

An Examination of the Evolutionary Game of Enterprise Quality Supervision under Credit Linkage

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Abstract

This paper addresses resource misallocation and systemic risks caused by enterprises' passive compliance in China's enterprise quality supervision. To tackle these issues, an evolutionary game model is developed between enterprises and supervision authorities, incorporating dynamic credit adjustment. The model avoids distortion of supervisory motivation by designing a linkage between credit and supervision and ensuring incentive compatibility. Equilibrium stability is analyzed using the Jacobian matrix, and the evolutionary dynamics between government and enterprise behaviors are explored through PyCharm multi-agent simulation. Results indicate that system equilibrium depends on the profit differential between the two parties. The dynamic punishment mechanism can raise the supervisory efficiency threshold, thus promoting enterprise compliance. The simulation rigorously verifies the existence of the sunk cost effect, and the cooperative equilibrium exhibits a compound adjective evolutionary path: "policy initiation-market relay-cooperative stability", providing a robust theoretical basis for addressing resource misallocation in quality supervision across various industries.

Keywords

Credit Linkage, Enterprise Quality Supervision, Evolutionary Game, Time-Lag Effect, Incentive Compatibility

1. Introduction

Enterprise quality supervision is a widespread challenge across many industries. The pharmaceutical industry, due to its direct connection to national health and safety, exemplifies the need for intensive quality oversight. Drug quality and safety

are crucial to public security, directly affecting lives and social stability. Governance efficiency in the pharmaceutical sector is essential for high-quality development and is closely tied to the success of the “Healthy China 2030” strategy. Currently, China’s pharmaceutical industry is undergoing both rapid expansion and structural upgrading. In 2024, industry revenue neared 3 trillion yuan ([China Pharmaceutical Enterprises Management Association, 2024](#)), with new trends such as online prescription drug sales, clinical trials of innovative drugs, and cross-border pharmaceutical supply chains emerging quickly. The industrial ecosystem is increasingly diverse and cross-regional. For example, the integration of online and offline supervision for online-prescribed drugs and ensuring quality traceability for cross-border drugs have heightened demands for a more adaptable supervision system.

Despite industrial prosperity, the core issues of quality supervision in the pharmaceutical sector mirror those in other heavily regulated industries like food and chemical engineering. First, there is a significant imbalance between the supply and demand of supervisory resources. By the end of 2020, China had 7690 drug manufacturers and over 570,000 drug distribution enterprises, with only 842 GMP inspectors and 11,925 GSP inspectors. The per capita supervision workload is much higher than in countries such as the United States and Japan. Additionally, the loss of experienced enforcement staff and poor interdepartmental coordination further exacerbate resource waste ([Liu, Zhang, & He, 2022](#)). Second, the traditional supervisory model has become ineffective. The “passive compliance + bottom-line control” approach is inadequate for managing risks from new business models. Incidents such as those involving Qier Pharmaceutical and Changsheng Vaccines show that this model cannot eliminate systemic safety hazards ([Zhou et al., 2025](#)). Furthermore, [Hai et al. \(2022\)](#) found in their risk analysis of 570 drug wholesalers in Hunan Province that this model encourages companies to view meeting minimum standards as the ultimate goal of quality management. Third, there are issues in implementing credit supervision. Although the government has revised the “Drug Administration Law” to establish whole-life cycle supervision, local pilot programs—such as high-frequency inspections after credit downgrades in Xinjiang and tiered dynamic evaluations in Zhejiang—face challenges. [Chen et al. \(2023\)](#) confirmed that credit supervision can improve efficiency by incentivizing trustworthy behavior and punishing untrustworthy conduct. However, [Xiong et al. \(2024\)](#) noted that the system still lacks an endogenous link and a smooth update mechanism between credit and supervision, making policy implementation difficult.

Existing research has three main limitations. First, technically, the integration between credit classification and intelligent supervision tools like AI and big data is unclear, and credit evaluation is mostly discrete, hindering smooth parameter input ([Liu et al., 2022](#)). Second, at the modeling level, evolutionary games often assume “fine collection for profit”, including fines as supervisory revenue ([Wang, Tian, & Xiao, 2022](#)), which contradicts the “Measures for the Administration of

Confiscated and Detained Properties” and distorts supervisory objectives. Third, methodologically, static analysis methods such as DEA (Duan & Wang, 2022) cannot adapt to the dynamic evolution of enterprise compliance behaviors. Additionally, evolutionary game models typically use fixed parameters, failing to follow Yan’s (2023) credit mechanism classification or incorporate the reduction of information asymmetry, as discussed by Liu and Li (2024), into the profit function. To address these widespread issues and research gaps, this study uses the pharmaceutical industry as a case and focuses on three questions: 1) How can the threshold for resolving resource misallocation be quantified through the endogenous link between credit rating and supervision intensity? 2) How does credit supervision influence the evolutionary direction of enterprise compliance and supervisory strategies, and what are the conditions for the two equilibrium types—market self-regulation and cooperative supervision? 3) How can a smooth credit update mechanism be designed to coordinate the withdrawal of supervision and enterprise self-regulation?

To address these questions, this study adopts a compound adjective research approach: theoretical modeling, stability analysis, and numerical simulation. First, considering common cross-industry factors such as bounded rationality, limited supervisory resources, and information asymmetry, the study defines binary strategies for enterprises (strict/loose quality control) and supervisory authorities (credit/static supervision), incorporates a four-level dynamic credit update rule (D/C/B/A), and builds a game profit matrix. To clarify the parameter mapping between inspection frequency, punishment intensity, and credit rating, the study draws on key concepts from Boltzmann probability theory (Viswanathan & Gopinathan, 2025). The credit stability quantification framework, based on inverse comprehensive energy scores, uses a percentile threshold mechanism to differentiate credit states, demonstrating that dynamic thresholds can address the asymmetric transition issues present in traditional Markov chain models. This provides international methodological support for the parameter mapping rules proposed in this paper. Second, replicator dynamic equations for both parties are derived, equilibrium stability is analyzed using the Jacobian matrix, and the coupling mechanism between supervisory profit differentials and enterprise strategy choices is explained. Finally, simulations are run on the PyCharm2023 platform, comparing the evolutionary trajectories of enterprise strategy proportions, supervisory strategy proportions, and credit ratings under both smooth and non-smooth modes, and verifying the convergence paths of the two equilibrium types. This design aligns with the government-enterprise game simulation framework proposed by Chen and Zhu (2025), while adding a dynamic credit update component to address research gaps. The model’s conclusions can be extended to other industries requiring intensive quality supervision, such as food and chemical engineering.

This research introduces three major innovations. First, the endogenous mechanism overcomes the limitations of traditional models, which set supervisory strat-

egies exogenously. Drawing on insights from the Xinjiang pilot project, a closed-loop system is constructed, linking enterprise behavior, credit rating, and supervisory parameters. This allows for dynamic adjustment of inspection frequency and penalty intensity according to credit ratings, shifting supervision from external enforcement to feedback-driven behavior. Second, incentive compatibility is strictly observed according to the “Measures for the Administration of Confiscated and Detained Properties”, treating fines only as costs incurred by enterprise violations. Supervisory revenue is defined as the sum of basic revenue and social benefit rewards minus inspection costs, thus avoiding distortions in supervisory motivation from fine collection. Third, path embedding prevents sudden shifts in credit ratings using a hyperbolic tangent smoothing function and incorporates both a self-termination mechanism (credit supervision withdrawal triggered by sustained enterprise compliance) and a cooperative stability mechanism (the coexistence of high-quality production and credit supervision) with time-lag update rules, clarifying equilibrium threshold calculations.

The value of this study lies in both theoretical and practical aspects. Theoretically, it challenges the traditional “fine collection for profit” assumption in evolutionary game models by integrating a dynamic credit function, enriching the analysis framework of credit-supervision-enterprise behavior, and addressing gaps related to credit time-lag effects and system stability. Additionally, the study builds a comprehensive analysis chain—dynamic credit adjustment, evolutionary game modeling, stability verification, and multi-agent simulation—to derive the relationship between supervisory efficiency thresholds and enterprise strategy profit differentials, revealing common equilibrium patterns in enterprise quality supervision systems. Practically, the system provides a tool for dynamic threshold regulation. Simulation results show that when the proportion of enterprises using strict quality control strategies surpasses a critical value, phased credit supervision withdrawal can prevent inefficient allocation of supervisory resources, which is relevant to industries such as pharmaceuticals and food. The plan also proposes a hierarchical supervision adaptation strategy: high-credit Grade A enterprises can use the non-smooth mode, while medium- and low-credit enterprises must use the smooth mode. Finally, by focusing on excellence in quality management systems, the study encourages enterprises to move beyond compliance and pursue higher quality through credit incentives, offering a functional mechanism for modernizing quality supervision in the pharmaceutical and other industries.

2. Model Construction: Assumptions, Profit Structure, and Game Framework

This study uses pharmaceutical enterprises as examples of the game subjects. The model’s strategy setting and equilibrium logic can be extended to other industries that require intensive quality supervision, such as food and chemical engineering. Pharmaceutical enterprises and drug supervision authorities are the main participants in the game concerning drug quality and safety supervision. Their inter-

action is shaped by three realistic, cross-industry constraints: Firstly, bounded rationality: decisions are limited by information, cognition, and resources. Secondly, supervision resources are limited, making full-coverage supervision impossible. Thirdly, information asymmetry: enterprises hold an information advantage throughout the production process, while supervision authorities only obtain partial information through random inspections. Enterprises aim to maximize profits, and their decision-making focuses on balancing compliance and violation costs. Supervision authorities are legally responsible for ensuring public drug safety, aim to maximize social benefits, and are subject to strict resource constraints such as budgets and personnel. They must choose the optimal allocation between static supervision and dynamic credit supervision. Information asymmetry further increases complexity: enterprises may reduce quality investment due to their information advantage, while the randomness of supervision inspections influences their strategic choices, creating a dynamic interaction system. To establish a theoretical model that accurately reflects this interaction, this paper proposes four core assumptions, based on realistic observations in the pharmaceutical industry and the policy document “Interim Measures for the Classification Management of Drug Safety Credit”. These assumptions have universal logic.

H1 (Assumption of Strategy Choice and Rationality Basis): To support simulation and stability analysis, this assumption first clarifies the binary strategy choices of pharmaceutical enterprises and supervisory authorities. Enterprises can choose between strict quality control (x)—investing in compliance costs to meet supervisory standards and accumulate credit—or loose quality control ($1 - x$), which reduces short-term investment by cutting costs but risks penalties for violations. Supervision authorities can choose credit supervision (y), which allocates resources based on enterprises’ historical credit ratings, or static supervision ($1 - y$), which supervises at a fixed frequency regardless of credit differences. Both parties operate under bounded rationality and cannot immediately identify the optimal strategy. Instead, they dynamically adjust strategy proportions through “profit comparison-strategy imitation”, matching the practical features of supervision requiring long-term verification and gradual development of compliance behaviors. The credit rating L_t is divided into four levels (D, C, B, A), corresponding to a quantitative range of 1 - 5, which is normalized to a continuous value in $[0, 1]$ for calculation ($L_t = 0$) is Grade D, ($L_t = 1$) is Grade A, with the conversion: actual grade = $4L_t + 1$). In both simulation and stability analysis, the credit rating at time t , L_t , depends on the enterprise strategy x_{t-1} and the previous credit rating L_{t-1} from the prior cycle, ensuring continuity in credit evaluation.

H2 (Assumption of Profit Trade-Off and Incentive Compatibility): As a general setting for simulation and stability analysis, this assumption defines the profit calculation principles for both players and clarifies incentive compatibility. For enterprises, the benchmark payoff of strict quality control (R_1) is lower than that of loose quality control (R_2) because of higher compliance costs. The final profit

depends on the supervision regime. Under credit supervision, strict operation yields credit incentives and may become more profitable than loose operation. Under static supervision, compliance costs are not compensated, so strict strategies may yield lower profit than loose strategies. Expected violation costs increase with punishment intensity and detection probability, reducing the net payoff of noncompliance.

For regulatory authorities, incentive compatibility is strictly satisfied. Included in regulatory payoff: basic revenue G_1 or G_2 , social benefit rewards (B), and deduction of inspection costs (S). Excluded from regulatory payoff: fines (F) from enterprise violations, which are treated only as enterprise costs and never counted as regulatory income. This design strictly follows the “Measures for the Administration of Confiscated and Detained Properties” to eliminate distortion of regulatory objectives, ensuring that supervision always targets public safety in drug use rather than revenue generation.

H3 (Special Assumption for Stability Analysis): The H3 assumption is used only for system stability analysis to streamline the theoretical derivation process. The credit rating update uses a linear logic model: at time t , the credit rating L_t is calculated as $L_t = L_{t-1} + \gamma(x_{t-1} - L_{t-1})$ gamma $(x_{t-1} - L_{t-1})$. Here, L_t directly responds to the difference between the strategy and credit $(x_{t-1} - L_{t-1})$, with the change proportional to this difference. The adjustment is stepwise, with no smooth transitions, minimizing nonlinear effects on stability derivation. For credit parameter linkage, core supervision parameters are linked to the current credit rating L_t . The parameters themselves are fixed constants, with intensity adjusted only through L_t . Specifically, the inspection frequency coefficient is $\alpha_t = \alpha(1 - L_t)$, so higher credit ratings mean lower inspection frequency. The credit incentive is $A_t = AL_t$, so higher credit means greater incentives. The punishment intensity coefficient is $\beta_t = \beta(1 - L_t)$, so higher credit means less punishment. There is an inverse relationship between credit rating and punishment intensity: as credit rating decreases, punishment intensity increases. This configuration avoids increased derivation complexity from parameter changes, focusing on the regulatory intensity adjustment through credit ratings.

H4 (Special Assumption for Simulation): This assumption is used only for multi-agent simulation analysis, aiming to approximate a realistic supervision scenario and allowing parameter flexibility for other industries if needed. The credit rating update has two modes: smooth and non-smooth. In smooth mode, the credit rating L_t at time t is updated as $L_t = \text{clip}\{L_{t-1} + \gamma \tanh[k(x_{t-1} - L_{t-1})]\} v_t$. Here, k is the sensitivity parameter, and v_t is the dynamic smoothing factor. The tanh function achieves nonlinear gradual convergence of credit changes, while the clip function keeps L_t within $[0, 1]$. In non-smooth mode, the system responds directly to strategy and credit differences, showing stepwise jumps—if the difference is large, the target value is reached directly without a smooth transition.

The core logic of dynamic credit rating update includes two clear, reproducible steps: quantification and classification. First, the Inverse Comprehensive Energy

Score is calculated to quantify credit stability as:

$InverseEnergyScore = 1 - (1-x)(1-y) \frac{S}{G_1 + G_2} \theta$, where $(1-x)(1-y)$ is the enterprise violation probability, $\frac{S}{G_1 + G_2}$ is the ratio of regulatory cost to total

benchmark revenue, and θ is a calibrated coefficient consistent with pharmaceutical industry supervision practice. Second, a percentile-threshold mechanism maps the score to four credit grades: D, C, B, and A. The percentile thresholds are determined from the empirical credit distribution in pharmaceutical industry pilots. The credit rating L_t is normalized to the interval $[0, 1]$, where $L_t = 0$ represents Grade D and $L_t = 1$ represents Grade A. In each period, L_t is updated using the enterprise strategy x_{t-1} and the previous credit value L_{t-1} , ensuring temporal continuity and full reproducibility from input variables to final credit grade. The credit-linked parameters are dynamically adapted: the inspection frequency coefficient α_t and penalty intensity coefficient β_t decrease exponentially with L_t , while the credit incentive A_t increases in an arctangent S-shape. This design follows the principle of low intervention for high-credit enterprises and strict supervision for low-credit enterprises, ensuring both regulatory adaptability and practical implementability.

The mapping of credit-linked parameters to actual regulatory behaviors is materialized through model symbols consistent with Assumption H3, and the strategy and payoff matrix of both game players are constructed and shown in **Table 1**. Inspection frequency is the product of the credit-dependent inspection frequency coefficient and the proportion of credit supervision strategy y . Punishment intensity is the product of the credit-dependent punishment intensity coefficient and the fine amount F . The detection probability P is set with reference to the actual detection rate of drug regulatory sampling inspections. All coefficient values comply with the statutory ranges and policy standards of pharmaceutical regulation, ensuring consistency with practical ranges. Strategy proportions x and y are constrained within $[0, 1]$ by soft constraints that slow adjustment near boundaries. Original credit ratings (1 - 5) and normalized values (0 - 1) are dynamically scaled to prevent numerical overflow.

Table 1. Strategy and payoff matrix of pharmaceutical companies and regulatory authorities.

Pharmaceutical Company/Regulatory Authority	Credit Supervision y	Static Supervision $(1-y)$
Strict Quality Control x	$R_1 + AL_t \cdot G_1 + B$	$R_1 \cdot G_2 - S + B$
Lenient Quality Control $(1-x)$	$R_2 - \beta PF(1-L_t) \cdot G_1 - \alpha SL_t + PB$	$R_2 - pF \cdot G_2 - S + pB$

The definitions of all model parameters involved in this study are summarized in **Table 2**, including the specific connotations of credit supervision and static supervision strategies in the pharmaceutical industry.

Table 2. Definitions of model parameters.

Parameter	Explanation	Parameter	Explanation
R_1	Benchmark profit of enterprises' strict quality control	R_2	Benchmark profit of enterprises' loose quality control
A	High-quality credit incentive for enterprises with strict quality control	S	Supervision and inspection cost of static supervision
P	Probability of detecting non-compliant production under credit supervision	p	Probability of detecting non-compliant production under static supervision
G_1	Revenue of supervision authorities choosing credit supervision	G_2	Revenue of supervision authorities choosing static supervision
α	Supervision and inspection intensity coefficient for low-credit enterprises	β	Punishment intensity coefficient for low-credit enterprises
γ	Credit adjustment rate	L_t	Credit rating at time t
F	Fine amount for enterprises' non-compliant production	B	Social benefit reward for supervision authorities

3. Model Solution and Equilibrium Analysis

3.1. Stability Analysis of Pharmaceutical Enterprises

Based on the payoff matrix in **Table 1**, we calculate the expected fitness of pharmaceutical enterprises adopting the strict quality control strategy U_e^h , the expected fitness of those adopting the lenient quality control strategy U_e^l , and the average fitness of all enterprises \bar{U}_e as follows:

$$\begin{cases} U_e^h = R_1 + \gamma AL_t \\ U_e^l = R_2 - F[yP\beta(1-L_t) + (1-\gamma)p] \\ \bar{U}_e = xU_e^h + (1-x)U_e^l \end{cases} \quad (1)$$

According to evolutionary game theory, the rate of change in the proportion of a strategy is proportional to the degree to which its fitness exceeds the average fitness. Thus, the replicator dynamics equation for enterprises' quality control strategy selection is:

$$F(x) = \frac{dx}{dt} = x(U_e^h - \bar{U}_e) = x(1-x)(U_e^h - U_e^l) \quad (2)$$

Through the stability analysis of the differential equation, we set $F(x) = 0$ and solve for three equilibrium points of the system: $x = 0$, $x = 1$, and

$$y^* = -\frac{R_1 - R_2 + pF}{AL_t + \beta PF(1-L_t) - pF} < 0. \text{ When the supervision intensity is sufficiently}$$

high ($y > y^*$) and the net incentive of dynamic supervision (including the credit incentive A and the deterrence gain of punishment βF) can offset the profit differential ($AL_t + \beta PF(1-L_t) - pF > 0$), the system will converge to the stable state where all enterprises adopt strict quality control.

The core role of dynamic supervision is to significantly increase the risk cost of the lenient quality control strategy by strengthening the inspection frequency (α) and punishment intensity (β). This raises the critical value y^* and drives enterprises to choose compliant behaviors from a long-term profit perspective.

It is important to note that if enterprises exhibit a short-sighted tendency (the profit differential between the first and second options $R_1 - R_2 + pF$ is negative), external intervention is required to break the low-quality equilibrium. This intervention can take the form of increasing the proportion of credit supervision. Otherwise, the market will fall into a vicious cycle of accumulating safety risks. This finding provides a theoretical basis for understanding the necessity of supervision intervention, with important implications for heavily regulated industries such as pharmaceuticals and food.

3.2. Analysis of Regulatory Authorities

Based on the same logic, we derive the expected fitness of regulatory authorities adopting credit supervision U_r^d , the expected fitness of those adopting static supervision U_r^s , and their average fitness \bar{U}_r as follows:

$$\begin{cases} U_r^d = G_1 + B[x + (1-x)P] - (1-x)\alpha SL_t \\ U_r^s = G_2 - S + B[x + (1-x)p] \\ \bar{U}_r = yU_r^d + (1-y)U_r^s \end{cases} \quad (3)$$

The replicator dynamics equation for the strategy selection of regulatory authorities is:

$$S(y) = \frac{dy}{dt} = y(U_r^d - \bar{U}_r) = y(1-y)(U_r^d - U_r^s) \quad (4)$$

Similarly, according to the stability theorem of differential equations, the system has three equilibrium points: the specific proportion of enterprises adopting strict quality control $x^* = 1 + \frac{G_1 - G_2 + S}{(P-p)B - \alpha SL_t}$, complete static supervision by regulatory authorities ($y = 0$), and complete credit supervision ($y = 1$).

Stability analysis shows that when $x = x^*$, $\frac{dS(y)}{dy} \equiv 0$, meaning the expected fitness of regulatory authorities choosing credit or static supervision is equal, and the system's strategy direction is uncertain. When $x < x^*$, $S(y) = 0$ and $\frac{dS(1)}{dy} < 0$, so credit supervision ($y = 1$) is the evolutionary stable strategy (ESS). This indicates that in a high-quality market environment, precise credit supervision can better optimize resource allocation, constrain corporate behavior, and drive industry quality improvement; thus, regulatory authorities should prioritize this strategy. Conversely, when $x > x^*$ and $G_1 - G_2 + S < 0$, $S(y) = 0$ and $\frac{dS(0)}{dy} < 0$, so static supervision ($y = 0$) becomes the evolutionary stable strategy. This suggests that

when the industry's quality level is high but maintaining high-intensity supervision is cost-ineffective, appropriately reducing supervision intensity and adopting static supervision is more economically rational.

In summary, the optimal supervision of the pharmaceutical industry is not static but rather an adaptive process that adjusts in real time according to the costs of supervision G_1 and the social benefits B . Supervisory authorities should provide enterprises with guidance on continuous quality improvement through refining punishment mechanisms, optimizing incentive measures, and improving cost management. However, if the authorities are faced with excessively high credit supervision costs or are motivated by short-term objectives, the critical value will increase. Consequently, static supervision will become a viable strategy in a broader range of scenarios, diminishing the efficacy of quality supervision over time. Policymakers must judiciously balance the short-term expenses of supervision and the long-term benefits of enhanced safety to ensure the economic sustainability of supervision strategies and to safeguard the integrity of pharmaceutical products.

3.3. Stability Analysis of the Evolutionary Game Model

The system of equations describing the system's evolutionary path is obtained by combining the two replicator dynamic Equations (2) and (4):

$$\begin{cases} \frac{dx}{dt} = x(1-x)(R_1 - R_2 + F[yP\beta(1-L_t) + (1-y)p] + yAL_t) \\ \frac{dy}{dt} = y(1-y)\{G_1 - G_2 + S + (1-x)[(P-p)B - \alpha SL_t]\} \end{cases} \quad (5)$$

The analysis of the stability of the system's equilibrium points necessitates the linearization of the aforementioned replicator dynamic equations, followed by the solution of their respective Jacobian matrices. The local asymptotically stable points (ESS) can be determined by evaluating the signs of the eigenvalues of the Jacobi matrix. The Jacobi matrix, denoted by "J", of the system is derived based on the above equations.

$$J = \begin{bmatrix} (1-2x) \begin{pmatrix} R_1 - R_2 + (1-y)pF \\ +yAL_t + yP\beta(1-L_t)F \end{pmatrix} & (1-x)F[P\beta(1-L_t) - p] \\ -y(1-y)[(P-p)B - \alpha SL_t] & F(1-2y) \begin{Bmatrix} G_1 - G_2 + S - \alpha SL_t \\ + (1-x)[(P-p)B] \end{Bmatrix} \end{bmatrix} \quad (6)$$

Suppose the strategy adjustment rates satisfy ($F(x) = 0$) and ($S(y) = 0$). Four equilibrium points in the strategy space $\{(x, y) | x, y \in [0, 1]\}$ can be solved: $E_1(0, 0)$, $E_2(0, 1)$, $E_3(1, 0)$, and $E_4(1, 1)$. While additional solutions may exist mathematically, if their coordinates do not fall within the $[0, 1]$ interval, they do not represent valid strategy proportions. If the determinant ($\det J$) of the Jacobi matrix (5) is greater than zero and the trace ($\text{tr} J$) is less than zero, the point is a local asymptotically stable point (ESS). The stability of each equilibrium point and its conditions are detailed in **Table 3**.

Table 3. Local stability of equilibrium points.

Equilibrium Point	Stability Condition	Stability
$E_1(0,0)$	-	Unstable Point
$E_2(0,1)$	-	Unstable Point
$E_3(1,0)$	$G_1 - G_2 + S < 0$ and $R_1 - R_2 + pF > 0$	ESS
$E_4(1,1)$	$G_1 - G_2 + S > 0$ and $R_1 - R_2 + AL_t + \beta PF(1 - L_t) > 0$	ESS

As shown in **Table 3**, the system's evolutionarily stable strategies (ESS) and their economic implications are as follows:

Initially, the system can reach a state of equilibrium called the "cooperative supervision equilibrium", denoted by $E_4(1,1)$. This can be defined as the ideal state of strict quality control by enterprises and the implementation of credit supervision by supervisory authorities. Such equilibrium requires that the net profit advantage of credit supervision, where the social benefit reward (S) surpasses its Benchmark payoff disadvantage ($G_1 - G_2$), and that credit supervision expands the enterprise strategy profit differential. Specifically, credit supervision enhances the deterrence effect by providing incentives and increasing punishment intensity, raising the profit of enterprises due to strict quality control and increasing the cost of a lax strategy. Consequently, the profit differential is significantly higher than under static supervision. In this context, dynamic credit supervision can effectively restrain enterprises' behavior while maximizing the profit of supervisory authorities, thus establishing a positive cycle of supervision and quality enhancement.

Secondly, the system can facilitate the establishment of a self-regulation equilibrium within the market, denoted as $E_3(1,0)$. This equilibrium is characterized by the dynamic interplay between enterprises engaging in self-regulation and supervisory authorities adopting a static supervisory approach. Maintenance of equilibrium depends on the premise that, under static supervision, the profit of enterprises subject to strict control (R_1) surpasses the risk cost of violation ($R_2 - pF$), while credit supervision shows a net profit disadvantage. By calibrating parameters such as punishment intensity and detection probability, the anticipated violation risk cost can be elevated sufficiently to ensure that the market self-regulation mechanism sustains high standards, even with minimal supervision.

In summary, optimizing the enterprise quality supervision system requires considering the profit structures of both enterprises and supervisory authorities. When dynamic credit supervision offers significant net profit advantages and increases the profit gap between enterprise strategies, its use should be promoted. Otherwise, it is necessary to establish an incentive-compatible mechanism by appropriately setting parameters such as penalties and follow-up costs, encouraging enterprises to maintain high-quality standards under static supervision. Ultimately, this approach aims to achieve the optimal allocation of supervisory resources.

4. Numerical Simulation Analysis

Jacobi matrix analysis (**Table 3**) shows that the system contains two evolutionary stable strategies (ESS). To verify the dynamic evolution of the credit supervision system, this study uses evolutionary game numerical simulations on the PyCharm 2023 platform. The main goal is to evaluate the convergence paths of these two ESS types and thereby verify Hypothesis H2. The analysis examines the effects of parameters such as the credit incentive coefficient A and the punishment intensity coefficient β on the self-termination mechanism and the cooperative equilibrium, and further provides practical guidelines for setting supervisory mode conversion thresholds. Implicit cost is constructed to cover personnel costs, inspection frequency costs, and administrative operation and maintenance costs, with the expression $ImplicitCost = (\omega_1 G_1 + \omega_2 G_2 \alpha y + \omega_3 S) k_{credit}$, where ω_1 , ω_2 , and ω_3 denote the weight coefficients of the three cost components respectively and k_{credit} represents the credit adjustment coefficient, and the unit is set as millions of RMB to conform to the statistical caliber of regulatory costs in the pharmaceutical industry; resource efficiency is defined as the ratio of regulatory efficiency to total regulatory input, calculated by

$$ResourceEfficiency = \frac{xy(G_1 + G_2)}{B + ImplicitCost} \times 100\% \quad \text{with the unit \% per million RMB,}$$

in which the numerator characterizes regulatory efficiency and the denominator denotes total regulatory input, including explicit social benefits and implicit operational costs. The simulation is set with a time step of 0.5 years consistent with semi-annual credit update practices and a total duration of 50 years, which is sufficient for the system to evolve to a steady state, and the convergence criterion is defined as $|x_{t+1} - x_t| < 10^{-4}$ and $|y_{t+1} - y_t| < 10^{-4}$ for three consecutive steps, with a soft constraint function to maintain reasonable parameter ranges; the single-cycle update follows a time-lag sequence consistent with real supervision logic, in which the enterprise strategy share x is first updated according to the payoff differences of the previous period, followed by the update of the regulatory strategy share y , and the credit score L is updated in a differentiated manner between even and odd time steps to reflect information lag in credit evaluation, where direct adjustment based on the updated enterprise strategy share is applied in even steps and the average of the current credit value and enterprise strategy share is adopted in odd steps, and after the credit value is updated, the inspection frequency coefficient α , penalty intensity coefficient β and credit incentive A are adjusted under smooth or non-smooth modes accordingly before the convergence condition is checked to determine whether to terminate the simulation. The multi-agent simulation maintains strict consistency with the replicator dynamic equations, as the fitness of each agent is defined as the expected payoff derived from the game payoff matrix that is identical to the theoretical model, agents update their strategies by imitating peers with higher fitness following the principle that the growth rate of a strategy is proportional to its fitness advantage over the population average, and the aggregate shares x and y are obtained by counting the proportion of agents adopting each strategy, so that the

macroscopic evolutionary trends of the agent-based system fully reproduce the replicator equations $\frac{dx}{dt} = x(1-x)(U_e^h - U_e^l)$ and $\frac{dy}{dt} = y(1-y)(U_r^d - U_r^s)$ to ensure direct comparability between simulation results and theoretical equilibrium analysis. Fundamental parameters are selected based on pharmaceutical industry practice and can be adjusted for other regulated sectors, with key values including $S = 0.3$, $F = 6$, $\beta = 2.2$, $A = 0.95$, $\alpha = 1.5$, $P = 0.9$, $p = 0.7$, $\gamma_{smooth} = 0.42$, $\gamma_{no-smooth} = 0.17$, $k = 1.6$, $v_t = 0.5$ and $B = 0.85$, and benchmark parameters such as R_1 , R_2 , G_1 , G_2 and p are set to capture profit differentials between strict and loose quality control and the effectiveness of credit supervision, with specific values and adjustment logic tailored to scenario analysis objectives.

4.1. Market Self-Discipline Equilibrium $E_3(1,0)$ and the Self-Termination Mechanism of Credit Supervision

To test whether, after the enterprise compliance rate reaches a critical point, supervision net profit becomes insufficient and the market maintains equilibrium through self-regulation, differentiated parameters are set in this scenario. Assume $R_1 = 2$ and $R_2 = 5$ (to highlight the limited compliance incentive under static supervision and amplify profit differentials). Also, $G_1 = 1$ and $G_2 = 2$ (to illustrate that the net profit of credit supervision is lower than that of static supervision, meeting the profit condition for withdrawing credit supervision). Finally, $P = 0.9$ (to simulate compensation for high-frequency inspections). These parameters ensure that a strict enterprise strategy is dominant, but credit supervision is less profitable, $G_1 - G_2 + S < 0$ and $R_1 - R_2 + pF > 0$. By comparing evolutionary paths in both smooth and non-smooth modes, the impact of initial supervision intensity on the trigger threshold is analyzed. This reveals the role of institutional inertia in the timing of supervision withdrawal and provides a quantitative basis for setting practical standards for withdrawing supervision resources. The results are shown in **Figure 1**.

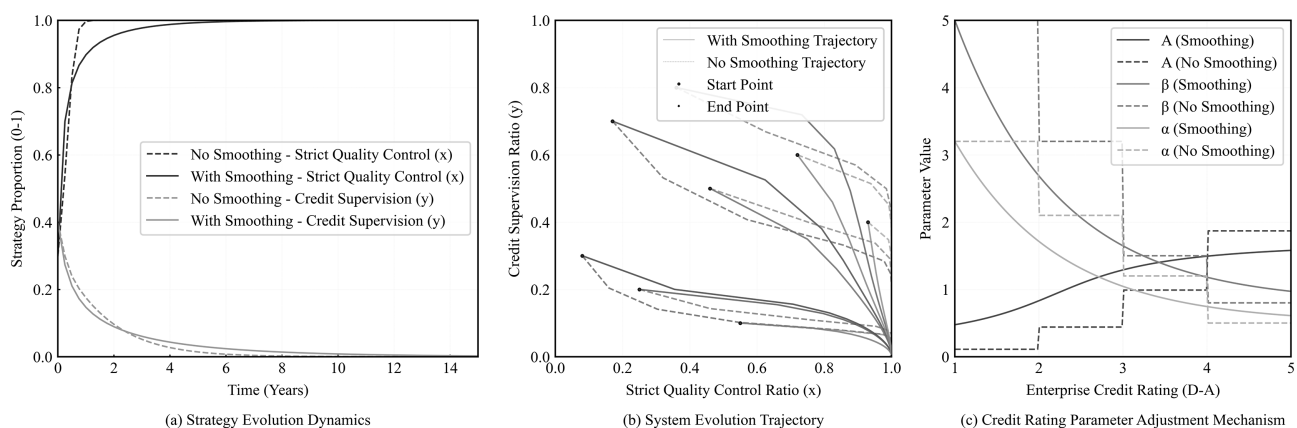


Figure 1. Evolutionary dynamics of the self-termination mechanism.

As shown in **Figure 1(a)**, the dynamic evolution of credit supervision and en-

enterprise strategies is especially noteworthy. In the early stage, credit supervision rapidly increases the proportion of enterprises adopting strict quality control. When this proportion exceeds a critical threshold, the marginal net profit from credit supervision falls below its cost, causing the use of this strategy to gradually decline to zero. As a result, nearly all enterprises maintain strict quality control, converging to equilibrium state 3, where the relevant parameters are one and zero, respectively. The smooth mode curve is continuous and clearly illustrates the compound adjectives of “initial promotion-critical transition-mechanism withdrawal”, aligning well with the gradual changes in profit and cost observed in reality. The non-smooth mode also reflects the main trend, but its stage transitions are more abrupt.

Figure 1(b) highlights differences in system evolution under varying initial credit supervision intensities. Higher initial intensity (γ) leads to a steeper slope at the end of the evolutionary path, resulting in a persistent residual supervision proportion—evidence of institutional inertia and the sunk cost effect of earlier high-intensity supervision. Lower initial intensity allows the system to reach equilibrium more quickly. In the smooth mode, the evolutionary paths for different initial strategies are more continuous, helping to reveal subtle effects such as institutional inertia. In contrast, the non-smooth mode shows more abrupt changes, making it harder to interpret the finer details of the dynamic process.

Figure 1(c) demonstrates the adjustment logic linking credit ratings, supervision parameters, and enterprise strategies. In the smooth mode, credit ratings adjust continuously in response to enterprise strategies, which in turn prompts gradual realignment of supervisory parameters such as α , and P , β . This creates a dynamic and adaptive link between credit classification, resource allocation, and enterprise strategy, closely matching real-world adaptation and incremental adjustment. In the non-smooth mode, credit ratings change in steps, and responses from supervisory parameters and enterprise strategies are more abrupt. The credit rating adjustment mechanism helps ensure supervisory resources are more accurately matched to enterprise compliance. This supports the gradual withdrawal of supervision in the “self-termination mechanism”, allowing high-credit enterprises to benefit from relaxed supervision while avoiding abrupt policy changes through continuous rating feedback.

4.2. Formation Conditions and Evolutionary Dynamics of Collaborative Regulation Equilibrium $E_4(1,1)$

To explore the formation mechanism of cooperative equilibrium between enterprises' high-quality production and active supervision, differentiated parameters are set as follows. The parameters used in this analysis are critically important. First, R_1 and R_2 are set to 2.4 and 4, respectively, ensuring that the profit differential remains within a reasonable range to allow room for incentive overtaking. Second, G_1 and G_2 are set to 2 and 1.8, respectively, to maintain the effectiveness advantage of credit supervision. Finally, parameter p is set at 0.5,

indicating limited accuracy. These parameters satisfy the conditions for both the enterprise's strict strategy and the credit supervision strategy to be dominant, that is, $G_1 - G_2 + S > 0$ and $R_1 - R_2 + AL_i + \beta PF(1 - L_i) > 0$. The hypothesis that credit supervision reaches a cooperative steady state through positive feedback is verified by analyzing the two-stage characteristics of "coupled growth-convergent stability" in evolutionary trajectories and differences among multiple initial points. The simulation results are shown in **Figure 2**.

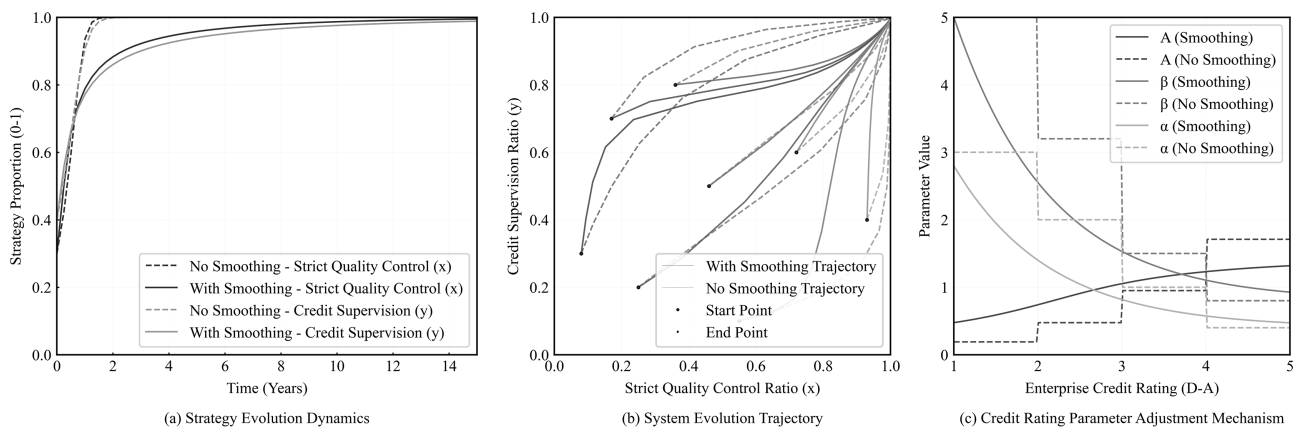


Figure 2. Evolutionary dynamics of the coordinated equilibrium.

As shown in **Figure 2(a)**, the formation of cooperative equilibrium, represented by $E_4(1,1)$, occurs in two stages. During the initial coupled growth period, credit supervision drives a synchronous increase in both the proportion of enterprises practicing strict quality control and the intensity of supervision through rating incentive signals, forming strong cooperation between policy traction and market follow-up. This demonstrates efficient interaction between supervisory impetus and enterprise behavior adjustment. In the subsequent convergent stability period, the growth rate of both slows and approaches 1, indicating that high-quality production has become the norm. At this stage, credit supervision enters regular maintenance, and the system achieves a steady state of dynamic balance between costs and benefits. The curve of the smooth mode is more coherent, clearly presenting the gradual transition from coupled growth to steady-state convergence, consistent with the gradual release of policy effects and market responses. In contrast, the non-smooth mode captures the trend but shows less fluency in stage transitions.

Figure 2(b) shows that evolutionary rhythm varies under different initial supervision intensities. All trajectories eventually converge to the equilibrium point $E_4(1,1)$, but the initial state significantly influences the evolutionary rhythm. Specifically, lower initial supervision intensity (denoted by "y") leads to a steeper incline in the enterprise quality strategy trajectory near $E_4(1,1)$, indicating faster transformation due to the dividend effect of credit incentives. Conversely, higher initial supervision intensity results in a more gradual trajectory, reflecting the restraining effect of institutional inertia. All trajectories maintain the cooperative

attribute of synchronous improvement in quality and supervision, confirming the positive feedback loop of “credit rating improvement-supervision parameter optimization-enterprise behavior reinforcement”. In the smooth mode, continuity among different initial trajectories highlights the subtle role of positive feedback in dynamic evolution. In contrast, the non-smooth mode shows more abrupt changes, making the process less interpretable in detail.

Figure 2(c) illustrates the gradient linkage between credit rating and supervision parameters. In the smooth mode, parameters α , β , and A allow for continuous gradient adjustment, enabling a transition from Grade D to Grade A in the credit rating scale. Enterprises with low credit ratings face “high punishment-low incentive”, while those with high ratings benefit from “high incentive-low punishment”. This creates a refined chain of “credit gradient classification-precise supervisory regulation”. This design avoids the inefficiency of a one-size-fits-all approach and aligns with the gradual accumulation of enterprise credit, enabled by continuous parameter modification. It provides a quantifiable basis for maintaining cooperative equilibrium dynamically. In the non-smooth mode, the parameters increase in steps, which do not match the gradual process of credit accumulation and lead to reduced regulatory accuracy. The smooth credit rating parameter linkage supports positive interaction between high-quality enterprises and active supervision.

4.3. Cost-Efficiency Characteristics and Model Comparison of Credit-Based Hierarchical Regulation

This section assumes that the evolutionary mechanism of credit supervision can be verified. It compares static supervision with credit classification supervision (smooth and non-smooth modes) in terms of implicit cost and resource efficiency, aiming to reveal the cost and efficiency characteristics of different supervision modes in high-credit scenarios. The goal is to provide quantitative references for selecting enterprise supervision modes in the pharmaceutical and other industries. The specific simulation results are shown in **Figure 3**.

Figure 3(a) shows that the implicit cost of static supervision is always 9.99 million, setting a benchmark for the traditional mode’s input-output ratio. For Grade A credit ratings, the implicit cost in the smooth mode is notably higher than in the non-smooth mode, mainly due to differences in parameter setting. The non-smooth mode directly uses the lowest inspection frequency and punishment intensity coefficients for Grade A, reducing operating costs. In contrast, the smooth mode’s continuous function results in slightly higher parameter end values, which increase annual costs. This highlights cost differentiation between the two modes in Grade A scenarios.

Figure 3(b) further shows that the resource efficiency of static supervision is consistently 1.25% per million, serving as the benchmark for the traditional mode. For Grade A credit ratings, the resource efficiency in the non-smooth mode is much higher than in the smooth mode. This is because efficiency is inversely related to

implicit cost, and the non-smooth mode reduces costs. The discrete, low-parameter settings in the non-smooth mode suit lighter supervision needs, while the continuous parameters in the smooth mode allow for future adjustments, resulting in slightly lower efficiency. This confirms the link between cost and efficiency in Grade A scenarios.

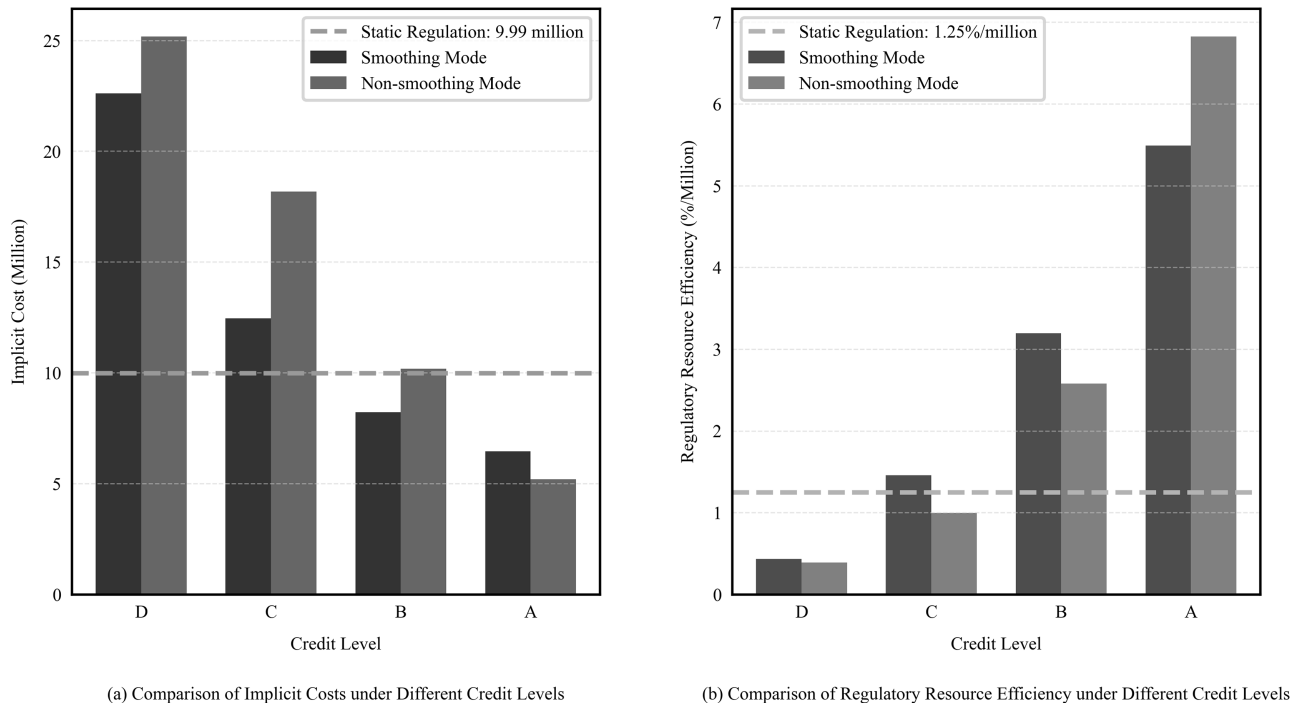


Figure 3. Comparison of regulatory implicit costs and resource efficiency under different credit ratings.

Overall, **Figure 3** highlights the Grade A credit rating scenario, demonstrating the main features of both supervision modes. Only for Grade A credit does the non-smooth mode provide advantages in cost control and resource efficiency, supporting the goal of “high credit-low intervention”. Although the smooth mode has slightly higher costs and lower efficiency for Grade A, its continuous parameters better match the real-world scenario of gradual credit changes. For practice, if cost efficiency is the priority when supervising Grade A enterprises, the non-smooth mode is better. However, if simulating dynamic parameter adjustments is needed, the smooth mode is more suitable, emphasizing the importance of choosing the right supervision mode for different situations.

5. Conclusion and Outlook

Using the pharmaceutical industry as an example, this study uncovers the evolutionary patterns and adaptation mechanisms of the credit-supervision linkage within the enterprise quality supervision system. By constructing an endogenous linkage evolutionary game model, the study demonstrates that the system has two stable equilibrium states: 1) a market self-regulation equilibrium, where enterprises

produce high-quality products and credit supervision is withdrawn, and 2) a cooperative supervision equilibrium, where enterprises produce high-quality products and credit supervision remains active. These findings provide theoretical support for optimizing the allocation of supervision resources and enhancing the efficiency of quality governance. Importantly, the sustainability of credit supervision is shown to depend on two key constraints: net profit advantage and the difference in enterprise strategy profit. Furthermore, the initial supervision intensity and the choice of mode (smooth or non-smooth) serve as critical levers for influencing the system's evolutionary trajectory. The smooth mode is particularly valuable for simulating real-world supervision scenarios because it offers a detailed depiction of the dynamic process. These conclusions can also be applied to other heavily regulated industries, such as food and chemical engineering.

To validate these mechanisms, this study systematically combines theoretical derivation with numerical simulation. Theoretically, the threshold effect of supervision efficiency is rigorously derived: enterprise strategy choices are governed by a critical value of supervision intensity, and dynamic punishment can raise this threshold. The study further clarifies the necessary and sufficient conditions for the sustainability of credit supervision: it must deliver a significant net profit advantage and widen the enterprise strategy profit differential; otherwise, a self-termination mechanism will be triggered. Parameter sensitivity experiments at the simulation level reveal that the formation of a market self-regulation equilibrium is accompanied by a sunk cost effect. The smooth mode more precisely captures the gradual coordination between supervision withdrawal and enterprise quality improvement through continuous adjustment (see [Figure 1](#)). The cooperative supervision equilibrium exhibits a compound adjective, nonlinear process: "cooperative steady state". The smooth mode presents nuanced dynamic feedback between policies and the market due to its continuity advantage, making stage transitions more consistent with real-world institutional change logic (see [Figure 2](#)). In the highest credit rating (Grade A) scenario, the non-smooth mode achieves lower cost and higher efficiency due to preset discrete parameters. However, the smooth mode better reflects the realistic dynamics of gradual credit changes and provides continuous simulation support for dynamic supervision. The difference between the two modes arises from their distinct parameter-setting approaches (see [Figure 3](#)).

Firstly, a dynamic threshold regulation mechanism should be established to precisely trigger or withdraw credit supervision based on the net profit threshold. Additionally, a stepwise adjustment strategy should be implemented, considering the sunk cost effect, to prevent inefficient allocation of supervision resources.

Secondly, the initial configuration and mode adaptation should be optimized. The initial supervision intensity must be carefully set to balance convergence efficiency and institutional inertia. For Grade A enterprises, priority should be given to the non-smooth mode to enhance cost efficiency. The smooth mode's continuity advantage should be leveraged to improve simulation authenticity when mod-

eling the gradual process of credit changes or the release of policy effects.

Thirdly, a risk prevention and quality enhancement guidance system should be established. Active intervention is necessary at the critical transition point of cooperative equilibrium to avoid the risk of “high quality-weak supervision”. Enterprises should be encouraged to move from the “bottom line of compliance” to the “high bar of excellence” by amplifying credit incentives and punitive deterrents.

This study has several limitations. First, the model does not fully capture enterprise heterogeneity, such as strategic differences between innovative and generic drug manufacturers, which may limit the generalizability of the supervision strategies. Second, the influence of third-party supervision forces, including public participation and industry self-regulation, is not considered in the evolutionary path. Third, the complexity of actual supervision networks requires more accurate representation. Fourth, the model does not account for real-world constraints, such as variations in supervision capabilities and data silo costs, which may affect the effectiveness of policy implementation. Future research will incorporate enterprise micro-behavior data, introduce heterogeneous parameters and third-party supervision variables, and develop a “multi-dimensional cooperative evolutionary model” that better reflects real-world practice. This will further enrich the policy toolbox for precise supervision.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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