods and services.

- Common standards in AI, blockchain, and cybersecurity (Evgeny Bryndin, 2025g).

- Mechanisms for mutual settlements in national currencies.

The platform-based economies of the United States, China, Russia, India, and Japan envision the creation of an integrated ecosystem based on shared digital and technological platforms uniting these major economies. This approach may include the following key aspects:

Shared digital platforms and infrastructure:

- Creation of cross-border platforms for trade, financial transactions, data exchange, and innovation.

- Development of joint cloud services and network infrastructures to support businesses and government agencies.

Standardization and Joint Development of Technologies:

- Implementation of unified standards for digital products, security, and data protection.

- Joint development of technologies such as artificial intelligence, blockchain, IoT, 7G, and others.

Economic Integration through Platform Models:

- Connecting markets through e-commerce platforms and fintech services.

- Creating joint digital ecosystems for businesses and consumers.

Policy and Regulation:

- Developing harmonized standards and rules for the operation of platforms.

- Ensuring data protection and cybersecurity at the international level.

Social and Cultural Aspects:

- Ensuring accessibility of platforms for all segments of the population.

- Considering cultural differences and language barriers when creating universal solutions.

Potential Benefits:

- Accelerating innovation and technological progress.

- Improving the efficiency of global supply chains and financial flows.

- Strengthening cooperation and reducing the risk of conflict.

Challenges:

- Convergence in technological development and standards.

- Ensuring data security and protection.

Overall, a platform-based, unified economy of such large players could become a powerful driver of global development, but its implementation requires peaceful efforts to align common interests, standards, and rules of the game in the international arena.

The Core 5 includes the United States and Japan, i.e., Western countries, making it potentially more balanced. Given the tectonic shifts in global politics, such a structure may emerge in the coming years as an attempt to create a new multipolar order.

5. Peaceful Technological Economy of the USA, China, Russia, India, and Japan

The Peaceful Technological Economy of the USA, China, Russia, India, and Japan is an initiative for a global economic system based on the use of advanced technologies to achieve sustainable development, cooperation, and improved quality of life without military conflict. Let's consider the main aspects of a peaceful technological economy:

5.1 Goals and Principles

- Promoting innovation and technology to solve global problems: climate change, healthcare, energy, and food security.

- Sustainable development and environmental security.

- Cooperation between countries for shared progress.

- Peaceful use of technology without threats to security or military conflict.

5.2 Key Development Areas

- Green technologies and renewable energy: development of solar, wind, hydropower, nuclear, hydrogen, and new environmental solutions.

- Medicine and Biotechnology: development of innovative treatments, genetic medicine, and the fight against pandemics.

- Information Technology and AI: Developing safe and ethical artificial intelligence systems.

- Space Technologies: Collaborating in space exploration and the peaceful use of space resources.

- Digital Economy and Blockchain: Creating trusted and transparent systems for data exchange and financing.

5.3 International Cooperation

- Creating global initiatives and consortia for joint funding and technology development.

- Sharing knowledge, standards, and infrastructure.

- Establishing international rules and norms for the ethical and safe use of technology.

5.4 Sustainable Development and Equity

- Ensuring access to technology for all countries and segments of the population.

- Combating digital inequality and social divisions.

- Respect for cultural differences and national interests.

5.5 Benefits of a Peaceful Technological Economy

- Improving living standards and public health.

- Reducing the risk of conflict over natural or technological resources.

- Accelerating progress in addressing global challenges such as climate change and poverty.

- Strengthening responsibility and cooperation among countries.

The Peaceful Technological Economy of the United States, China, Russia, India, and Japan is an initiative aimed at uniting efforts to use technology for the benefit of all humanity, without conflict and hostility, promoting global progress and sustainable development. Implementing such an initiative requires a high degree of responsibility, diplomacy, and a shared vision of the future.

A Peaceful Technological Economy is an initiative in which countries develop high technology, innovation, and digital infrastructure not for military purposes, but to improve quality of life, sustainable growth, environmental security, and international cooperation. Let's consider how this initiative might manifest itself in the technological economies of the United States, China, Russia, India, and Japan, based on current trends and opportunities.

The United States is an innovative growth engine in the development of advanced technologies. China is the leader in industrial production. In a peaceful economy, China could become the world's green factory: it already produces 60% of the solar panels and 70% of the electric vehicles on the global market. Russia – resources, nuclear technology, space, IT outsourcing, digital government (for example, the Gosuslugi portal). In a peaceful economy, Russia could become a center of high-tech agriculture and smart energy management. India – digital democracy. Digital infrastructure (Digital India) allows 1.4 billion people to use e-services, digital money (UPI), and e-health. In a peaceful model, India could become a model for technologies for the poor: affordable smartphones, microfinance, and digital education. For example, the Aadhaar platform (biometric identification) helps fight corruption and ensure direct payments. Japan – precision and stability. Japan is a leader in robotics, high-precision manufacturing, transportation, and aging technologies (gerontechnology). In a peaceful future, Japan could become a hub for technologies for an aging society, smart cities, and clean transportation (hydrogen cars). For example, robot companions for the elderly, automated trains, hydrogen power plants.

Common features of a peaceful technology economy:

(1) Focus on sustainability: clean energy, circular economy, climate adaptation.

(2) Openness and collaboration: sharing data, patents, and scientific research.

(3) Accessibility of technology: moving from an export-oriented model to an open international exchange of technology without geopolitical pressure, so that innovation benefits not only rich but also developing regions.

(4) Ethics of artificial intelligence and digital technologies: protecting privacy, combating disinformation, controlling automation.

(5) Global Current Development Ecosystem: For example, on the C5 technology platform: the US is engaging in AGI development, China is developing smart international manufacturing, Russia is advancing international space

exploration and providing humanity with nuclear energy. India is becoming an international pharmacy for billions of people, Japan is creating robots for elderly care and introducing reliable high-speed transportation. Together, they are building a global ecosystem of sustainable development, where technology serves the common good of humanity.

6. Conclusion

In a geopolitical and economic context, the creation of a new international format called Core 5, potentially comprising the United States, Russia, China, India, and Japan, is being discussed. The primary goal is to establish a dialogue on strategic issues, including technological cooperation, energy security, and global economic governance. The United States, according to some reports, sees this format as a way to restructure the global security and economic architecture. A direct "connection of technology economies" involving all five countries has not yet been observed, but formats that could lead to this are being discussed, especially if the geopolitical situation changes.

The future ecosystem of the Core5 corporate digital transformation strategy, as a future platform ecosystem (2026–2030). Core5 is a future multi-industry digital platform uniting five key countries, each responsible for fundamental areas of life and business:

(1) CoreGov – the digital state.

- Integration with Gosuslugi, digital profile, eID, and the digital ruble.

- Automation of tax deductions, licensing, and vendor verification through Chestny ZNAK and the Unified Identification and Authentication System.

- Direct payments, subsidies, and grants for SMEs and startups—no paper applications.

(2) CoreTrade—a unified trade and logistics platform.

- Aggregation of Ozon, Wildberries, Avito, SberMarket, and marketplaces.

- A unified delivery system using drones and transport hubs.

- Transparent supply chains with digital twins and blockchain labeling.

(3) CoreData — a national trusted data environment.

- Centralized data exchange between businesses, the government, and citizens.

- Open APIs for developers with regulatory compliance.

- Personal data protection through quantum encryption and edge computing.

(4) CoreAI — an artificial intelligence platform.

- Access to national AI models.

- Content generation, business process automation, service personalization.

- Integration with digital twins of enterprises and smart cities.

(5) CoreEco — an environmental and energy platform.

- Accounting for the carbon footprint of companies and citizens.

- Trading of green certificates, integration with renewable energy projects.

- Smart energy grids, platforms for energy exchange between households.

(6) Key technologies underlying Core5:

- Artificial intelligence — for behavior analysis, prediction, and automation.

- Blockchain and Web3 — for transparency and decentralization.

- Digital twins — for industrial, logistics, and urban management.

- Open API and microservices — for flexible integration.

- Edge computing — for fast data processing.

(7) Platform economy as a foundation.

A platform economy is a model in which value is created by products and the interactions of participants through a digital ecosystem. In the case of the Core5, this means creating a unified digital platform where participating countries exchange data, resources, technologies, logistics flows, and financial instruments (including digital currencies). Such a platform could function as a global digital marketplace, uniting producers, consumers, suppliers, and developers from all five countries.

(8) Infrastructure base. Connecting economies will require:

- A unified API system for data exchange between public and private platforms.

- Digital twins of national economies for modeling interactions.

- Cloud and edge computing to reduce latency and improve fault tolerance.

- Digital ruble, yuan, rupee, yen, and dollar – integrated into a single settlement mechanism, possibly on a blockchain platform (Web3).

(9) Benefits of Core5.

- Reduced transaction costs between the world's largest economies.

- Accelerated time-to-market for joint products and technologies.

- Creation of an open ecosystem for startups and SMEs.

- Collaboration on global challenges: climate, energy, food, security.

- Simplifying market entry for startups.

- Accelerating the digital transformation of business and government services.

- Increased investment and job creation.

Today, Core5—an initiative to connect economies through digital platforms—is a real possibility and is already being implemented within other associations. Core5 has the potential to become a powerful driver of global digital transformation, provided it is accountable, transparent, and aligned with common interests.

The integration of the economies of the United States, China, Russia, India, and Japan (the Core5 project countries) can be achieved based on the UN principles of sustainable development (Evgeny Bryndin, 2025h).

The integration of economies can begin in the Core3 format of three countries: China, Russia, and India (Evgeny Bryndin, 2022; Evgeny Bryndin, 2021; Evgeny Bryndin, 2025i). Financial transactions can be carried out on the basis of a single cryptocurrency, using blockchain technology.

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Research on the Protection Path of Minority Shareholders' Rights and Interests Under the Mandatory Delisting System

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Abstract

With the continuous development of the capital market, the mandatory delisting system has become an important means to maintain market health. Since the implementation of the *Opinions on Strictly Implementing the Delisting System*, the number of listed enterprises subject to mandatory delisting has increased sharply, significantly enhancing the market's capacity for clearing out inefficient entities. However, the issue of minority shareholders' rights and interests being impaired during the delisting process has become increasingly prominent, making the protection of these rights a major social concern. Taking the mandatory delisting case of Guanghui Automotive, whose stock closed below 1 yuan for 20 consecutive trading days, as the research object, this paper explores the internal and external causes of the company's mandatory delisting against the backdrop of the current delisting system. It further analyzes the root causes of the infringement on minority shareholders' rights and interests, and proposes targeted counter-measures including improving the information disclosure system, strengthening accounting supervision, implementing compensation mechanisms, perfecting the representative litigation system, and enhancing investor education. This study aims to provide theoretical support and practical reference for protecting minority shareholders' rights and interests under the capital market delisting system, and promote the construction of a more fair, transparent, and efficient capital market environment.

Keywords: mandatory delisting, minority shareholders' rights and interests, information disclosure

1. Introduction

Mandatory delisting refers to the termination of a listed company's listing qualification by securities regulatory authorities and exchanges in accordance with laws and regulations when the company fails to meet listing standards, such as non-compliant stock market prices, poor operating conditions, or serious violations of securities exchange rules or regulatory laws. The Shanghai Stock Exchange, Shenzhen Stock Exchange, and Beijing Stock Exchange classify delisting into voluntary delisting and mandatory delisting, with the latter further divided into four categories: trading-based delisting, financial-based delisting, regulatory compliance-based delisting, and major violation-based delisting. Unlike voluntary delisting, mandatory delisting does not require an application from the issuer. When a listed company triggers specific delisting criteria, regulators or exchanges directly issue a delisting ruling and force the relevant securities to withdraw from market trading. The core objectives of mandatory delisting are to maintain the standardization of securities market operations, protect the legitimate rights and interests of investors, and thus promote the healthy development of the market.

Amid sluggish economic recovery, China's new energy vehicle sector has disrupted the traditional fuel vehicle market. Coupled with sufficient supply chains and changing consumer demand, the automotive industry has entered a period of profound restructuring. In 2024, 6 automotive companies were delisted, tying with the power equipment industry for the highest number of delistings. Among them, 3 companies including Guanghui Automotive and Jianye B were delisted due to stock price below par value, while 2 were delisted for failing to meet financial indicators. Industry-wide operational pressures are prone to triggering financial and regulatory compliance issues, ultimately leading to delisting. As a key part of the automotive industry chain, dealers face dual pressures from upstream brand authorization adjustments and downstream market demand changes. Once a leading domestic automotive dealer group, Guanghui Automotive was subject to trading-based delisting after its stock closed below 1 yuan for 20 consecutive trading days, and was transferred to the New Third Board for trading in 2025. Following delisting, the company fell into multiple crises, resulting in severe damage to minority shareholders' rights and interests. Some minority shareholders spontaneously organized class actions, collecting authorizations and loss information through online platforms, but faced high costs and difficulties in evidence collection during the rights protection process. Delisting has led to the failure of corporate governance and asset freezes, which have undermined the company's compensation capacity. This not only exacerbates the difficulties faced by minority shareholders in protecting their rights, but also exposes the gap between individual rights protection efforts and institutional safeguards. Since the implementation of the new delisting regulations, the contradiction between the sharp increase in mandatory delistings and the weak rights protection mechanism has become increasingly prominent. How to protect minority shareholders' rights and interests, address the current delisting system's shortcomings of prioritizing market clearing over investor protection, and strengthen accounting supervision have become pressing issues.

Regarding research on the causes of mandatory delisting, Abdelhakeem A (2025) explored the potential impact of corporate governance reforms on delisting from the Egyptian Exchange, finding that approximately 60% of delisted enterprises were forced to withdraw due to non-compliance with corporate governance regulations. Du Yan (2024), through a case study of ST Kedi, identified flaws in financial indicators, corporate governance structures, violations of information disclosure rules, and dereliction of duty by audit institutions as the fundamental causes of mandatory delisting. Yang Yi (2025) argued that to ensure the smooth operation of the capital market's exit mechanism, the delisting system is an important supporting measure for the registration-based reform. In terms of research on minority shareholders' rights protection, Yuji Lin (2025) pointed out that the weak information disclosure system in securities laws allows some enterprises to engage in selective disclosure and conceal important information, exacerbating information asymmetry between minority shareholders and controlling shareholders. Using voting data of minority shareholders collected by Chen Yunsen et al. (2025), the study indicated that the registration-based reform has promoted the awakening of minority shareholders' awareness of exercising their rights by enhancing their motivation to participate in corporate governance and their ability to utilize information. Ma Deshui et al. (2023), taking the Kangmei Pharmaceutical case as an example to study delisting in the pharmaceutical industry, argued that the participation of the China Securities Investor Services Center in litigation can stimulate and encourage minority shareholders to actively protect their rights. Yan Qiyue et al. (2025) proposed promoting the reconstruction of corporate governance and strengthening minority investors' awareness of rights protection and their participation in corporate management. By sorting out special investor protection cases across "five regions and three jurisdictions", Mao Yirong (2025) proposed constructing a four-dimensional collaborative system of "regulation, judicature, market, and enterprises": at the regulatory level, strengthen penetrating supervision over information disclosure and impose rapid penalties for violations. Jin Xuan (2024), Shen Bing & Long Xingliao (2022), and Kusuma et al. (2025) all put forward suggestions on improving the information disclosure system, dispute resolution mechanisms, and special representative litigation systems to address the damage to minority investors' interests caused by mandatory delisting.

In summary, existing research on mandatory delisting focuses on the period of institutional reform, with an emphasis on the implementation of the new *Company Law*, registration-based reform, and the normalization of delisting. Research on minority shareholders' rights protection has shifted from macro-institutional studies to the implementation of micro-mechanisms, generally characterized by the integration of theory and practice and multi-perspective analysis. However, existing research has two shortcomings: first, there is a lack of in-depth studies on how listed companies can practically protect minority shareholders' rights and interests under the new delisting regulations; second, there is insufficient industry pertinence, making it difficult to adapt to the characteristics of automotive industry distributors. Based on domestic and foreign research, this paper takes the delisting of Guanghui Automotive as a case study, starting from the new delisting regulations, combining industry characteristics and enterprise data to analyze the specific impact of mandatory delisting on the protection of minority shareholders' rights and interests, and explore corresponding protection paths. This study aims to enrich the theoretical research on minority shareholders' rights protection in the automotive dealer industry and provide more targeted reference for corporate practice.

2. Analysis of the Causes of Guanghui Automotive's Mandatory Delisting

On June 21, 2024, Guanghui Automotive issued a warning announcement stating that its stock closed at 0.98 yuan per share on June 20, 2024, falling below 1 yuan for the first time and facing the risk of delisting due to stock price below par value. By July 17, 2024, the company's stock had closed below 1 yuan for 20 consecutive trading days, triggering the delisting conditions. On August 21, 2024, Guanghui Automotive issued an announcement on the termination of listing and delisting of its stocks and convertible corporate bonds. Compared with its peak market value of over 100 billion yuan, the company's market value plummeted to only 6.471 billion yuan on the delisting day, a decrease of nearly 94%. After being forcibly delisted, Guanghui Automotive was transferred to the New Third Board, where its stock price further dropped to 0.07 yuan per share, and the company fell into multiple crises following delisting.

An in-depth analysis of the causes of Guanghui Automotive's mandatory delisting reveals the following aspects:

2.1 Macroeconomic Pressure

China's macroeconomic operation has gradually entered a recovery track, but the international political and economic situation has become increasingly complex and severe, with the global economic recovery remaining sluggish and high inflation persisting. Affected by these factors, China's economic development continues to face pressure, and the momentum of consumer confidence and demand recovery has fallen short of expectations. As shown in Figure 1, China's overall GDP has maintained an upward trend, but the year-on-year growth rate experienced declines and significant fluctuations in 2020 and 2022.

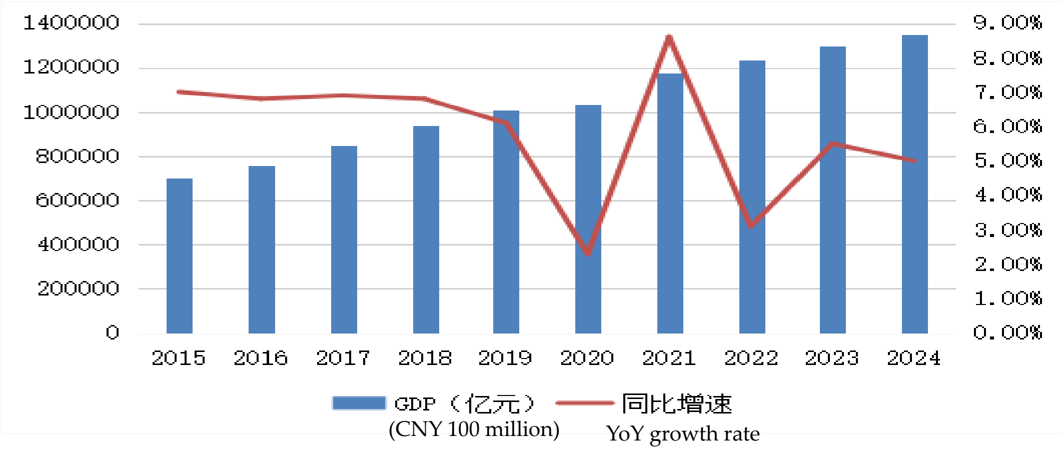

Figure 1. Changes in China's GDP Growth Rate (2015-2024)

Data source: National Bureau of Statistics.

Supported by steady growth policies in 2023, the domestic automotive industry chain and supply chain accelerated their recovery, and automotive consumption rebounded rapidly. However, after the initial rapid recovery driven by policies, the overall operation of the automotive industry still faces significant challenges, and the industry remains in a phase of slow recovery. Currently, the complex and volatile external environment has a major impact on consumer confidence, with some consumers showing weak confidence in spending. First-time car purchase demand has underperformed compared with replacement demand. To further stimulate automotive consumption, the central government and local governments have successively introduced relevant consumption policies, combined with various regional auto shows and shopping festivals. Although these measures have achieved certain results, their sustainability is relatively limited, and the release of demand has not met expectations. Against the backdrop of the contradiction between excessive capacity release and relatively insufficient demand in the automotive industry, market supply-demand imbalance has triggered price wars. Automotive dealers are thus forced to continuously adjust their strategies under the dual pressures of accelerated product transformation and intensified market competition.

2.2 Intensified Industry Transformation

In recent years, China's automotive industry has been in a critical period of transformation and upgrading. The 2024 Government Work Report proposed consolidating and expanding the leading advantages of industries such as intelligent connected new energy vehicles and boosting bulk consumption of intelligent connected new energy vehicles. The rise and vigorous development of new energy vehicles have continuously squeezed the market space of traditional fuel vehicles, leading to increasingly fierce competition in the fuel vehicle market. Independent brands, new energy vehicles, and export business have become the core drivers of industry growth. With the rapid development of new energy vehicles, the pattern of the domestic automotive terminal market has undergone significant changes in a short period, and the trend of new energy vehicles replacing traditional fuel vehicles has become increasingly obvious. As the end of the automotive industry chain, the automotive distribution service industry is in a stage of digesting various adverse factors brought about by industry adjustments, coupled with the slow recovery of the automotive consumer market. To seize market share, various automotive brands have intensified price competition in the passenger car market, which has had a profound impact on the automotive dealer industry. The economic interests of automotive dealers at the end of the industry chain have been further squeezed, leading to increased capital and operational pressures, rising operational risks, and a growing proportion of loss-making enterprises. The profit and loss situation of the automotive dealer industry from 2015 to 2024 is shown in Figure 2.

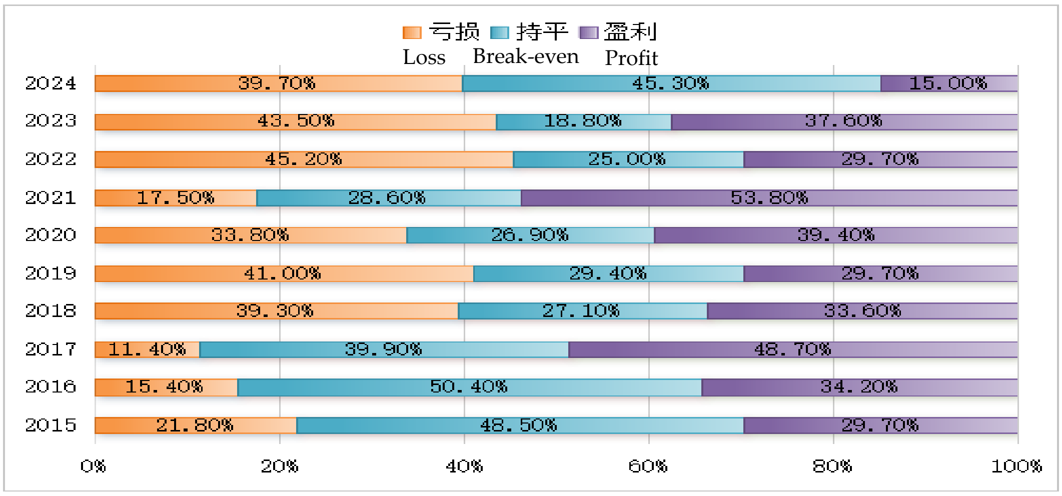

Figure 2. Profit and Loss Ratio of Domestic Automotive Dealers (2015-2024)

Data source: China Automobile Dealers Association.

As shown in Figure 2, the proportion of loss-making automotive dealers has increased year by year over the past decade, while the levels of profitability and break-even have fluctuated significantly, showing an inverse relationship. In 2023, the proportion of loss-making dealers reached 43.5%, compared with 37.6% of profitable dealers and 18.8% of break-even dealers, marking a high point of loss ratio in recent years. However, as the link closest to the terminal market in the automotive industry chain, leading automotive dealers possess mature and indispensable resources such as distribution networks, after-sales service systems, supporting services, and refined management, which will remain a key link in promoting the restructuring of the entire automotive consumer market.

2.3 Gradually Tightened Delisting System

The delisting system is a key basic system of the capital market. Since the issuance of the *Implementation Plan for Improving the Delisting Mechanism of Listed Companies* in 2020, the normalization of the delisting system has been initiated. To further deepen the reform, achieve a pattern of orderly entry and exit and timely market clearing, and better protect the legitimate rights and interests of minority shareholders, the China Securities Regulatory Commission (CSRC), based on a careful summary of reform experience and full consideration of national conditions and market conditions, issued the *Opinions on Strictly Implementing the Delisting System* in April 2024. The three major exchanges in Shanghai, Shenzhen, and Beijing have simultaneously implemented the reform requirements, revised and issued new rules, further tightened mandatory delisting standards, broadened diversified exit channels, increased efforts to clear out zombie enterprises and bad actors, and strengthened the protection of investors in delisted companies. The CSRC has severely cracked down on market manipulation and insider trading behind "shell speculation" to maintain trading order; strengthened supervision over information disclosure and transaction monitoring, urging companies to promptly disclose delisting risks; and intensified regulatory efforts against violations aimed at evading delisting, resolutely delisting companies that meet delisting criteria. The number of A-share listed companies delisted from 2015 to 2024 is shown in Figure 3.

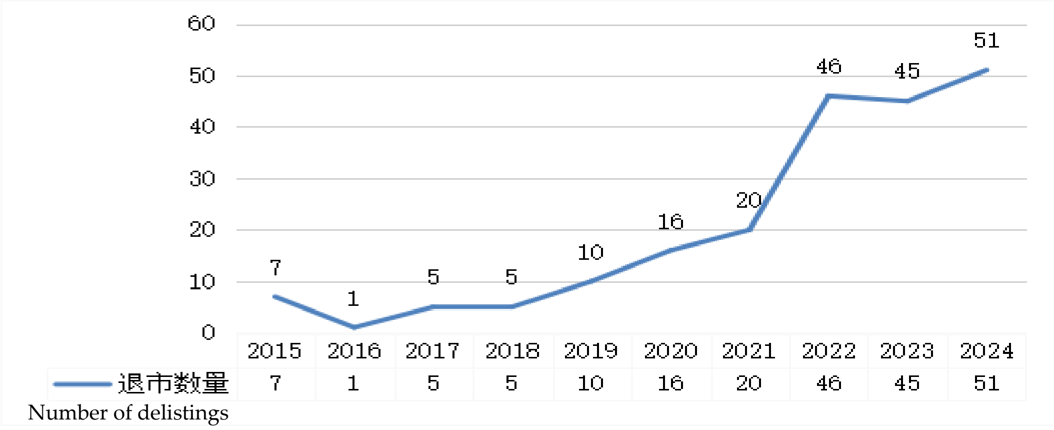

Figure 3. Number of Delisted A-share Listed Companies (2015-2024)

Data source: Shanghai Stock Exchange and Shenzhen Stock Exchange.

As shown in Figure 3, the number of delisted A-share listed companies reached 51 in 2024, setting a new record. Among them, 39 were subject to trading-based mandatory delisting, 10 to financial-based mandatory delisting, 1 to major violation-based mandatory delisting, and 1 to voluntary delisting, with trading-based delisting accounting for more than 70%, mostly due to stock prices falling below par value. With the strict implementation of the new delisting regulations, the normalized delisting mechanism has been gradually improved, which is crucial for further strengthening the virtuous cycle of survival of the fittest in the capital market.

2.4 Decline in Corporate Operating Performance

The overall economic downturn and price wars launched by major automakers to compete for market share have led to a continuous decline in automotive sales prices, which has had a certain impact on the market order of the automotive industry and corporate profits, especially bringing enormous operational pressure to distributors like Guanghui Automotive.

2.4.1 Overall Performance

Guanghui Automotive's operating income showed a steady upward trend from 2015 to 2019, but peaked in 2019 and has been on a downward trend since 2020. As shown in Figure 4, the operating income remained relatively stable in 2020 and 2021, and dropped to 133.544 billion yuan in 2022. In terms of net profit, there has been a relatively obvious fluctuation with a downward trend. The net profit reached 2.046 billion yuan in 2021, turned into a loss of 2.719 billion yuan in 2022, and rebounded to 629 million yuan in 2023. In 2022, the company not only suffered its first loss since listing, but also ended its 11-year consecutive record of being the industry leader. Although there was a recovery in 2021 and 2023, the overall trend was not favorable. In the first half of 2024, the net profit was -686 million yuan, falling into loss again.

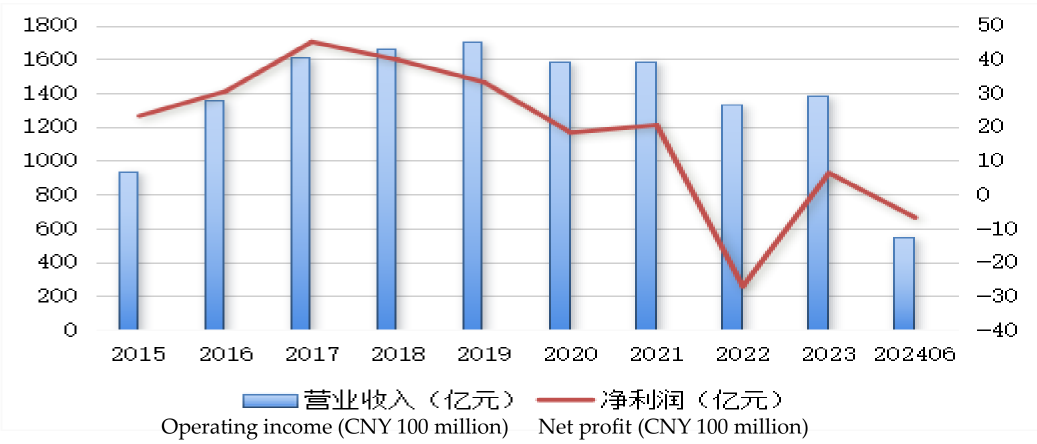

Figure 4. Changes in Operating Income and Net Profit of Guanghui Automotive (2015-2024)

Data source: Annual Reports of Guanghui Automotive (Note: Since Guanghui Automotive only disclosed financial data for January-June 2024, all financial data in this paper are up to June 2024.)

2.4.2 Gradually Diminishing Profitability

As shown in Figure 5, Guanghui Automotive's sales gross profit margin and net profit margin have shown a trend of decline followed by recovery since 2019. Although there was a rebound in 2021 and 2023, neither has exceeded the 2019 level. The sales gross profit margin stood at 6.48%, 8.29%, and 7.87% from 2022 to June 2024, respectively, while the corresponding net profit margin was -2.04%, 0.46%, and -1.26%. The net profit margin fell into negative territory in 2022 and June 2024, reflecting the gradual decline in the company's operating conditions in recent years.

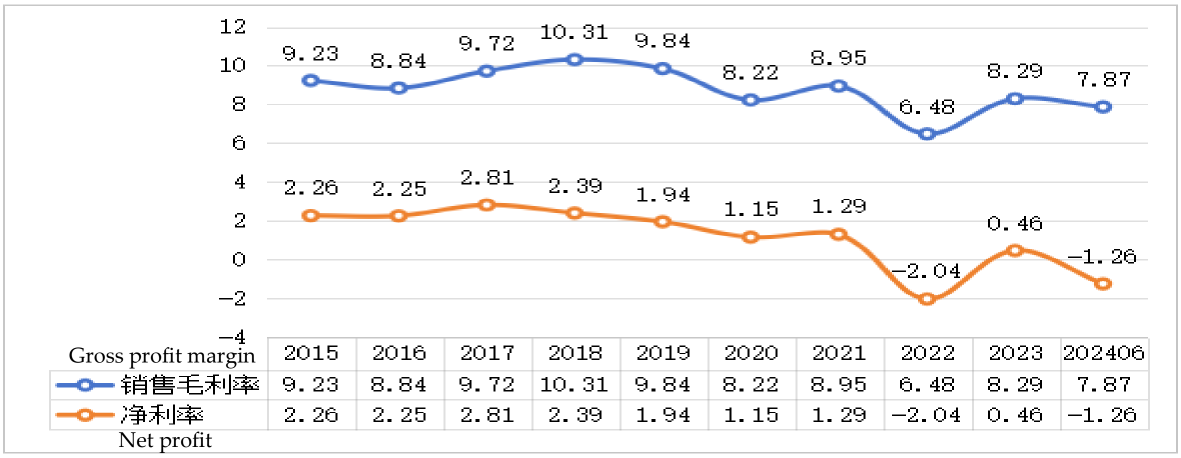

Figure 5. Changes in Sales Gross Profit Margin and Net Profit Margin of Guanghui Automotive (2015-2024)

Data source: Compiled based on East Money Information Co., Ltd.

2.4.3 Income Structure Analysis

In the current domestic automotive sales market, most dealers still focus on traditional fuel vehicle sales as their core business. However, with the steady increase in the market share of new energy vehicles, coupled with the intensifying automotive price wars since 2023 and the accelerated popularization of the direct sales model, dealers at the end of the automotive industry chain are facing pressure from multiple aspects. The changes in the proportion of Guanghui Automotive's income structure in 2023 are shown in Figure 6.

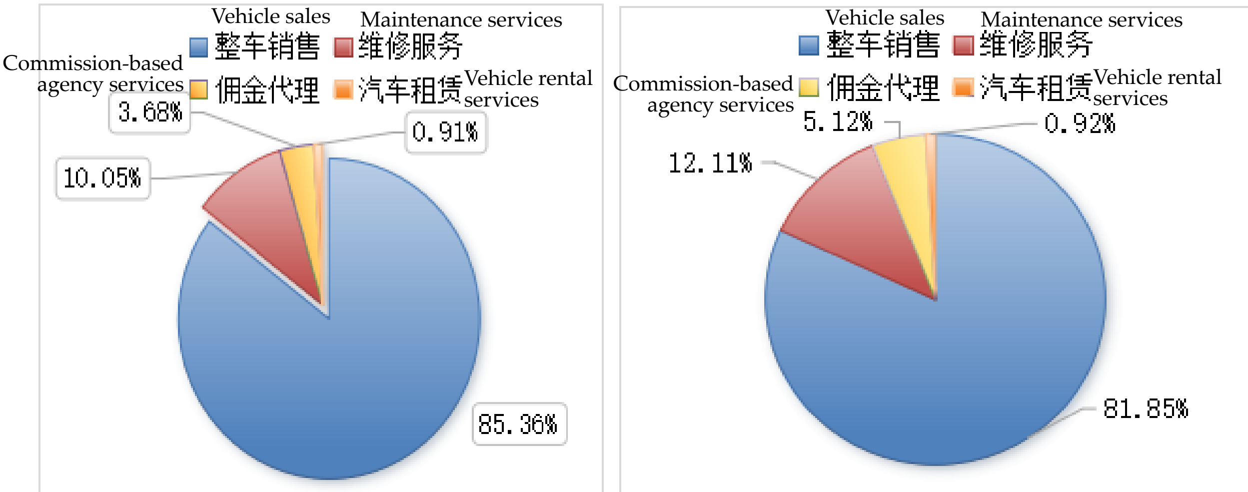

Figure 6. Distribution of Main Business Income Structure of Guanghui Automotive in 2023

Data source: Type and proportion of main business income in Guanghui Automotive's 2023 Annual Report.

Against the backdrop of price wars, the profitability of automotive dealers has further weakened, with losses from new car sales being one of the biggest challenges. As shown in Figure 6, like most dealers, Guanghui Automotive focuses on vehicle sales. Compared with 2023, the proportion of vehicle sales in main business income decreased by 3.51% in the first half of 2024, while the proportion of maintenance services increased by 2.06%, showing the most significant growth. The proportion of commission agency and leasing business remained almost unchanged. The increase in the proportion of maintenance services indicates a slight enhancement in the contribution of non-sales businesses. Although adjustments have been made to the business strategy, the profit margin of vehicle sales has been continuously compressed and rebates have been delayed, ultimately leading to losses in the first half of 2024.

3. The Impact of Guanghui Automotive's Mandatory Delisting on Minority Shareholders' Rights and Interests

3.1 Information Disclosure Violations Exacerbate Information Asymmetry

Information disclosure violations have a multi-faceted impact on the decision-making of minority shareholders. Information asymmetry prevents minority shareholders from accurately understanding the true situation of the company, putting them at a disadvantage in investment decision-making. Most minority shareholders can only rely on the information disclosed by the company to evaluate its value and risks, and then make investment decisions. In the 10 trading days before delisting, Guanghui Automotive issued an optimistic announcement stating that it "is advancing the transformation to new energy vehicles" but failed to warn of the risk of delisting due to stock price below par value. At that time, the company's stock price had been in a prolonged slump, and the risk of delisting was imminent, yet the company did not truthfully inform minority shareholders of this critical situation in the announcement. On the contrary, the release of such an optimistic announcement was likely to mislead minority shareholders, making them believe that the company's operating conditions were sound and its future development prospects were promising, thus choosing to continue holding or buying the company's stock. According to statistics, 32,000 minority shareholders bought the stock in the price range of 0.8-1 yuan, ultimately becoming "bag holders". Misled by the company's false information, these minority shareholders bought the stock without full knowledge of the risks and ultimately suffered heavy losses as the company was delisted.

When a company discloses false information or deliberately conceals key information that would have a significant impact on investors, minority shareholders, who are in a disadvantaged position in terms of information access, will make incorrect investment judgments, thereby suffering losses to their economic interests. Such violations also undermine market fairness and transparency, and damage market confidence. If investors lose trust in the information disclosed by companies, it will have a negative impact on the healthy development of the entire capital market, weakening its vitality and dynamism.

3.2 Liquidity Exhaustion and Direct Economic Losses

The most direct impact of delisting on minority shareholders is the sharp decline in stock prices. For creditors, the company's fund shortage has led to overdue loans, while for suppliers, payment for goods has been delayed. As shown in Figure 7, after the delisting announcement was released, Guanghui Automotive's stock price plummeted sharply, and the market value of the stocks held by minority shareholders also shrank accordingly. Many minority shareholders bought the stock at a relatively high price, and after delisting, the stock price may drop to an extremely low level, resulting in a substantial loss of investment principal. The value of their stocks may be reduced to only a fraction of the original price or even lower, potentially wiping out years of savings. Liquidity exhaustion is another important issue. After delisting, the trading of the company's stock on the main board market is restricted, and liquidity is greatly reduced, making it extremely difficult for minority shareholders to cash out their stocks, which may become a "hot potato". Due to the far lower trading activity of the New Third Board compared with the main board market, it is difficult for minority shareholders to find suitable buyers on the New Third Board, and even if they can sell their stocks, they may have to do so at a much lower price, further expanding their losses. Reduced dividends are also inevitable. As the company's operating conditions have already deteriorated, its profitability has dropped significantly, and its ability to pay dividends has been severely affected. Minority shareholders originally expected to obtain a certain return on investment through dividends, but after delisting, dividends may be reduced or even completely cancelled, which will further damage their economic interests.

Figure 7. Stock Price Trend of Guanghui Automotive Before Delisting

Data source: East Money Information Co., Ltd.

4. Root Causes of the Infringement on Minority Shareholders' Rights and Interests

4.1 Deficiencies in Internal Corporate Governance

As shown in Table 1, Xinjiang Guanghui Industrial Investment (Group) Co., Ltd. is the largest shareholder of Guanghui Automotive, holding a high proportion of shares that enable it to exert a decisive influence on the company's decision-making process and strategic direction, and thus possess absolute control power. The combined shareholding ratio of CGAML and Guanghui Group exceeds 50%, reflecting their controlling power over Guanghui Automotive. It can also be seen that although other minority shareholders also have voting rights, their low shareholding ratios make it difficult for them to play a decisive role in the company's decision-making process. Sun Guangxin holds more than 50% of the shares of Guanghui Group, which is equivalent to indirectly controlling Guanghui Automotive, making him the actual controller of the company. He can also easily gain access to the general meeting of shareholders and control the board of directors and the audit committee. When Guanghui Group conducts equity pledges, the management and minority shareholders have limited ability to restrict such actions.

Table 1. Top 10 Shareholders of Guanghui Automotive in 2024

Shareholder Name	Number of Shares Held (10,000 shares)	Shareholding Ratio (%)
Xinjiang Guanghui Industrial Investment (Group) Co., Ltd.	2,526,119.6	31.14
CHINA GRAND AUTOMOTIVE (MAURITIUS) LIMITED	1,620,000.0	20.00
Blue Chariot Investment Limited	189,049.9	2.33
Guanghui Industrial Corporation Pledge Special Account	111,527.2	1.37
Shaanxi International Trust · Jinyu No.11 Securities Investment Collective Fund Trust Plan	69,565.2	0.86
Hong Kong Securities Clearing Company Limited	57,963.9	0.71
Gu Hefu	54,152.2	0.67

Shareholder Name	Number of Shares Held (10,000 shares)	Shareholding Ratio (%)
Guohua Life Insurance Co., Ltd. - Own Funds	50,847.8	0.63
Ma Guoqin	46,860.0	0.58
Wu Fang	46,489.4	0.57

Data source: 2024 Annual Report of Guanghui Automotive.

From 2015 to 2023, Guanghui Automotive conducted equity pledges frequently, with a total of 82 pledge executions and 51 pledge cancellations during this period, amounting to 133 transactions in total, indicating the frequency of equity pledges by the company, which has taken equity pledge as its main financing method. Equity pledge by controlling shareholders will lead to the separation of control rights and cash flow rights, allowing controlling shareholders who hold control rights to influence the company's internal governance, weakening the supervisory and management functions of effective internal controls, thereby triggering interest encroachment behaviors and damaging corporate value. The equity pledge behavior of controlling shareholders will affect the company's investment preferences, which is likely to lead to inefficient investment or over-investment, exacerbating cash flow constraints and financial risks, and affecting corporate performance. In the long run, such behavior may damage corporate value and the rights and interests of minority shareholders. The equity pledge behavior of controlling shareholders will also affect the economic behaviors of other non-controlling major shareholders, increasing the instability of the equity structure and the difficulty of financing, undermining trust and cooperation among shareholders, and harming the long-term development of the company. In 2016, Guanghui Group illegally transferred 200 million yuan from Guanghui Automotive's fund-raising special account to its own account without approval, reflecting that Guanghui Group's control over the subsidiary's finances has seriously damaged the subsidiary's capital security and independence. In addition, Guanghui Group used the name of Guanghui Automotive to provide guarantees for itself without going through relevant approval procedures. When pursuing the maximization of corporate value, the controlling shareholder failed to balance the protection of the interests of relevant stakeholders, reflecting the company's governance problems.

4.2 Inadequate External Supervision

In the delisting incident of Guanghui Automotive, regulatory authorities were derelict in their duties, and regulatory work suffered from lag, failing to detect the company's violations in a timely manner. When the company faced problems such as prolonged stock price slump and deteriorating operating conditions, regulatory authorities failed to take effective measures in a timely manner, neither supervising the company to strengthen risk management nor safeguarding the rights and interests of minority shareholders promptly. Regarding the company's information disclosure violations, such as concealing fund occupation and failing to warn of delisting risks, regulatory authorities did not intervene in investigations and disposal in a timely manner, resulting in minority shareholders suffering losses without full knowledge of the facts.

Insufficient coordination between regulatory authorities is also a prominent problem. When Guanghui Automotive conducted equity pledges, the pledge announcements only included basic information such as time and ratio, and did not explain key information such as specific purposes and capital flow directions, yet regulatory authorities did not conduct in-depth investigations and handling of this issue. The delisting process of Guanghui Automotive involved multiple regulatory authorities including the CSRC, stock exchanges, and local financial bureaus, but the lack of effective communication and coordination mechanisms among these departments led to regulatory loopholes. Weak regulatory enforcement has had a serious negative impact on the protection of minority shareholders' rights and interests. Regulatory lag has prevented the timely correction of the company's irregular operations, leaving the rights and interests of minority shareholders in a state of being infringed upon.

4.3 Inadequate Institutional Construction and Implementation

China's current delisting system has shortcomings, one of which is the excessive reliance on the rule of delisting due to stock price below par value. Guanghui Automotive was delisted for triggering the par value delisting clause after its stock closed below 1 yuan for 20 consecutive trading days. Although this rule seems simple and clear, it has many drawbacks. Stock prices are affected by various factors such as market sentiment and macroeconomic environment, and are highly volatile, making it difficult to accurately reflect the company's true value and operating conditions. The decline in Guanghui Automotive's stock price cannot be entirely attributed to poor management; external factors such as the overall market downturn and intensified industry competition have also played a significant role. Deciding whether to delist a company solely based on its stock price below par value may lead to the wrongful delisting of some companies with sound fundamentals, ultimately harming the rights and interests of minority shareholders.

The lack of supporting compensation mechanisms is another flaw in the delisting system. When a listed company is delisted for various reasons, minority shareholders often suffer huge economic losses due to the sharp decline in stock prices leading to asset impairment and the inability to cash out in a timely manner. At present, China does not have a sound compensation mechanism, making it difficult to effectively compensate minority shareholders for their losses. In the delisting incident of Guanghui Automotive, since the company was not delisted due to financial fraud or major violations of laws and regulations, it could not trigger the "investor compensation during the delisting transition period" clause in the *New Delisting Regulations*, forcing minority shareholders to bear all losses on their own. This situation is not only unfair to minority shareholders, but also weakens investors' confidence in the market, affecting its healthy development.

4.4 Limitations of Minority Shareholders Themselves

Minority shareholders have deficiencies in professional knowledge and information acquisition capabilities. When faced with Guanghui Automotive's financial statements, minority shareholders may be unable to identify existing problems, leading to incorrect investment decisions.

4.4.1 Inadequate Information Acquisition Capabilities

In terms of information acquisition, minority shareholders have always been in a relatively passive and disadvantaged position. Information about listed companies is mainly released through announcements, news media and other channels. Minority shareholders have relatively narrow channels for obtaining information and often lag behind in the timeliness of information reception. Compared with controlling shareholders and management, minority shareholders cannot promptly understand the company's internal situation and major decisions, making them more vulnerable to misleading under conditions of information asymmetry. The optimistic announcement issued by Guanghui Automotive before delisting may have misled minority shareholders into believing that the company's operating conditions were sound, while ignoring the potential risk of delisting.

4.4.2 Blindness in Investment Decision-Making

Investment itself requires certain professional knowledge such as financial analysis and industry research to accurately judge the value and potential risks of listed companies. However, most minority shareholders have not received systematic financial knowledge training, have limited ability to analyze financial statements, and struggle to accurately judge the company's operating conditions and development prospects from complex financial data. Due to their lack of professional knowledge and information acquisition capabilities, minority shareholders tend to make blind investment decisions. They lack in-depth research on the market and the company, and make investment decisions based solely on intuition or the recommendations of others, making them vulnerable to market sentiment and falling into the trap of chasing rising prices and selling at falling prices. When Guanghui Automotive's stock price was rising, some minority shareholders may have blindly followed the trend to buy, and when the stock price fell, they sold in a panic, resulting in losses on their investments. The weak awareness of rights protection among minority shareholders is also a common problem. When their rights and interests are infringed upon, many minority shareholders are unclear about the legal channels available to protect their rights, or choose to abandon their rights protection efforts due to high costs and complex procedures. In the delisting incident of Guanghui Automotive, although a large number of minority shareholders suffered huge losses, only a small number chose to claim compensation through legal channels, while most chose to silently bear the losses. This not only means that the rights and interests of minority shareholders are not effectively protected, but also to a certain extent condones the irregular behaviors of listed companies and controlling shareholders.

5. Paths for Protecting Minority Shareholders' Rights and Interests After Guanghui Automotive's Mandatory Delisting

5.1 Strengthen Compliance Supervision Over Information Disclosure by Listed Companies

In the supervision of the US capital market, information disclosure supervision is carried out for different industries, with industry-specific key indicators reflecting the competitiveness and risks of enterprises in the sector. Since the implementation of the registration-based reform in China's capital market, supervision has been strengthened at all links, and a comprehensive chain supervision system has been continuously improved to resolutely crack down on violations, enhance the deterrent effect of law enforcement and information transparency, and promote the further purification of the capital market. The CSRC can continue to strengthen the penalties for listed companies that violate information disclosure regulations, and at the same time clarify the requirements for information disclosure regarding corporate finances, risks, and operations, forming a sufficient deterrent to make enterprises fully aware of the serious consequences of violating the information disclosure system. The key to reducing such violations is to maintain consistent penalty intensity for different types of information disclosure violations. The information disclosure obligations of intermediary institutions can be increased. At present, minority shareholders often rely on the credibility of intermediary institutions to judge listed companies, so intermediary institutions must exercise due diligence. Enterprises can use blockchain technology and data visualization to improve information transparency, and establish direct communication channels with minority shareholders to increase communication and interaction.

5.2 Improve the Internal Corporate Governance Structure

5.2.1 Optimize the Equity Structure

Guanghui Automotive should take measures to diversify its equity and prevent excessive concentration in the hands of a few shareholders. The shareholding ratio of controlling shareholders can be reduced through private placements and the introduction of strategic investors, thereby enhancing the checks and balances effect of the equity structure. When conducting private placements of new shares, the company can issue shares to multiple different investors to increase the number of shareholders and reduce the shareholding ratio of individual shareholders. Strategic investors with rich industry experience and resources, such as upstream and downstream enterprises in the automotive industry or financial institutions, can be introduced. These strategic investors can not only inject capital into the company, but also provide reasonable suggestions for its development and help achieve the goal of collaborative development by virtue of their professional knowledge and resources.

Optimizing the equity structure can balance the power of controlling shareholders. When equity is diversified, controlling shareholders will find it difficult to unilaterally control the company's decision-making by virtue of their absolute holding position, which can reduce the possibility of controlling shareholders damaging the rights and interests of minority shareholders for their own selfish interests. Different shareholders can form a mutual restraint relationship, and all parties can fully express their opinions when making corporate decisions, leading to more scientific and fair decisions. The introduction of strategic investors can also bring new management concepts and technologies to the company, improve its governance level and competitiveness, and fundamentally protect the rights and interests of minority shareholders.

5.2.2 Strengthen Internal Control and Supervision

First, improve the internal control system. Establish and improve internal control elements such as risk assessment, control activities, information and communication, and internal supervision. Formulate detailed internal control rules and implement them at all levels of the company to ensure that the company's operational activities are legal and compliant, capital is secure, and the information related to financial reports is true and reliable. Strengthen the control over key business links and high-risk areas such as fund management and investment decision-making, and establish an effective risk early warning mechanism to timely identify and resolve potential risks.

Second, strengthen the supervisory function of the audit committee of the board of directors. The audit committee should earnestly perform its supervisory duties, strengthen the inspection of the company's financial situation, business activities, and the behavior of the management. Regularly verify the company's financial statements to ensure the authenticity and accuracy of financial information, and supervise the company's major decisions and events to prevent the abuse of power by the management. Independent directors should maintain independence and professionalism, play a supervisory and balancing role in corporate governance, actively participate in strategic decision-making, issue independent opinions on major matters, and safeguard the rights and interests of minority shareholders.

Third, improve the efficiency and quality of internal audit. The internal audit department should conduct regular audit evaluations of the company's internal control system, timely identify defects and loopholes in the system, and put forward improvement suggestions. Attach importance to the application of internal audit results, promptly rectify the problems identified, and ensure that the internal control system is effectively implemented. By strengthening internal control and supervision, problems in the company's operation can be timely identified and corrected, risks can be prevented, and the infringement on the rights and interests of minority shareholders can be reduced.

5.2.3 Regulate the Behavior of the Management

First, improve the salary incentive and restraint mechanism, and closely link the salary of the management with the company's performance and long-term development. Design a reasonable salary structure, increase the proportion of performance bonuses, stock options and other salary components linked to corporate performance, and incentivize the management to strive to improve operating performance and maximize shareholder interests. Establish a strict salary restraint mechanism, reasonably control the salary level of the management, and prevent excessive pursuit of personal interests at the expense of the company and shareholders' interests due to excessively high salaries. For the management who causes the company's performance to decline or damages shareholder interests due to poor management, their salaries should be reduced or corresponding penalties should be imposed. Second, strengthen the integrity education of the management and clarify the accountability for legal liability. Regularly organize the management to participate in integrity training and legal education, help them enhance their awareness of integrity and legal literacy, and make them realize the importance of protecting shareholder interests. Establish and improve a legal liability investigation system, and in accordance with the law, investigate the civil liability, administrative liability, and even criminal liability of the management for illegal and irregular behaviors that damage shareholder interests. Finally, increase the penalties for violations to form an effective deterrent, and make the management consciously abide by laws, regulations and the company's articles of association, faithfully perform their duties, and protect the rights and interests of minority shareholders. By regulating the behavior of the management, the interest conflicts between the management and minority shareholders can be reduced, the company can achieve healthy and stable development, and the legitimate rights and interests of minority shareholders can be safeguarded.

5.3 Strengthen External Supervision and Institutional Construction

5.3.1 Improve the Delisting System

Optimize the rule of delisting due to stock price below par value to reduce the impact of stock price fluctuations on corporate delisting. Drawing on the experience of the United States and other countries, the period of consecutive trading days for triggering delisting can be extended from 20 to more than 60 trading days, giving listed companies sufficient time to improve their stock price performance. Introduce reference indicators such as corporate market value, operating income, and net profit to comprehensively evaluate whether a company should be delisted, avoiding delisting decisions based solely on stock price below par value. For companies whose stock price is temporarily below par value but have sound fundamentals and development potential, a certain buffer period can be granted to help them improve their operating conditions and boost their stock price through strengthened supervision and guidance.

5.3.2 Establish a Sound Compensation Mechanism

When the delisting of a listed company leads to damage to the rights and interests of minority shareholders, the subject of liability and the method of compensation should be clarified. For companies delisted due to their own reasons such as financial fraud and information disclosure violations, the company, controlling shareholders, and management should bear corresponding compensation liabilities; for companies delisted due to uncontrollable factors such as market conditions, consideration can be given to establishing a delisting investor protection fund, jointly funded by regulatory authorities, listed companies, securities companies and other parties, to provide appropriate compensation to minority shareholders. Clarify the scope and standards of compensation to ensure that the losses of minority shareholders can be reasonably compensated. By continuously improving the delisting system, delisting decisions can be made more scientifically and reasonably, the protection of minority shareholders' rights and interests can be strengthened, and the fairness and stability of the securities market can be maintained.

5.3.3 Strengthen Regulatory Coordination and Law Enforcement

Regulatory authorities such as the CSRC, stock exchanges, and local financial bureaus should strengthen collaborative cooperation and establish an effective communication and coordination mechanism. Clarify the division of responsibilities of each regulatory authority in the supervision of listed companies to avoid regulatory gaps and redundant supervision. In the delisting incident of Guanghui Automotive, all regulatory authorities should share information and jointly supervise the company's operating conditions, financial situation, and information disclosure to form a joint force of supervision. Establish a joint law enforcement mechanism to conduct coordinated investigations and punishments for illegal and irregular behaviors of listed companies, improving law enforcement efficiency.

Regulatory authorities should improve law enforcement efficiency and strengthen daily supervision and risk monitoring of listed companies. Establish and improve a regulatory indicator system, and use technical means such as big data analysis and artificial intelligence to timely detect abnormal situations and potential risks of listed companies. For the problems identified, timely investigations and handling should be carried out, and corresponding regulatory measures such as ordering rectification, imposing fines, and suspending listing should be taken to prevent the further deterioration of problems. Increase the penalties for illegal and irregular behaviors to raise the cost of violations for listed companies. For serious illegal and irregular behaviors such as information disclosure violations, financial fraud, and insider trading, severe penalties should be imposed in accordance with the law, not only punishing the company, but also imposing fines on relevant responsible persons, prohibiting them from entering the market, and investigating criminal liability, forming an effective deterrent to protect the rights and interests of minority shareholders. By strengthening regulatory coordination and law enforcement, the illegal and irregular behaviors of listed companies can be effectively curbed, the order of the securities market can be maintained, and the legitimate rights and interests of minority shareholders can be protected.

5.4 Promote the Improvement of Minority Shareholders' Awareness of Self-Protection

5.4.1 Strengthen Investor Education

Carry out a series of activities to popularize investment knowledge for minority shareholders, mainly to help them improve their professional skills and analytical capabilities. Through a combination of online and offline methods, organize investment lectures, training courses, seminars and other activities, inviting financial experts, scholars, investment consultants and other professionals to share investment basic knowledge, financial analysis methods, investment strategies and other content with minority shareholders. Provide a simulated investment platform to allow minority shareholders to learn investment skills and accumulate investment experience in practice, improving the scientificity and prudence of investment decision-making.

5.4.2 Enhance Risk Awareness and Rights Protection Education

Help minority shareholders understand the risks behind investment. Through case analysis, risk tips and other methods, introduce the risk characteristics of different investment products to minority shareholders, as well as the impact of risk factors such as market risks, credit problems, and industry changes on investments. Guide minority shareholders to establish a correct investment philosophy, rationally view investment returns and risks, and avoid blind following and excessive investment. At the same time, strengthen the publicity of rights protection to improve minority shareholders' awareness of rights protection. Popularize relevant laws, regulations and policies to minority shareholders, so that they understand their rights and obligations in the securities market, as well as the rights protection channels and methods available when their rights and interests are infringed upon. Through media publicity, distribution of publicity materials and other means, enhance minority shareholders' awareness of rights protection and encourage them to actively safeguard their own rights and interests. By strengthening investor education, the investment literacy and risk awareness of minority shareholders can be improved, their ability to protect their rights and interests can be enhanced, enabling them to better protect their own interests in the securities market.

5.4.3 Improve the Rights Protection Mechanism for Minority Shareholders

The construction of a centralized rights protection mechanism is a systematic project. First, establish a special rights protection assistance agency for minority shareholders to provide legal consultation, legal aid, and rights protection guidance services. The agency should be composed of professional lawyers, accountants, financial experts and other professionals with rich knowledge of securities laws and rights protection experience. When the rights and interests of minority shareholders are infringed upon, they can timely obtain professional help and support, reducing the difficulty of rights protection. Second, reduce the cost of rights protection for minority shareholders and improve the efficiency of rights protection. The rights protection procedures can be simplified, reducing cumbersome formalities and links, making it more convenient for minority shareholders to exercise their rights to protect their interests. Establish a small claims procedure to quickly resolve rights protection cases involving small amounts of money through simplified procedures, reducing the litigation costs of minority shareholders. Strengthen legal aid for rights protection cases and provide free legal services to minority shareholders with financial difficulties, reducing the economic burden of rights protection. Finally, improve the class action system, optimize the special representative litigation mechanism of the China Securities Investor Services Center, and enhance the rights protection capacity of minority shareholders. Drawing on the experience of class actions in the United States and other countries, clarify the scope of application, procedures and rules of class actions, lower the threshold for class actions, and allow more minority shareholders to participate in them. Strengthen the organization and guidance of class actions, encourage minority shareholders to unite and jointly safeguard their legitimate rights and interests. By improving the rights protection mechanism for minority shareholders, more effective rights protection channels and means can be provided for them, enhancing their ability to protect their rights and effectively safeguarding their legitimate rights and interests.

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