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Strategic interaction between institutional investors and supervision department: a theoretical analysis of low-price collusion in SBIC

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Abstract

We introduce evolutionary game method to analyze low-price collusion in inquiry market of Sci-Tech Innovation Board of China (SIBC) from the perspective of strategic interaction between large institutional investors (LIIs), small and medium-sized institutional investors (SMIIs), and supervision department (SD). The results show that supervision behaviors of SD, and quotation behaviors of institutional investors, are subject to supervision conditions. Under the condition that benefits of tough supervision are lower a lot than minimum benefits of light supervision (light supervision condition), SD will choose light supervision and institutional investors will turn to illegal quotation in response. Finally, a steady-state equilibrium with low-price collusion will form in SIBC's inquiry market even with a large supervision penalty for illegal quotation. On the contrary, under the condition that benefits of tough supervision are higher a lot than maximum benefits of light supervision (tough supervision condition) and with a large penalty for illegal quotation, SD and institutional investors will choose tough supervision and legal quotation. Further numerical simulations under light supervision condition show that: (1) High-price culling rule will become a booster for low-price collusion and accelerate SMIIs' evolutionary process to imitative quotation. (2) Blindly increasing penalties for illegal quotation or reducing the culling rate is not an appropriate approach to solve the problem of low-price collusion since it cannot shift supervision condition from light into tough and make SD supervise toughly. (3) Institutional investors' choices of quotation strategies are more volatile and highly susceptible to supervision behaviors of SD when facing exogenous uncertainty. Therefore, the keys to solving the problem of low-price collusion are shifting supervision condition from light into tough through increasing incremental benefits of tough supervision, and providing institutional investors with a stable and predictable supervision policy. In conclusion, the creation of a fair inquiry market doesn't only depend on restraint and punishment to institutional investors, but also requires the establishment of supervision mechanism those are compatible with market-based inquiry.

Keywords: Sci-Tech Innovation Board of China, Low-price collusion, Supervision condition, Tripartite evolutionary game

Introduction

In recent years, the establishment of Sci-Tech Innovation Board of China has played an important role in continuously deepening the financial supply-side reform, and provided a new channel for equity financing of small and medium-sized enterprises (SMEs) with scientific and technological attributes. However, with the running of SIBC, inquiry market begins to appear low-price collusion phenomenon. Some institutional investors with larger capital and pricing advantages conspire to drive down the quotation for new shares and win the bid at a significantly low price, causing some SMEs to fail to go public or finance less than expected.[1] Since low-price collusion occurs in SIBC's inquiry market, enterprises with scientific and technological attributes cannot avoid facing a new financing dilemma. They may have channel of SIBC for equity financing, but it's difficult for them to finance at a reasonable price.[2] This phenomenon has also aroused the high attention of the public, government and industry stakeholders in China.

The monthly average pricing deviation rate, which measures underpricing degree of new stock's initial price compared to comparable stocks, is shown as Fig. 1 with a time interval from September 2019 to December 2021.[3] It's obvious that the pricing deviation rate of SIBC had an overall downward trend from September 2019 to July 2021 in general while that of Non-SIBC was relatively stable. And from May 2021 to July 2021, the former was even much lower than the latter, which happened to be the period that low-price collusion was widely discussed. Until SSE and CSRC took action in August 2021, the pricing deviation rate of SIBC quickly turned from negative to positive and far exceeded that of Non-SIBC. In conclusion, the initial pricing as well as low-price collusion in SIBC's inquiry market showed an evolutionary nature and was affected by regulatory action. In addition, there are another two facts in the SIBC's inquiry market deserving attention. One is that large institutional investors (LIIs) could dominate the quotation in SIBC due to their industry influence and scale advantage, and the other is that dependent quotation of small and medium-sized institutional investors (SMIIs) is more likely to limited by high-price culling rule. Therefore, we conduct our research on low-price collusion in SIBC's inquiry market based on the above facts.

Earlier studies related to SIBC mainly investigated topics of information disclosure and pricing efficiency. For example, Zhang and Wu (2021) confirmed that basic institutional reform of SIBC can reduce IPO underpricing in a whole. Xue and Wang (2022) conducted an empirical study by using text information of IPO companies, and found that valuation divergence of institutional investors and the company's IPO underpricing on SIBC is significantly negatively correlated with quality of information disclosure. Liang

[1] From July 2019 to December 2021, the proportion of companies with insufficient finance on SBIC is about 44.68%, Compared to 20.14% on Non-SBIC. The samples and raw data are from Wind database.

[2] IPO of Swancor Advanced Materials Company is a typical example. ninety-six per cent of the institutional investors involved in the inquiry offered price at ¥ 2.49, which barely meets the minimum market capitalization criteria of SIBC. And the closed price of its first trading day is ¥ 15.15. We also notice a similar phenomenon happened in the field of construction project in the Netherlands whose specific form is bidders colluded with each other to form price alliances and imposed restrictions on quotations.

[3] Average pricing deviation rate = (PE ratio of initial price—PE ratio of listed companies in the same industry) / PE ratio of listed companies in the same industry. The samples and raw data are from Wind database. The reasons for choosing this period are: 1) SIBC was officially launched in July 2019 and we adopted the measure of three-month window moving average; 2) low-price collusion eventually disappears by the end of 2021 with the regulatory actions of SSE and CSRC.

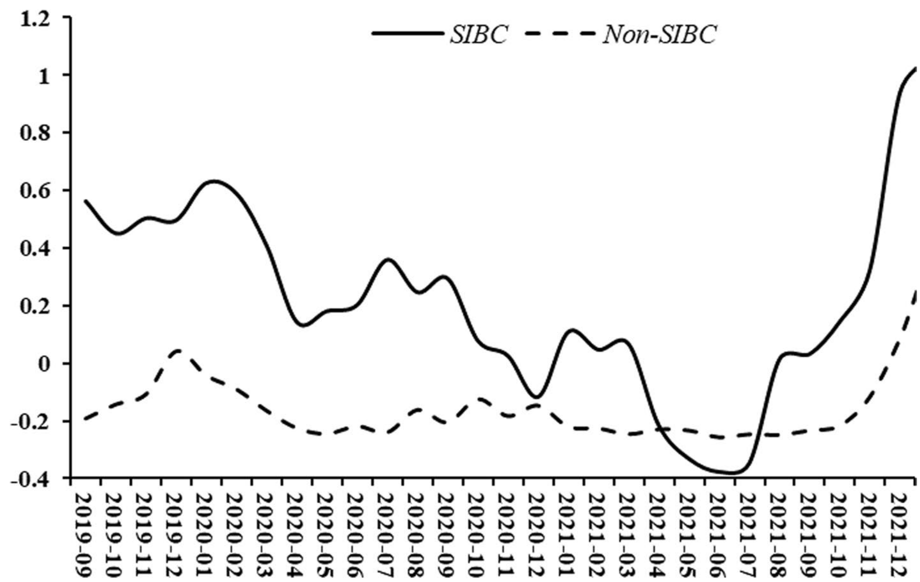

Fig. 1 monthly average pricing deviation rate of SIBC and Non-SIBC

et al. (2022) conducted that although trading system of SIBC can improve the pricing efficiency of new shares, it may also lead to problem of liquidity attenuation and excessive fluctuation. However, these studies mainly focused on the impact of SIBC's system on certain indicators from the macro level, and lack investigation of institutional investors' micro behavior and low-price collusion under SBIC's system.

While allotment unfairness and conveyance of benefits between different subjects in inquiry market have been heavily discussed by earlier literature (for example, Reuter 2006; Goldstein et al. 2011; Jenkinson et al. 2018), strategy choice of institutional investors' quotations has not received widespread attention. Some studies have empirically pointed out that it plays an important role in initial pricing of new shares (for example, Liu et al. 2011; Yu et al. 2013), but its influencing factors and institutional condition still remain lots of things unclear. Additionally, there are also many studies that examined the impact of supervision behavior on institutional investors and financial markets in statistics (for example, Chen et al. 2019; Wang et al. 2021). But they all regarded supervision behavior as an exogenous variable and ignored its dynamic, strategic and endogenous nature. Hence, we endogenously investigate quotation strategy of institutional investors and supervision behavior of SD in SIBC's inquiry market and attempt to fill the literature gap in this field.

Accordingly, the main novelty of this study is to develop a theoretical framework to discuss the theoretical mechanism, institutional condition and regulatory governance of low-price collusion in SIBC's inquiry market from the perspective of strategic interaction. In detail, we firstly assume fair quotation and rapacious quotation are alternative strategies for LIIs, with the former quoting a normal price close to value of new stock, and the latter quoting a price far below value of new stock. Then, we assume independent quotation and imitative quotation are alternative strategies for SMIIs, with the former independently quoting a price that matches value of new stock, and the latter imitating the strategy of rapacious quotation. Considering that LIIs have more bargaining power in reality due to their scale advantage and SMIIs is more likely to limited by high-price culling rule, we assume that price of independent quotation is higher than that of fair quotation. Finally, we assume tough supervision and light supervision are alternative strategies for SD, with the former penalizing illegal quotation behaviors (rapacious quotation and imitative quotation), and the latter not penalizing any illegal quotation behaviors. Since evolutionary process of low-price collusion and strategy choice of market participants are dynamic, adaptive and endogenous, we naturally introduce evolutionary game method and consider market participants are all bounded rational and able to continuously iterate their own strategy through cognitive iteration.

Our framework mainly references the work of Huang et al. (2018) and Huang and Jia (2020), but conducts the following innovations. First, we consider SD as one of gamers in the evolutionary game model to endogenously describe the impact of supervision behavior on institutional investors' strategy choice rather than ignoring SD completely. Second, we divide institutional investors into LIIs and SMIIs, which differ in terms of quotation strategy, financial budget, and pricing power, to characterize and discuss the heterogeneity of institutional investors. Third, we add the unique system and typical characteristics of SIBC into the model such as high-price culling rule and rapacious quotation, which make our results closer to the reality of SIBC. Finally, due to there may be exogenous uncertainty in SIBC's inquiry market which cannot be fully encompassed, we introduce environmental uncertainty into the basic model, analyze the equilibrium conditions of evolutionary stable strategies (ESS) and carry out numerical simulations further.

The remainder of this paper is organized as follows. "Literature review" Section discusses the relevant literature. "Methodology and framework" Section introduces methodology and framework of this research. "Basic model" Section establishes a tripartite evolutionary game system including LIIs, SMIIs and SD under deterministic environment, discusses the ESS of this system, and conducts economic analysis in light of the reality of SIBC. "Model with stochastic shock" Section introduces environmental uncertainty into the basic model, investigates the marginal conditions of ESS under environmental uncertainty, and conducts numerical simulations according to SIBC's historical data and other supplementary information. "Conclusions and policy implications" Section concludes this paper and provides policy recommendations.

Literature review

The existing literature on pricing of new stock is abundant but mainly focuses on discovering the reason for cross-market gap and IPO underpricing. Many studies have discussed this topic from the aspects of information asymmetry, investor sentiment, valuation divergence, and legal circumvention (for example, Engelen and Essen 2010; Hanley and Hoberg 2012; Lowry and Shu 2012). Additionally, thanks to the contribution of Tian (2010), Song and Tang (2019) and Zhang and Wu (2021), the institutional factors leading to high IPO underpricing of China, as well as their specific mechanisms of influence on IPO underpricing, are already quite clear. Turing back to research on quotation process of inquiry market, Reuter (2006) found distribution of new shares in inquiry process is more inclined to institutional investors who have brokerage business with underwriter, especially for that with a return of more than 20% on the first day. Goldstein et al. (2011) conducted that some institutional investors will increase frequency of stock trading and commissions charged by brokers, so as to obtain the preemptive rights of allotment, and such behavior is common in non-regular investors. Zhang (2020) further pointed out that when there is price-earnings ratio regulation in primary market, fund companies can gain an advantage in IPO allotment by using their close partnership with underwriters. In the context of the registration system, some studies have verified that the reform of the registration system in China is conducive to decreasing IPO underpricing (for example, Zhang & Wu 2021; Lai et al. 2022; Wu and Zhang 2022). Yet, while IPO underpricing, allotment unfairness and benefit conveyance between different subjects have been heavily discussed by earlier literatures, choice of quotation strategy among institutional investors and low-price collusion in inquiry market has not gained widespread attention.

Liu et al. (2011) may be the earliest research that noticed the choice of quotation strategies among Chinese institutional investors. Through empirical research, this paper found that institutional investors may choose a collusive strategy that collude with each other to jointly lower initial price and get more benefits rather than compete with each other. Jiang (2014) found that institutional investors in China tend to offer a higher price when facing the rule that those who offer a highest-price will success. Huang et al. (2018) added that the quotation strategy adopted by institutional investors is related to cross-market price gap of new stocks and institutional investors are more likely to offer a high price with a high price gap. Although the above studies have studied strategic choice of institutional investors to a certain extent, they simply regarded institutional investors as a whole and ignored heterogeneity of institutional investors due to different endowments. At the same time, their models may not be fully consistent with reality due to oversimplification of inquiry system and neglect of SD.

In fact, supervision behavior of SD has an important impact on financial market. For example, Gu et al. (2016) found that the SFC's supervision behaviors do not only help to reveal information about corporate heterogeneity, but also help reduce market noise. Christensen et al. (2017) empirically found that the implementation of tough supervision policies will increase individual investors' investment in common stocks in the EU market. Chen et al. (2019) found that the surplus management behavior of listed companies will be suppressed after receiving inquiry letter supervision. Wang et al. (2021) found that tough supervision by SD can prompt small and medium-sized investors to pay more attention to value investment. However, the above studies all observe the macro effects of supervision behavior from a statistical perspective, and don't consider supervision behavior as an endogenous variable. Also, they ignored the dynamic evolution of supervision behavior and the interaction between SD and institutional investors.

The main contributions of this paper compared to the relevant literature are as follows. First, we investigate low-price collusion on SIBC's quotation process from the perspective of strategic interaction between institutional investors and SD, and gives the theoretical mechanism and institutional condition of low-price collusion. Second, we introduce strategy of SD into our model with an endogenous and adaptive form, and fill the research gap in regulatory governance of inquiry market. Third, we characterize institutional investors' heterogeneity of quotation strategy, financial budget, and pricing power and make our results closer to the reality of SIBC with more appropriate and reasonable model settings.

Methodology and framework

An introduction to EGT

Evolutionary game theory (EGT) is a classic theory for modeling dynamic, adaptive and endogenous problems. It introduces bounded rationality and the process of learning on the basis of traditional game theory, which means game players can continuously optimize their strategy choices through strategic interactions and repeated games. It is generally accepted in academia that EGT was formally created after Smith and Price (1974) proposed the concept of evolutionary stable strategy (ESS). After this, Taylor and Jonker (1978) further established the replicating dynamic equations (RDE), which endowed EGT with a quantitative analysis framework in mathematics. ESS and RDE constitute the most central constructs of EGT, the former describing the convergence state of strategy choices of every population in a repetitive game, and the latter quantitatively characterizing the convergence process to ESS from any given state.

According to Taylor and Jonker (1978) and Tan and Lv (2017), EGT can be defined as a theoretical framework that combines traditional game theory and differential dynamical system to analyze the dynamic process and dynamic characteristics of strategic interactions in multiple populations over time or the number of games under given game rules and certain evolutionary mechanism. EGT argues that the dominance of certain strategy in a population is a progressive and evolved process and the evolving speed (replicating rate) is determined not only by the nature of the strategy itself, but also by its return gaps compared to other alternative strategies and the frequency it appears in the competitive population. When a strategy eventually prevails in the entire population, every individual in the population will have to choose this strategy which is the same as others. EGT usually suppose the evolving speed or replicating rate follows RDE.

$$\frac{dx}{dt} = x(R_A - \overline{R}) \tag{1}$$

In Eq. (1), x represents the proportion of individuals adopting a certain strategy in the population. R_A represents the return of individuals who adopt strategy A in the current round of game. $\overline{R}$ represents the average return of the whole population in the current round of game. RDE implies that the fitness of certain strategy in a population is positively correlated with the gaps between expected return of this strategy and the average expected return of the whole population, and the greater the gaps, the more individuals will adopt this strategy in the next game. Given the initial state, the population evolves in strategy choice and produces a new generation in the next round of game according to RDE. Then, the new generation takes place of the previous one and the cycle never stops. It is an iterative process and may converge to a certain stationary state if some conditions are met. Such a state of strategy choice cannot be invaded by any new mutant strategies is defined as evolutionary stable strategy (ESS) and those conditions corresponding to a certain ESS is defined as marginal conditions of ESS. In mathematics, the iterative process, as well as ESS and its marginal conditions, can be characterized by differential dynamical systems.

After nearly 50 years of development, EGT has become a major vehicle to understand or explain some fundamental questions in biology, sociology and economics (for example, Zheng et al. 2018; Qi and Yang 2022; Grunert et al. 2021; Chen et al. 2022). There is also some literature that attempts to use EGT to study some of the issues in the financial sector. For example, Huang et al. (2018) constructed a tripartite evolutionary game model including issuers, investors and underwriters and discussed their strategic choices on inquiry process. Huang and Yu (2022) established a tripartite evolutionary game model to analyze strategic interaction between regulators, issuers and sponsors during IPO disclosure. Lu et al. (2022) used EGT to analyze the phenomenon of ostensible debt-to-equity swap under the background of the launch of market-oriented debt-to-equity swaps.

Research framework and process

This research mainly consists of three progressive stages (Fig. 2). In the first stage, a tripartite evolutionary game system including LIIs, SMIIs and SD is established under deterministic environment in order to discuss low-price collusion in SIBC's inquiry market from the perspective of strategic interaction. We firstly obtain model settings, game rules and strategy benefits according to the relevant literature and typical facts of SIBC. Then, we construct RDE to describe the fitness process of strategy choices of LIIs, SMIIs and SD over time and illustrate the possible evolutionary stable strategies and their equilibrium conditions under deterministic environment. Finally, we discuss the mapping relationship between basic model and reality and carry out economic analysis based on the results of basic model.

In the second stage, environmental uncertainty is introduced into the basic model for the purpose of better meeting the reality of SIBC. At first, we briefly illustrate the significance of introducing exogenous uncertainty and modify RDE in basic model with reference to the relevant literature. Then we discuss possible evolutionary stable strategies and their equilibrium conditions under uncertain environment by utilizing the methods of differential dynamical system. Finally, we explain the practical implications of results of the extended model.

In the third stage, numerical simulation and sensitivity analysis are carried out and conclusions and policy recommendations of this research are generated after that. First, we conduct numerical simulation with referring the stock market historical data to test the credibility of the model conclusions. Then, we analyze the effects of different variables on stability and convergence rate of tripartite evolutionary game system. Finally, we conclude the results of this research and make policy recommendations.

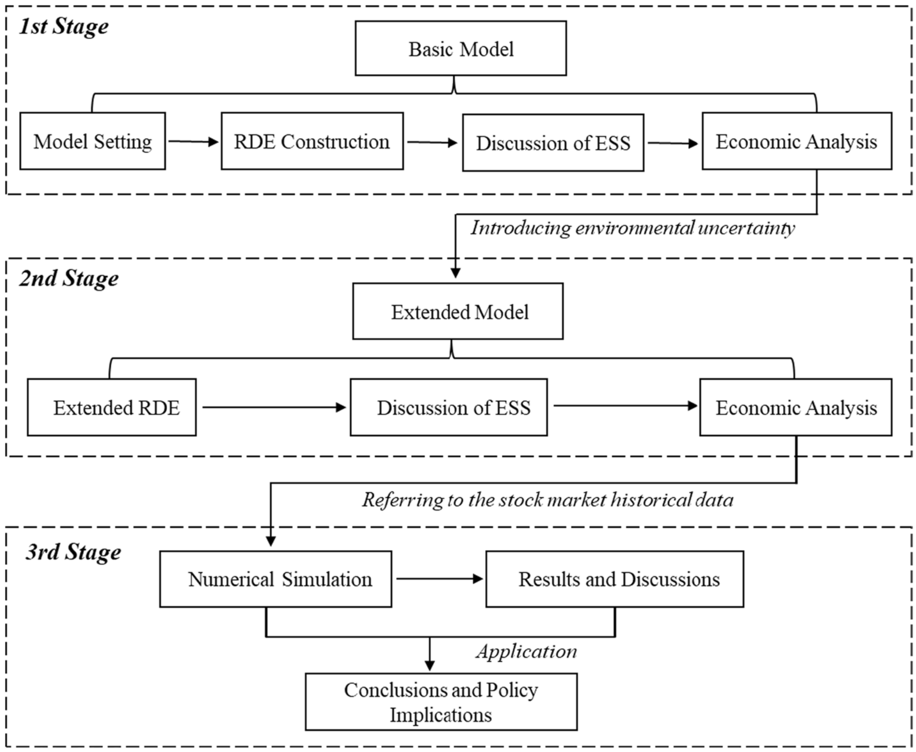

Fig. 2 Framework and process of this research

Basic model

Setting

In order to analyze the process of market participants' transition to evolutionary stability through learning, and analyze steady-state equilibrium point and its marginal conditions, we give the following assumptions.

Assumption 1: LIIs, SMIIs, and SD are all bounded rational and dynamic gaming in the inquiry process. And only institutional investor groups whose quotations are higher than the issue price is considered into the model.

Assumption 2: LIIs have two strategies: rapacious quotation and fair quotation. The former quotes p_1, lower a lot than value of the new stock; the latter quotes p_2, close to value of the new stock; SMIIs have two strategies: imitative quotation and independent quotation. The former learns about rapacious quotation strategy of LIIs and forms a same quotation strategy at the price of p_1 before the formal quotation process[4]; the latter quotes p_3, which is close to value of the new stock and $p_3 > p_2$.[5] SD has two supervision

[4] It actually assumes that SMIIs can learn about LIIs' quotation strategies before the formal quotation process. Since information communications between institutional investors usually occur before the formal quotation process, this assumption is generally reasonable and realistic.

[5] The reason for this assumption is LIIs have industry influence and scale advantage in reality, they will have more bargaining power and quote a lower price even in the case of fair bidding due to their industry influence and scale advantage and SMIIs are usually more likely to be limited by high-price culling rule in SIBC's inquiry market.

strategies: tough supervision and light supervision. The former would penalize institutional investors who have an illegal quotation; the latter would not penalize any illegal institutional investors. The proportion of LIIs adopting rapacious quotation, of SMIIs adopting imitative quotation and of SD adopting tough supervision is noted as x, y and z. Correspondingly, the proportion of LIIs adopting fair quotation, of SMIIs adopting independent quotation and of SD adopting light supervision is $1-x$, $1-y$ and $1-z$.

Assumption 3: Underwriter follows high-price culling rule, and the culling rate is k. Since the highest quotation is p_3, this assumption also means that SMIIs with independent quotations will have a probability k of being culled.

Assumption 4: Since underwriters can be also considered as special LIIs considering the mandatory follow-up requirement, we assume that the underwriters' pricing behavior is rapacious and self-serving and the issuance price which underwriters set will not be higher than p_1. According to Yu et al. (2013) and Jiang & Zhou (2015), we consider the issuance price is positively correlated with the overall quotations of institutional investors and is negatively correlated with the proportion of individuals adopting illegal quotation. Since SMIIs generally do not have pricing power in SIBC's inquiry market, and the impact of quotation behaviors of institutional investors on the issuance price is what this article concerns about, we simply assume that the price generation mechanism of the issuance price satisfies linear relationship as $p(x)=p_1-mx(m>0)$, where $0\leq x\leq 1$.[6]

Assumption 5: Financial budgets of LIIs and of SMIIs are noted as np_1 and ηnp_1. Since LIIs usually have scale advantage in capital, we assume that $\eta\in(0,1)$. Under the assumption of fixed financial budget, demand of LIIs adopting rapacious quotation and fair quotation is n and np_1/p_2 respectively and demand of SMIIs adopting imitative quotation and independent quotation is ηn and $\eta np_1/p_3$ respectively.

Assumption 6: The number of issued shares allocated to institutional investors is less than their quotation demand in reality, we note the actual allocation rate as α. And the actual allocation rate depends on total number of issued shares, the whole demand of institutional investors and the placement ratio of IPO for institutional investors. It will be an extremely huge and unsolvable project in an article if we take the above factors into account and internalize the actual allocation rate. To simplify the problem, we assume that the actual distribution rate is constant, which is consistent with the actual situation in SIBC's inquiry market.[7]

Assumption 7: Denote the equilibrium price of new stocks in the secondary market as p_L, and suppose $p_L>p_3>p_2>p_1$.

[6] Without assumption of linear continuous function, replicator dynamic equations may not derivative at some special points and strategy choices of institutional investors cannot be analyzed with differential dynamic system.

[7] Please refer to Appendix 1 for more details of statistics on the actual allocation rate of SIBC.

Table 1 Table of model parameters/variables

Parameter/variable	Meaning
x	Proportion of LIIs adopting strategy of rapacious quotation, $0 \leq x \leq 1$
y	Proportion of SMIIs adopting strategy of imitative quotation, $0 \leq y \leq 1$
z	Proportion of SD adopting strategy of tough supervision, $0 \leq z \leq 1$
p_1	Price corresponding to illegal quotation of the institutional investor, including rapacious quotation and imitative quotation
p_2	Price corresponding to fair quotation of LIIs
p_3	Price corresponding to independent quotation of SMIIs
p_L	Equilibrium price of new stocks in the secondary market, and $p_L > p_3 > p_2 > p_1$
m	Sensitivity of issuance price to x, $m > 0$
k	Culling rate of high-price culling rule, $0 < k < 1$
α	Allocation rate for new stock of institutional investors, $0 < \alpha < 1$
η	The ratio of SMIIs to LIIs in terms of financial budget
M_1	Penalty for illegal LIIs under tough supervision, M_1 is greater than the incremental benefits of LIIs' illegal quotations
M_2	Penalty for illegal SMIIs under tough supervision, M_2 is greater than the incremental benefits of SMIIs' illegal quotations
C	Additional cost of SD under tough supervision
I_1	rewards of SD under tough supervision
I_2	rewards when SD supervises lightly but illegal quotations are not exposed
λ	Sensitivity of exposure ratio to the proportion of the illegal quotation group, $0 < \lambda < 1$
N	Penalties by superior when SD supervises lightly and there are illegal quotations being exposed

Assumption 8: Note that the penalty for LII's illegal quotation and SMII's illegal quotation is M_1 and M_2 respectively. We assume M_1 and M_2 are higher than the incremental benefits of illegal quotations, otherwise the penalties will be meaningless. We notice that maximum incremental benefits of LII's illegal quotation and of SMII's illegal quotation are $\alpha n(p_L - p_1 + m)(p_2 - p_1)/p_2$ and $\alpha\eta n(p_L - p_1 + m)[p_3 - (1-k)p_1]/p_3$. Hence, Assumption 8 can be described in mathematics as $M_1 > \alpha n(p_L - p_1 + m)(p_2 - p_1)/p_2$ and $M_2 > \alpha\eta n[p_L - p_1 + m][p_3 - (1-k)p_1]/p_3$.

Assumption 9: Under tough supervision, SD has additional cost noted by C, which include material, time, and labor cost. Correspondingly, when SD supervises toughly, there is benefits to SD noted by I_1, including regular wages, performance rewards and good evaluation of society and superior. And when SD supervises lightly, SD can obtain benefits noted by I_2 which consist only of regular wages.

Assumption 10: When SD supervises lightly and there are illegal quotations being exposed in the inquiry market, SD will be punished by higher authorities. Note this penalty as N, and exposure rate of illegal quotations as $\lambda(x+y)/2$.

The relevant parameters/variables are detailed in Table 1.

Return matrix and replicator dynamic equation

Based on the above assumptions, the return matrix of LIIs, SMIIs, and SD under different strategies can be described as Table 2.

Table 2 Return matrix under different strategy choices

Supervision Department		Tough Supervision	Light Supervision
		$I_1 - C$	$I_2 - \frac{\lambda(x+y)}{2}N$
LIIs	Strategy choices	Tough supervision	Light supervision
	Rapacious quotation	$\alpha n[p_L - \overline{p}(x)] - M_1$	$\alpha n[p_L - \overline{p}(x)]$
	Fair quotation	$\frac{\alpha n p_1[p_L - \overline{p}(x)]}{p_2}$	$\frac{\alpha n p_1[p_L - \overline{p}(x)]}{p_2}$
SMIIs	Strategy choices	Tough supervision	Light supervision
	Imitative quotation	$\alpha \eta n[p_L - \overline{p}(x)] - M_2$	$\alpha \eta n[p_L - \overline{p}(x)]$
	Independent quotation	$\frac{\alpha \eta n p_1(1-k)[p_L - \overline{p}(x)]}{p_3}$	$\frac{\alpha \eta n p_1(1-k)[p_L - \overline{p}(x)]}{p_3}$

According to the idea of EGT, if the return of adopting a certain strategy is higher than the average return of the population in a round of games, this strategy will be selected by more individuals in the next round, so that the proportion of individuals adopting the pure strategy in the population will continue to increase until to reach the equilibrium state. Our model applies the method of Taylor and Jonker (1978) and uses replicator dynamic equation to describe this process.[8] And replicator dynamic equations for LIIs, SMIIs, and SD respectively are:

$$U_1(x) = \frac{dx}{dt} = x(1-x)\{\frac{\alpha n[p_L - \bar{p}(x)](p_2 - p_1)}{p_2} - zM_1\} \tag{2}$$

$$U_2(y) = \frac{dy}{dt} = y(1-y)\{\frac{\alpha \eta n[p_L - \overline{p}(x)][p_3 - (1-k)p_1]}{p_3} - zM_2\} \tag{3}$$

$$U_3(z) = \frac{dz}{dt} = z(1-z)[I_1 - C - I_2 + \frac{\lambda(x+y)N}{2}] \tag{4}$$

Steady-state equilibrium points and marginal conditions

Letting $U_1(x) = 0$,$U_2(y) = 0$,$U_3(z) = 0$, we can get eight local equilibrium points of the tripartite evolutionary game system: (0, 0, 0), (0, 0, 1), (0, 1, 0), (0, 1, 1), (1,0, 0), (1, 0, 1), (1, 1, 0), (1, 1, 1). From the dynamic replication equation, the Jacobian matrix of the evolutionary game system can be obtained as follows.

$$J = \begin{pmatrix} A(x,z) & 0 & -x(1-x)M_1 \\ y(1-y)\frac{\alpha nm\eta[p_3-(1-k)p_1]}{p_3} & (1-2y)B(x,z) & -y(1-y)M_2 \\ \frac{z(1-z)\lambda N}{2} & \frac{z(1-z)\lambda N}{2} & (1-2z)C(x,y) \end{pmatrix}$$

where

$$A(x,z) = (1-2x)[\frac{\alpha n(p_L - \overline{p}(x))(p_2 - p_1)}{p_2} - zM_1] + x(1-x)\frac{\alpha nm(p_2 - p_1)}{p_2} \tag{5}$$

[8] Please refer to Appendix 2 for more details of constructing replicator dynamic equation.

Table 3 local equilibrium points and their corresponding eigenvalue

	λ_1	λ_2	λ_3
$(0,0,0)$	$\frac{\alpha n(p_L-p_1)(p_2-p_1)}{p_2}(+)$	$\frac{\alpha\eta n(p_L-p_1)[p_3-(1-k)p_1]}{p_3}(+)$	I_1-C-I_2
$(0,0,1)$	$\frac{\alpha n(p_L-p_1)(p_2-p_1)}{p_2}-M_1$	$\frac{\alpha\eta n(p_L-p_1)[p_3-(1-k)p_1]}{p_3}-M_2$	$-(I_1-C-I_2)$
$(0,1,0)$	$\frac{\alpha n(p_L-p_1)(p_2-p_1)}{p_2}(+)$	$-\frac{\alpha\eta n(p_L-p_1)[p_3-(1-k)p_1]}{p_3}$	$I_1-C-I_2+\frac{1}{2}\lambda N$
$(1,0,0)$	$-\frac{\alpha n(p_L-p_1+m)(p_2-p_1)}{p_2}$	$\frac{\alpha\eta n(p_L-p_1+m)[p_3-(1-k)p_1]}{p_3}(+)$	$I_1-C-I_2+\frac{1}{2}\lambda N$
$(1,1,0)$	$-\frac{\alpha n(p_L-p_1+m)(p_2-p_1)}{p_2}$	$-\frac{\alpha\eta n(p_L-p_1+m)[p_3-(1-k)p_1]}{p_3}$	$I_1-C-I_2+\lambda N$
$(1,0,1)$	$M_1-\frac{\alpha n(p_L-p_1+m)(p_2-p_1)}{p_2}(+)$	$\frac{\alpha\eta n(p_L-p_1+m)[p_3-(1-k)p_1]}{p_3}-M_2$	$-(I_1-C-I_2+\frac{1}{2}\lambda N)$
$(0,1,1)$	$\frac{\alpha n(p_L-p_1)(p_2-p_1)}{p_2}-M_1$	$M_2-\frac{\alpha\eta n(p_L-p_1)[p_3-(1-k)p_1]}{p_3}(+)$	$-(I_1-C-I_2+\frac{1}{2}\lambda N)$
$(1,1,1)$	$M_1-\frac{\alpha n(p_L-p_1+m)(p_2-p_1)}{p_2}(+)$	$M_2-\frac{\alpha\eta n(p_L-p_1+m)[p_3-(1-k)p_1]}{p_3}(+)$	$-(I_1-C-I_2+\lambda N)$

$$B(x,z)=\frac{\alpha\eta n(p_L-\overline{p}(x))[p_3-(1-k)p_1]}{p_3}-zM_2 \tag{6}$$

$$C(x,y)=I_1-C-I_2+\frac{\lambda(x+y)N}{2} \tag{7}$$

If and only if the eigenvalues of the Jacobian matrix are all negative, the equilibrium point corresponding to the tripartite game system will be the evolutionary stable strategy (ESS). Substituting eight equilibrium points into the Jacobian matrix, we can obtain three eigenvalues corresponding to each equilibrium point. The results are shown in Table 3.

From Table 3, we can easily draw out that only the equilibrium points $(0,0,1)$ and $(1,1,0)$ may be stable equilibrium points under the assumptions of our model. Also, marginal conditions of steady-state equilibrium $(0,0,1)$ and $(1,1,0)$ can be given by using the discriminant of ESS.

Obviously marginal conditions of steady-state equilibrium $(0,0,1)$ are:

$$\alpha n(p_L-p_1)(p_2-p_1)/p_2-M_1<0 \tag{8}$$

$$\alpha\eta n(p_L-p_1)[p_3-(1-k)p_1]/p_3-M_2<0 \tag{9}$$

$$-(I_1-C-I_2)<0 \tag{10}$$

In contrast, marginal conditions of steady-state equilibrium $(1,1,0)$ are:

$$-\alpha n(p_L-p_1+m)(p_2-p_1)/p_2<0 \tag{11}$$

$$-\alpha\eta n(p_L-p_1+m)[p_3-(1-k)p_1]/p_3<0 \tag{12}$$

$$I_1-C-I_2+\lambda N<0 \tag{13}$$

Mapping relationship between model and reality

According to the setting of the tripartite evolution model, the situation represented by $(0, 0, 1)$ is that LIIs quote fairly, SMIIs quote independently, and SD supervises toughly, which is the ideal state of the real inquiry market. In contrast, $(1, 1, 0)$ represent the situation that LIIs quote rapaciously, SMIIs quote imitatively, and SD supervises lightly, corresponding to low-price collusion phenomenon in the real inquiry market. Note that Inequality (8)~(9) and Inequality (11)~(12) are clearly established under the model setting, so there are the following propositions:

Proposition 1: *There exists tough supervision condition in tripartite evolutionary game model that can guarantee SD supervises toughly, and this condition can maintain the normal order of the inquiry market.*

$$I_1 - C > I_2 \tag{14}$$

Obviously, $I_1 - C$ is benefit of SD with tough supervision, and I_2 is the maximum benefits of SD with light supervision (Since the penalty of superior is a probabilistic event). Therefore, Proposition 1 means only when benefits of tough supervision is higher than maximum benefits of light supervision, SD will choose tough supervision and a corresponding long-term regulatory mechanism can be formed. In this condition, $(0, 0, 1)$ will become a stable evolutionary state, and all institutional investors will legally participate in the quotation of new stock.

Proposition 2: *There exists light supervision condition in tripartite evolutionary game model that can inhibit SD from adopting tough supervision strategy, and this condition will cause low-price collusion phenomenon even with a large enough supervision penalty.*

$$I_1 - C < I_2 - \lambda N \tag{15}$$

Similarly, $I_2 - \lambda N$ is the minimum benefits of SD with light supervision. Therefore, Proposition 2 means when benefits of tough supervision is even lower than minimum benefits of light supervision, SD will choose light supervision due to lack of sufficient incentives. In this condition, $(1, 1, 0)$ will become a stable evolutionary state, and low-price collusion will become a common phenomenon for the inquiry market even with a large supervision penalty.

Model with stochastic shock

Extended RDE

Due to the fact that there are market shocks, policy adjustments, and irrational sentiments of institutional investors that cannot be included in the tripartite game model in practice, the game between LIIs, SMIIs, and SD may have exogenous uncertainty, so it is necessary to add a stochastic shock term on the basis of the above analysis to describe the possible impact of exogenous variables on the tripartite evolutionary game system. we introduce a stochastic shock term into the replicator dynamic equation of the multi-party evolutionary game. With reference to the ideas of Sun et al. (2016) and Li and Ren (2020), we modify replicator dynamic equation as follows.

$$dx(t) = x(t)\{\frac{\alpha n[p_L - \bar{p}(x)](p_2 - p_1)}{p_2} - zM_1\}dt + \sigma\sqrt{x(t)(1 - x(t))}d\omega(t) \tag{16}$$

$$dy(t) = y(t)\{\frac{\alpha\eta n[p_L - \overline{p}(x)][p_3 - (1-k)p_1]}{p_3} - zM_2\}dt + \sigma\sqrt{y(t)(1 - y(t))}d\omega(t) \tag{17}$$

$$dz(t) = z(t)[I_1 - C - I_2 + \frac{\lambda(x+y)N}{2}]dt + \sigma\sqrt{z(t)(1 - z(t))}d\omega(t) \tag{18}$$

σ is the intensity of the random disturbance. And $\omega(t)$ denotes to one-dimensional standard Brownian motion which is a random fluctuation phenomenon without rules and can well describe the effect of stochastic disturbance factors. In addition, when $t > 0$ and $h > 0$,$\Delta\omega(t) = \omega(t + h) - \omega(t)$ obeys the normal distribution with the expectation of 0 and the standard deviation of $\sqrt{h}$.

Possible solutions and marginal condition

It's obvious that the zero solution is the trivial solution for Eq. (16) ~ Eq. (18) when supposing that $x(0) = 0$,$y(0) = 0$,$z(0) = 0$. However, the initial value of the system is not necessarily all zero in reality. By using the existence and stability theorem of the trivial solution, we can narrow the range of each parameter and find out possible solutions of the tripartite evolution game model. The final conclusions are as follows.[9]

(1) If $z(t) \geq [p_2 + \alpha n(p_L - p_1 + m)(p_2 - p_1)]/M_1p_2$ always holds, there has the zero-solution exponential stability of Eq. (16). And if $z(t) \leq [-p_2 + \alpha n(p_L - p_1)(p_2 - p_1)]/M_1p_2$ always holds, there hasn't the zero-solution exponential stability of Eq. (16).

(2) If $z(t) \geq [p_3 + \alpha\eta n(p_L - p_1 + m)(p_3 - (1-k)p_1)]/M_2p_3$ always holds, there has the zero-solution exponential stability of Eq. (17). And if $z(t) \leq [-p_3 + \alpha\eta n(p_L - p_1)(p_3 - (1-k)p_1)]/M_2p_3$ always holds, there hasn't the zero-solution exponential stability of Eq. (17).

(3) If $(I_1 - C) - (I_2 - \lambda N) \leq -1$ always holds, there has the zero-solution exponential stability of Eq. (18). And if $(I_1 - C) - I_2 \geq 1$ always holds, there hasn't the zero-solution exponential stability of Eq. (18).

As the zero-solution exponential stability of Eq. (16)~(17) all depends on value of $z(t)$, we firstly discuss the zero-solution exponential stability of Eq. (18). And it's easy to find that if $(I_1 - C) - (I_2 - \lambda N) \leq -1$, $z(t)$ will converge to 0 and if $(I_1 - C) - I_2 \geq 1$, $z(t)$ will converge to 1. On condition that penalty is much higher than incremental benefits of illegal quotations, it's easily seen that:

$$0 < \frac{p_2 + \alpha n(p_L - p_1 + m)(p_2 - p_1)}{M_1p_2} < 1 \tag{19}$$

$$0 < \frac{p_3 + \alpha\eta n(p_L - p_1 + m)[p_3 - (1-k)p_1]}{M_2p_3} < 1 \tag{20}$$

[9] Please refer to Appendix 3 for the specific certification process.

Also, on condition that the equilibrium price of new stocks in the secondary market is enough high to ensure illegal quotations has enough benefit, we can clearly find that:

$$0 < \frac{\alpha n(p_L - p_1)(p_2 - p_1) - p_2}{M_1 p_2} < 1 \tag{21}$$

$$0 < \frac{\alpha \eta n(p_L - p_1)[p_3 - (1-k)p_1] - p_3}{M_2 p_3} < 1 \tag{22}$$

Hence, we can get similar conclusion as Proposition 1—2.

Proposition 3: *There exists tough supervision condition in stochastic tripartite evolutionary game model that can guarantee SD supervises toughly, and this condition can maintain the normal order of the inquiry market in conjunction with a large enough supervision penalty for illegal quotation.*

$$(I_1 - C) - I_2 > 1 \tag{23}$$

Proposition 3 shows that when uncertainty is introduced into tripartite evolutionary game model, there also exists tough supervision condition that can guarantee tough supervision and legal quotations with a large enough supervision penalty, but it's stricter than our model without uncertainty. Specifically, when benefits of tough supervision $(I_1 - C)$ is higher a lot than maximum benefits of light supervision (I_2),$(0,0,1)$ will become a stable evolutionary state, and all institutional investors will legally participate in the quotation of new stock with a large supervision penalty.

Proposition 4: *There exists light supervision condition in stochastic tripartite evolutionary game model that can inhibit SD from adopting tough supervision strategy, and if illegal quotation has enough benefit, this condition will cause low-price collusion phenomenon even with a large enough supervision penalty for illegal quotation.*

$$(I_1 - C) - (I_2 - \lambda N) < -1 \tag{24}$$

Proposition 4 shows that when uncertainty is introduced into tripartite evolutionary game model, there also exists tight supervision condition that can induce light supervision and illegal quotations with enough benefits of illegal quotations, and it's also stricter than our model without uncertainty. Specifically, when benefits of tough supervision $(I_1 - C)$ is lower a lot than minimum benefits of light supervision $(I_2 - \lambda N)$,$(1,1,0)$ will become a stable evolutionary state, and low-price collusion will become a common phenomenon for SIBC's inquiry market even with a large supervision penalty for illegal quotation.

Numerical simulation and sensitivity analysis

For stochastic differential equations, academia usually intercepts some terms on the basis of stochastic Taylor expansion for numerical simulation. This paper adopts the Milstein method and uses Matlab 2019a programming for numerical simulation and further sensitivity analysis. In order to simulate the market performance of the new shares represented by pricing deviation rate, we introduce earnings per share of the new shares

Table 4 List of determined value of parameters

Parameter	p_1	p_2	p_3	p_L	m	k	α	n	σ
Value	20	35	55	60	4	0.1	0.02	2000	1
Parameter	η	M_1	M_2	C	I_2	N	λ	e	pe
Value	5	18	6	8	5	10	0.5	0.5	40

and average P/E ratio of listed companies in the same industry and note them as e and pe respectively. Additionally, we determine the simulation data by referring to the stock market historical data and other supplementary information for the purpose of making our simulation more realistic.[10] The determined values of the parameters are shown in Table 4 and the unit of α is one percent, the units of n, M_1,M_2, C, I_2 and N are ten thousand and the units of other parameters are customary. With simulation data referring to the stock market historical data of SIBC, we can find that Inequality (19) ~ (22) are strictly valid under simulation data, which indirectly proves the suitability of Proposition 3 and Proposition 4 in inquiry market of SIBC.

Scenario 1: tough supervision condition ($(I_1 - C) - I_2 > 1$)

Assume $x(0) = 0.5$,$y(0) = 0.5$,$z(0) = 0.5$,$I_1 = 20$, and there will exist tough supervision condition in our model. In this scenario, Eq. (18) will not satisfy the zero-solution exponential stability condition, and Eq. (16) and Eq. (17) will satisfy the zero-solution exponential stability condition finally. Under scenario 1, the equilibrium strategies of LIIs and SMIIs respectively are fair quotation and independent quotation, and the equilibrium strategy of SD is tough supervision. As shown in

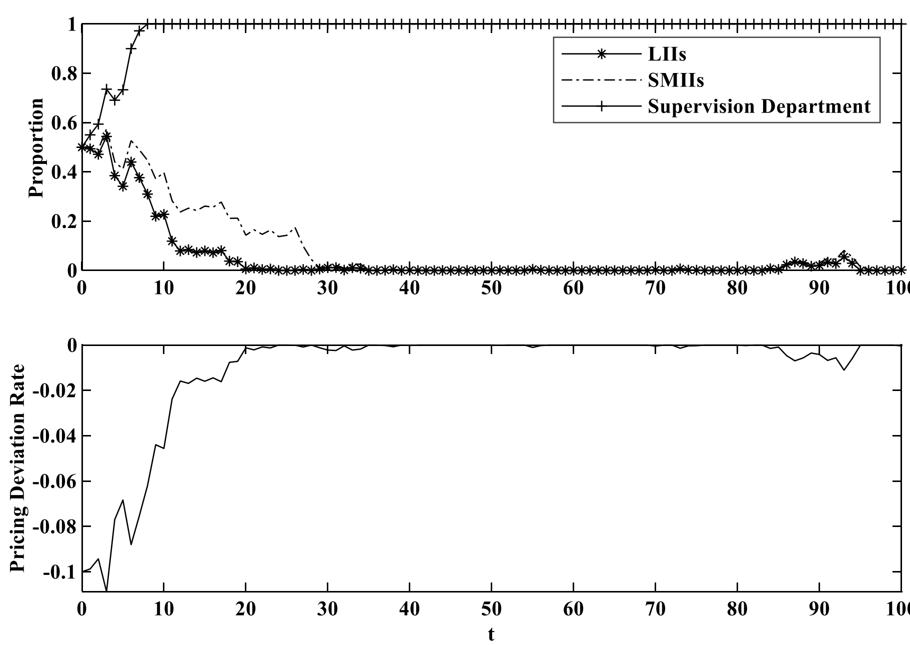

Fig. 3 strategy evolution and market performance under scenario 1

[10] Please refer to Appendix 4 for more details of determination of simulation data.

Fig. 3, pricing deviation rate has an increasing trend towards zero in general, which indicates that the quotation behavior of institutional investors in the inquiry market is gradually standardized and the overall pricing efficiency of the inquiry market has improved.

On this basis, we separately examine the impact and sensitivity of other important parameters on our model's evolutionary process. The results are as follows.

The impact of penalty for illegal quotation on evolutionary process

Take $M_1 = 10, 18, 25$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 4. It can be found that separately increasing penalty for LIIs' illegal quotation can accelerate LIIs' evolutionary process to fair quotation, but have little impact on SD's evolutionary process to tough supervision under scenario 1. The reason is as follows. As ultimate strategy evolution of SD is tough supervision under tough supervision condition, increasing penalty for LIIs' illegal quotations can reduce the benefits of illegal quotations continuously and make LIIs more inclined to quote legally, thereby reducing the proportion of LIIs with illegal quotations. And as penalty for LIIs' illegal quotation is not directly related to the benefits of SD, so it has little impact on its evolutionary process. Not surprisingly, increasing penalty for SMIIs' illegal quotation has a similar effect and the reason is the same. In conclusion, increasing penalties for illegal quotations can accelerate institutional investors' evolutionary process to legal quotation, but have little impact on evolutionary process of SD under tough supervision condition.

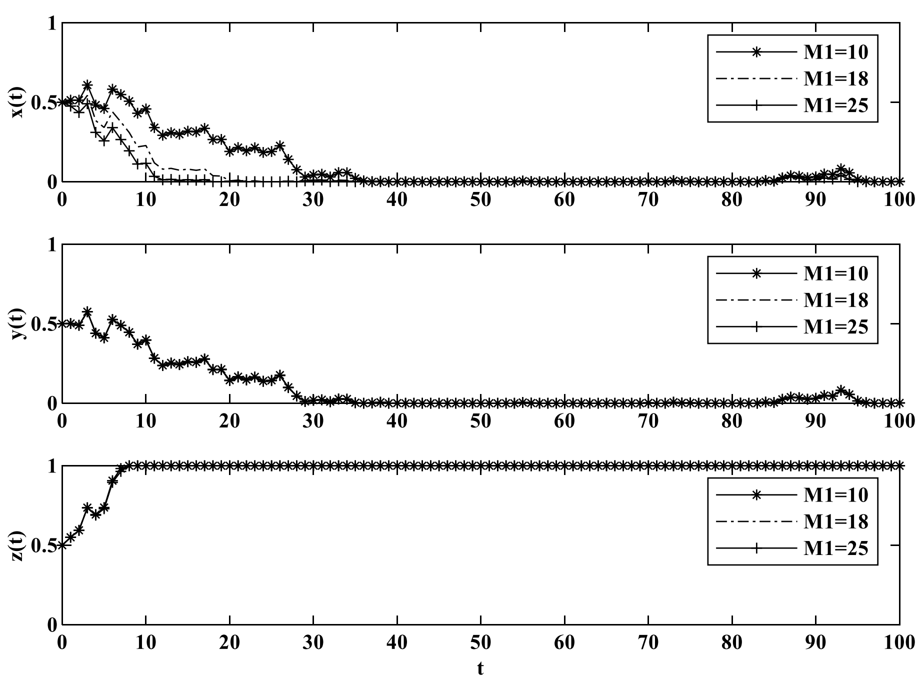

Fig. 4 Impact of illegal penalties (M_1) on evolutionary process under scenario 1

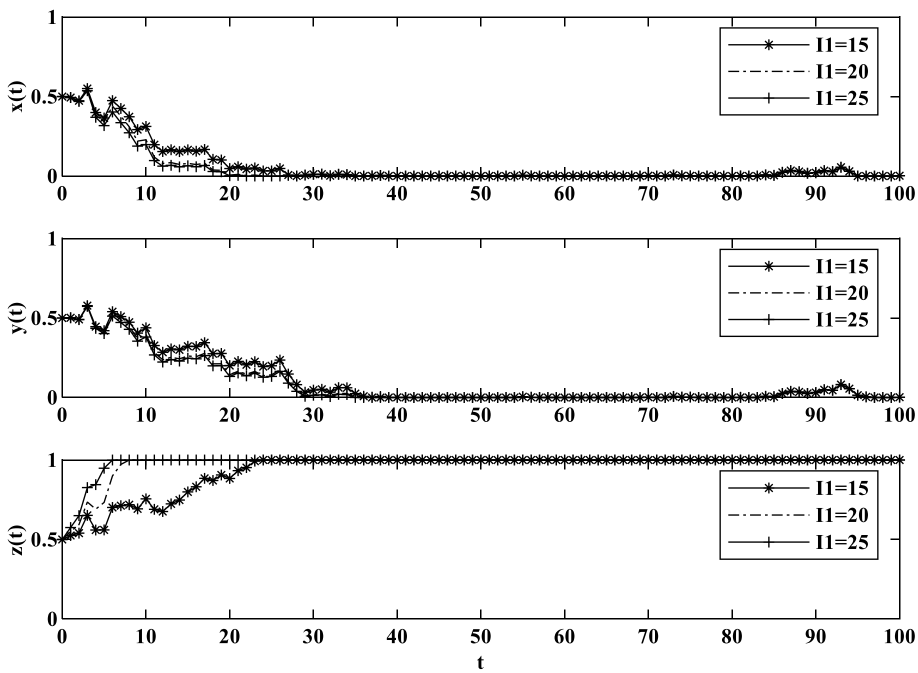

Fig. 5 Impact of supervise incentives on evolutionary process under scenario 1

The impact of SD's incentives on evolutionary process

Taking I_1= 15, 20, 25 respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 5. It can be found that increasing incentives for tough supervision can accelerate evolutionary process of LIIs, SMIIs, and SD at the same time. The reason is increasing incentives for tough supervision can increase the benefits of tough supervision and make SD more inclined to supervise toughly. With the probability of SD adopting strategy of tough supervision, the probability of being penalized for illegal quotation will increase. Therefore, the benefits of illegal quotation will decrease correspondingly and it prompts institutional investors to quote legally. As a result, evolutionary process of institutional investors to legal quotation will be accelerated.

The impact of SD's cost on evolutionary process

Taking C= 5, 8, 11 respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 6. It can be found that lowering cost of toughly supervising can accelerate evolutionary process of LIIs, SMIIs, and SD. The reason is that as ultimate strategy evolution of SD is tough supervision under tough supervision condition, lowering supervision cost can increase the benefits of tough supervision continuously, and make SD more inclined to supervise strictly, thereby reducing the benefits of illegal quotations. As a result, the tendency of institutional investors to quote legally will increase and evolution speed of LIIs and SMIIs turning to legal quotation will be improved.

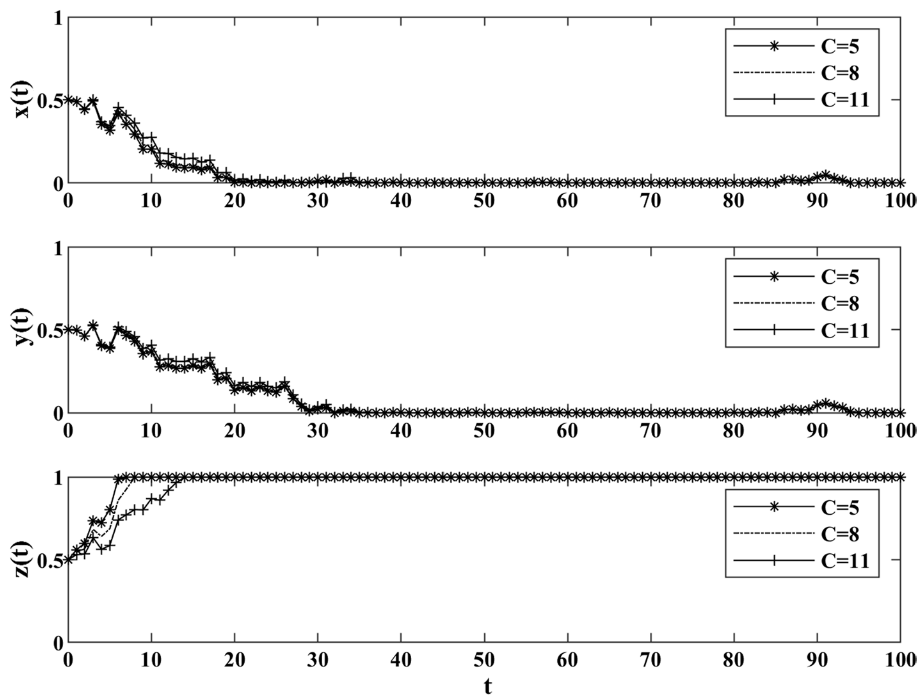

Fig. 6 Impact of SD's cost on evolutionary process under scenario 1

The impact of culling rate of high-price culling rule on evolutionary process

Taking k= 0.1,0.5, 0.9 respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 7. It can be found that increasing culling rate can decelerate SMIIs' evolutionary

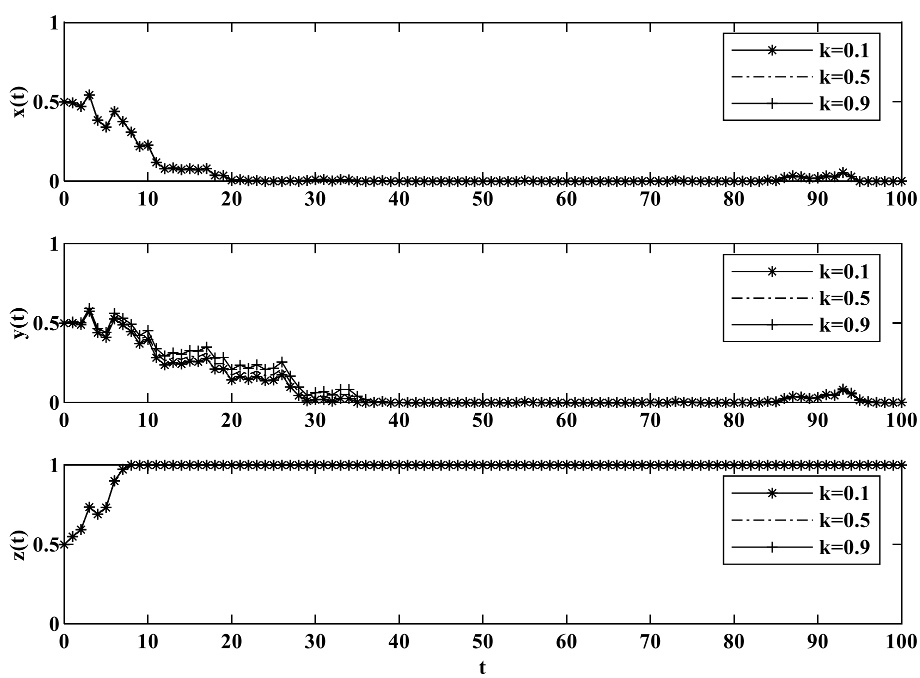

Fig. 7 Impact of culling rate on evolutionary process under scenario 1

process to independent quotation, but has little effect on evolutionary process of LIIs, and SD. The reason is that increasing culling rate can significantly lower the benefits of SMIIs with independent quotation, and improve the incremental benefits of SMIIs with imitative (illegal) quotation. As a result, SMIIs will be more inclined to illegal quotation and evolutionary process of SMIIs to independent quotation will be decelerated. And since culling rate of high-price culling rule is not directly related to the benefits of SD and LIIs, it has little impact on their evolutionary process. Hence, we can see that high-price culling rule will lower benefits of SMIIs with independent quotation, prevent SMII from choosing strategy of independent quotation, and decelerate SMIIs' evolutionary process to independent quotation under tough supervision condition.

The impact of ratio of SMIIs to LIIs in terms of financial budget on evolutionary process

Taking $\eta = 0.3, 0.4, 0.5$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 8. It can be found that increasing ratio of SMIIs to LIIs in terms of financial budget can decelerate SMIIs' evolutionary process to independent quotation, but has little effect on evolutionary process of LIIs, and SD. The reason is that increasing the ratio of financial budget can significantly improve the incremental benefits of SMIIs with imitative quotation. As a result, SMIIs will be more inclined to imitative quotation and evolutionary process of SMIIs to independent quotation will be decelerated. And as the ratio of financial budget is not directly related to the benefits of SD and LIIs, so it has little impact on their evolutionary process.

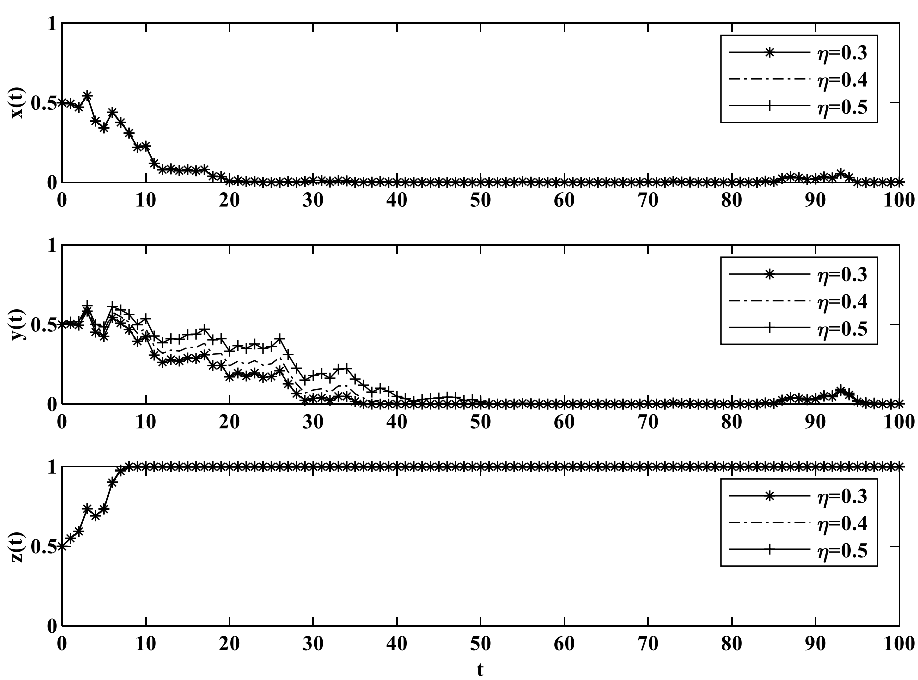

Fig. 8 Impact of ratio of financial budget on evolutionary process under scenario 1

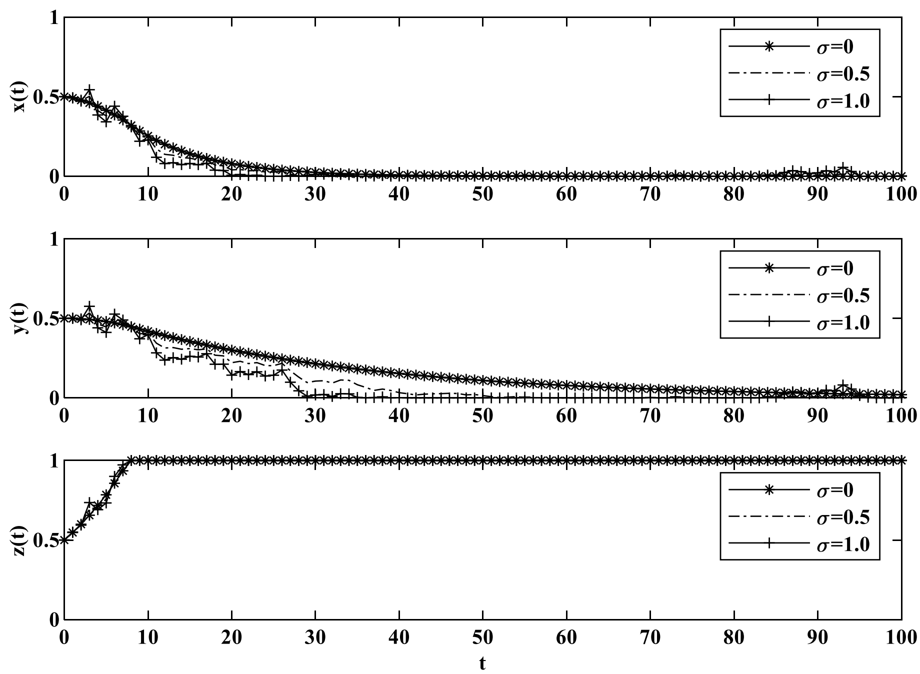

Fig. 9 Impact of disturbance intensity on evolutionary process under scenario 1

The impact of intensity of the random disturbance on evolutionary process

Taking $\sigma = 0, 0.5, 1$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 9. It can be found that with intensity of the random disturbance increases, evolutionary process of LIIs, SMIIs and SD becomes more unstable in general, and evolutionary process of LIIs and SMIIs is more sensitive to intensity of the random disturbance than that of SD. Its practical implication is that strategy choices of institutional investors are highly susceptible to supervision strategy while strategy choices of supervision strategy are less affected by quotation strategies of institutional investors under tough supervision condition.

Scenario 2: light supervision condition ($(I_1 - C) - (I_2 - \lambda N) < -1$)

Assume $x(0) = 0.5, y(0) = 0.5, z(0) = 0.5, I_1 = 6$, and there will exist light supervision condition in our model. In this scenario, Eq. (18) will satisfy the zero-solution exponential stability condition, and Eq. (16) and Eq. (17) will not satisfy the zero-solution exponential stability condition. Under scenario 2, the equilibrium strategies of LIIs and SMIIs respectively are rapacious quotation and imitative quotation, and the equilibrium strategy of SD is light supervision. As shown in Fig. 10, pricing deviation rate will generally have a decreasing trend, which is similar to Fig. 1. And it indicates that the overall pricing efficiency of the inquiry market will be significantly reduced.

On this basis, we separately examine the impact and sensitivity of other important parameters on our model's evolutionary process. The results are as follows.

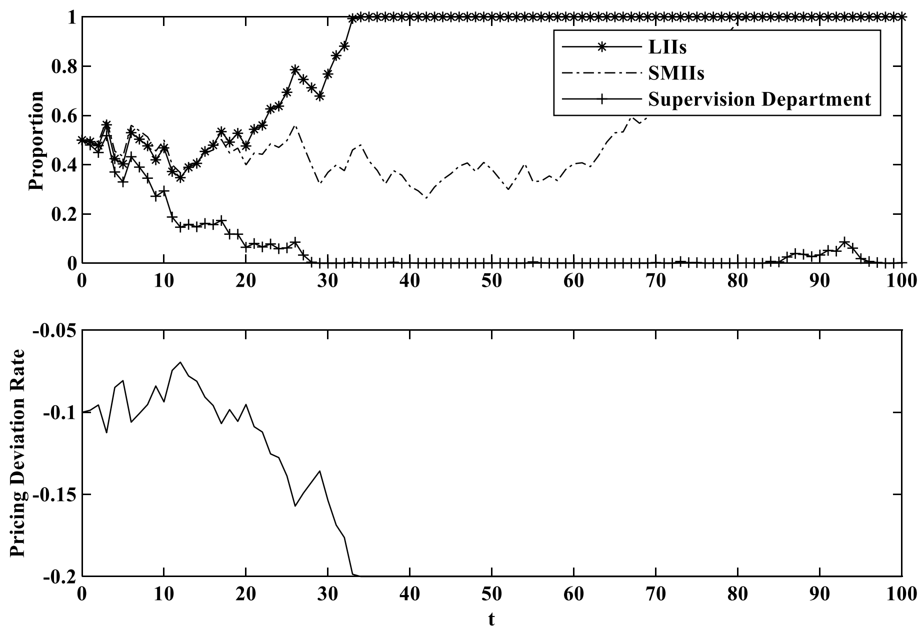

Fig. 10 Strategy evolution and market performance under scenario 2

The impact of penalty for illegal quotation on evolutionary process

Take M_1= 10, 18, 25 respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 11. We can see that although increasing penalties for rapacious quotations can reduce LIIs' illegal quotation tendency in the short term, but does not change its

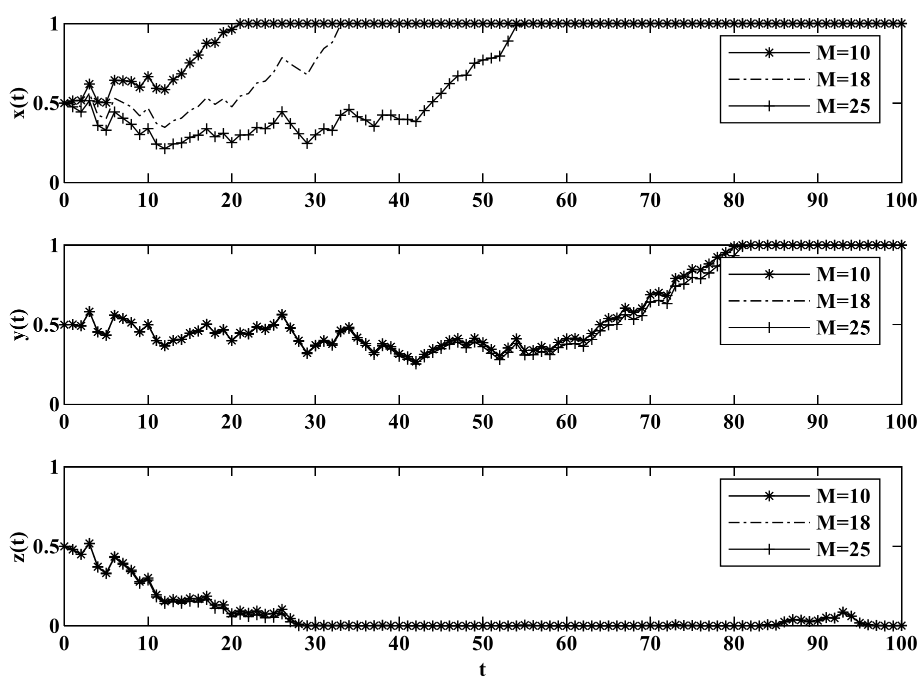

Fig. 11 Impact of illegal penalties on evolutionary process under scenario 2

evolutionary process to rapacious quotation. And the impact of penalty for SMIIs' illegal quotation on evolutionary process to imitative quotation, which is not presented, is also similar. The common reason is that strategic choice of SD will converge to light supervision in the long run because of insufficient incentives. In the absence of supervision, market participants will realize that their illegal quotation will not be punished through cognitive iterations and the benefits of illegal quotation is still much higher that these of legal quotation although penalties for illegal quotation increases. Hence, they will still choose illegal quotation such as rapacious quotation and imitative quotation. Additionally, as supervision penalty for illegal quotation is not directly related to the benefits of SD, so it has little impact on its evolutionary process.

The impact of SD's incentives on evolutionary process

Taking $I_1 = 5, 6, 7$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 12. It can be found that increasing supervise incentives can delay SD's evolutionary process to light supervision, but cannot change SD's stable evolution strategy of light supervision under light supervision condition. Similarly, although increasing SD's incentives can curb the tendency of LIIs to rapacious quotation and of SMIIs to imitative quotation in the short term, institutional investors will still form a steady-state equilibrium strategy of illegal quotations in the long run. Only if SD's incentives increase enough to change the light supervision condition, a huge shift will take place in the evolutionary process of LIIs, SMIIs and SD.

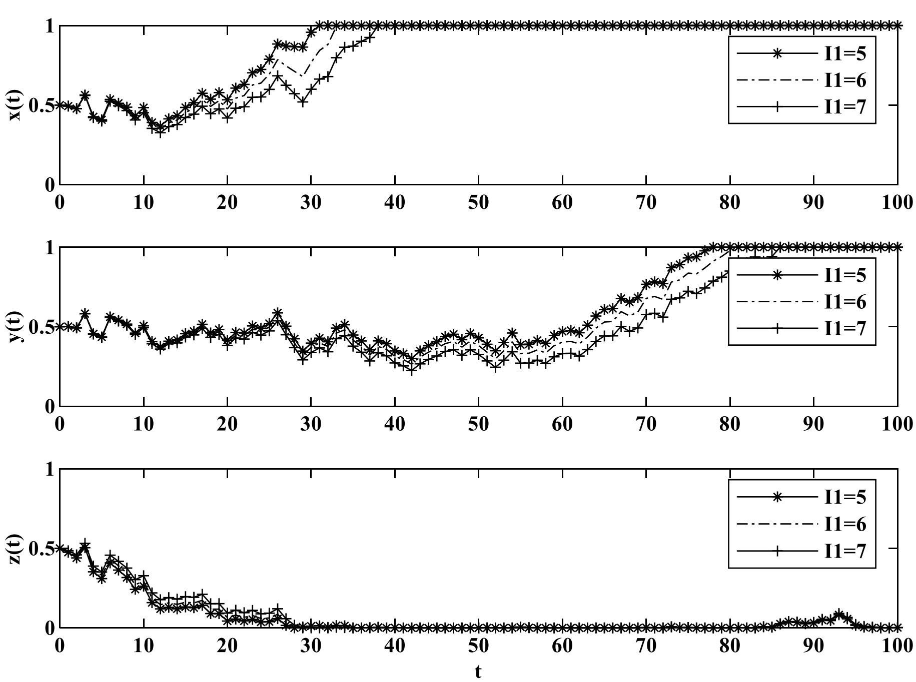

Fig. 12 Impact of supervise incentives on evolutionary process under scenario 2

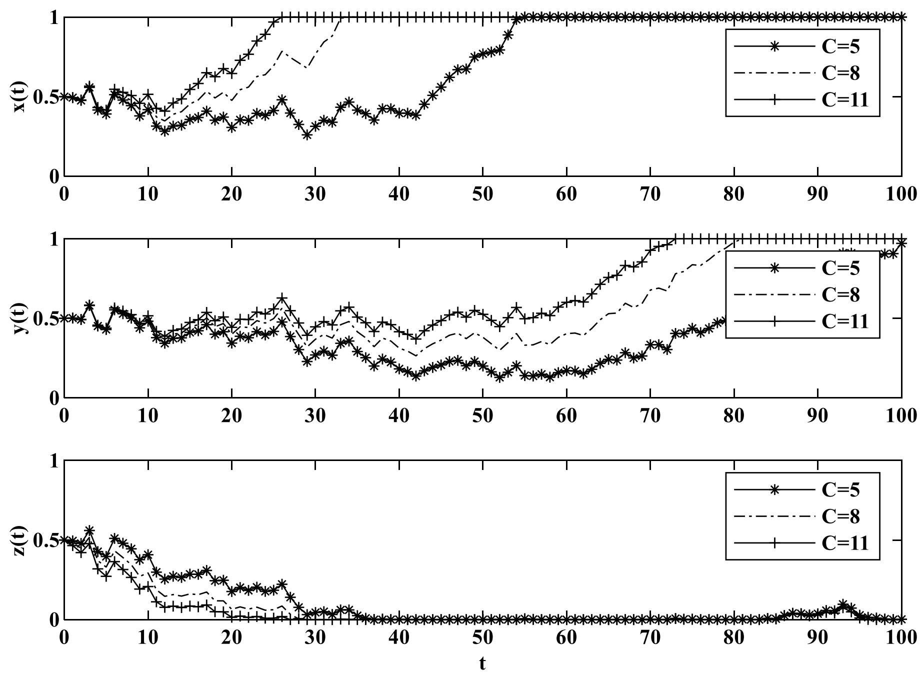

Fig. 13 Impact of SD's cost on evolutionary process under scenario 2

The impact of SD's cost on evolutionary process

Taking $C = 5, 8, 11$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 13. It can be found that lowering supervision cost can delay evolutionary process of SD, but cannot change SD's stable evolution strategy to light supervision under light supervision condition. Similarly, although reducing SD's cost can curb the LIIs' tendency of rapacious quotation and SMIIs' tendency of imitative quotation in the short term, inquiry market will still form a steady-state equilibrium strategy of illegal quotations in the long run. Only if SD's cost reduces enough to change the light supervision condition, a huge shift will take place in the evolutionary process of LIIs, SMIIs and SD.

The impact of culling rate of high-price culling rule on evolutionary process

Taking $k = 0.1, 0.5, 0.9$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 14. It can be found that increasing culling rate can accelerate evolutionary process of SMIIs to imitative quotation, but has little effect on evolutionary process of LIIs, and SD. The reason is that increasing culling rate can significantly lower the benefits of SMIIs with independent quotation, and improve the incremental benefits of SMIIs with imitative quotation. As a result, SMIIs will be more inclined to illegal quotation and evolutionary process of SMIIs to imitative quotation will be accelerated. And since culling rate of high-price culling rule is not directly related to the benefits of SD and LIIs, it has little impact on their evolutionary process. Hence, we can see that high-price culling rule will lower benefits of SMIIs with independent quotation, make SMIIs more willing to follow low price to ensure benefits of stock placement further, and accelerate SMIIs' evolutionary process to imitative quotation under light supervision condition.

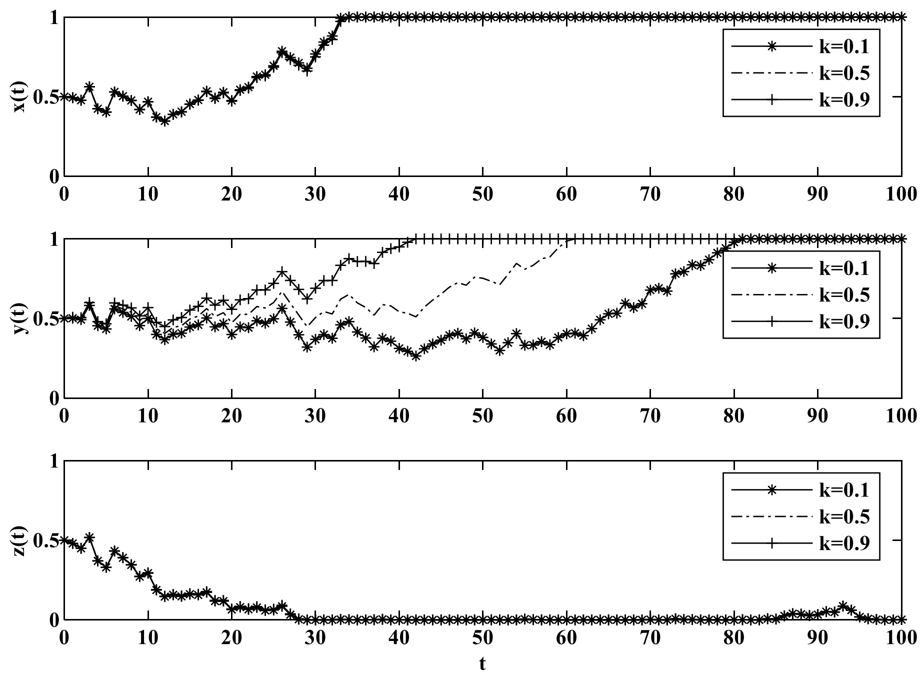

Fig. 14 Impact of culling rate on evolutionary process under scenario 2

The impact of ratio of SMIIs to LIIs in terms of financial budget on evolutionary process

Taking $\eta=$ 0.3,0.4, 0.5 respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 15. It can be found that increasing ratio of SMIIs to LIIs in terms of financial budget can accelerate evolutionary process of SMIIs to imitative quotation, but has little

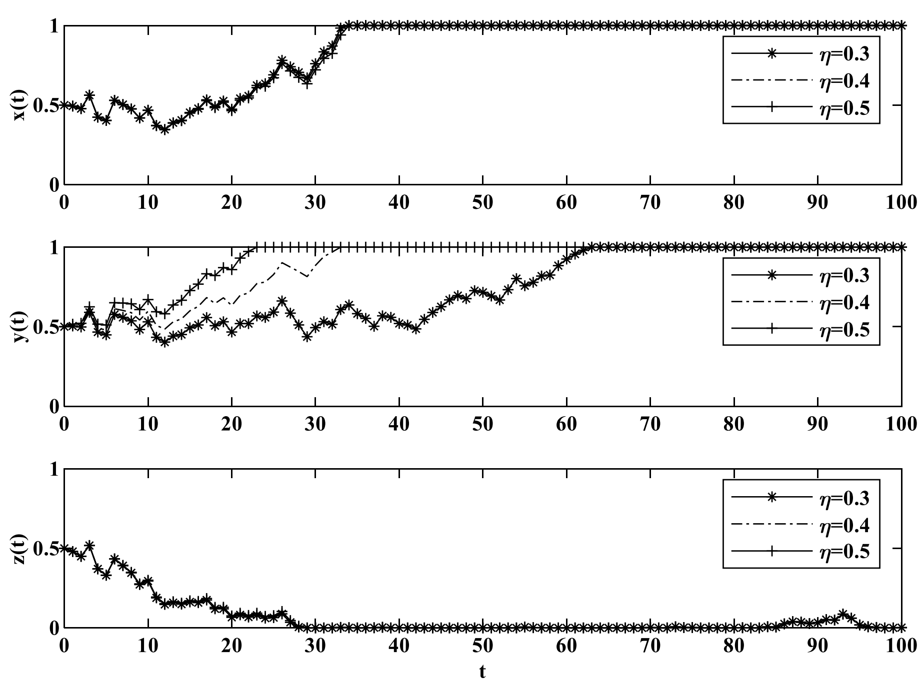

Fig. 15 Impact of ratio of financial budget on evolutionary process under scenario 2

effect on evolutionary process of LIIs, and SD. The reason is that increasing the ratio of financial budget can significantly improve the incremental benefits of SMIIs with imitative quotation. As a result, SMIIs will be more inclined to imitative quotation and evolutionary process of SMIIs to imitative quotation will be accelerated. And as the ratio of financial budget is not directly related to the benefits of SD and LIIs, it has little impact on their evolutionary process.

The impact of intensity of the random disturbance on evolutionary process

Taking $\sigma = 0, 1, 2$ respectively, evolutionary process of LIIs, SMIIs and SD is shown in Fig. 16. It can be found that with intensity of the random disturbance increasing, evolutionary process of LIIs, SMIIs and SD will become more unstable in general, and evolutionary process of LIIs and SMIIs is more sensitive to intensity of the random disturbance than that of SD. Its practical implication is that strategy choices of institutional investors are highly susceptible to supervision strategy while strategy choices of supervision strategy are less affected by quotation strategies of institutional investors under light supervision condition.

Results and discussions

As mentioned earlier, under tough supervision condition and with a large enough penalty to illegal quotation, the equilibrium strategies of LIIs, SMIIs and SD are respectively fair quotation, independent quotation and tough supervision. At this time, pricing deviation rate will have an increasing trend towards zero in general with the passage of time. Increasing penalties for illegal quotations can accelerate institutional investors' evolutionary process to legal quotation, but has little impact on SD's evolutionary process to tough supervision, while increasing SD's incentives, and reducing SD's costs can

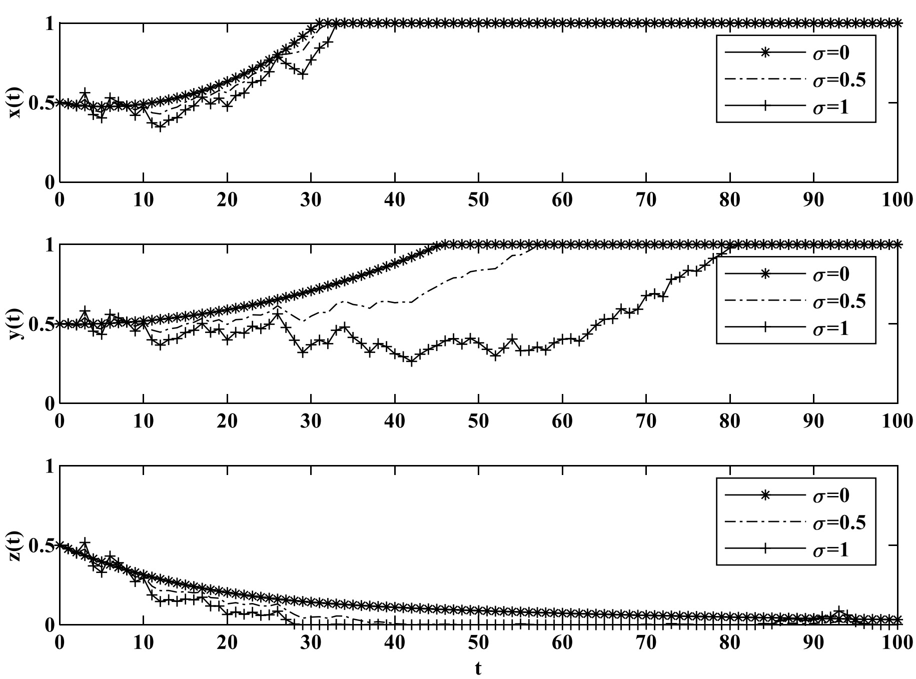

Fig. 16 Impact of disturbance intensity on evolutionary process under scenario 2

accelerate evolutionary process of them simultaneously. Hence, increasing SD's incentives and reducing SD's costs are prioritized over increasing regulatory penalties under tough supervision condition. Besides, increasing ratio of SMIIs to LIIs in terms of financial budget can decelerate SMIIs' evolutionary process to independent quotation, but has little effect on LIIs' and SD's evolutionary process. In addition, under tough supervision condition, high-price culling rule will lower expected benefits of SMIIs with independent quotation, prevent SMIIs from choosing strategy of independent quotation, and decelerate SMIIs' evolutionary process to independent quotation.

Under light supervision condition, the results have some differences. First, the equilibrium stable strategies of LIIs and SMIIs will become rapacious quotation and imitative quotation respectively, and the equilibrium strategy of SD will shift to light supervision. At this time, pricing deviation rate will have a decreasing trend in general with the passage of time and appear "low-price collusion" phenomenon similar to the situation in SIBC. Second, increasing penalties for illegal quotations will be meaningless as it doesn't change institutional investors' evolutionary process to illegal quotation in the long run. Third, only if the degree of SD's incentives increasing or SD's cost reducing is large enough to shift supervision condition from light into tough, evolutionary stable strategies of LIIs and SMIIs will shift into legal quotation. Otherwise, LIIs and SMIIs will still choose rapacious quotation and imitative quotation respectively. Fourth, increasing ratio of SMIIs to LIIs in terms of financial budget will accelerate evolutionary process of SMIIs to imitative quotation, rather than decelerate evolutionary process of SMIIs to independent quotation under tough supervision condition.

there are also some things in common no matter under tough or light supervision condition. For example, high-price culling rule will always lower expected benefits of SMIIs with independent quotation, make SMIIs more willing to choose imitative quotation. Additionally, when facing exogenous uncertainty, evolutionary stable strategy of SD is more stable than these of LIIs and SMIIs and strategy choices of institutional investors are more susceptible to supervision behavior.

In this vein, we believe that there is light supervision condition in SIBC's inquiry market which causes low-price collusion. In detail, high cost and insufficient incentives of tough supervision, as well as low exposure to social media in SIBC's inquiry market have formed light supervision condition, making SD unable to conduct tough supervision of illegal quotations continuously. On this condition, institutional investors will gradually realize that illegal quotation will not be punished, and tend to quote illegally. In addition, high-price culling rule in inquiry market will lower expected benefits of SMIIs with independent quotation, make SMIIs more willing to follow low price to ensure benefits of stock placement, and accelerate SMIIs' evolutionary process to imitative quotation further. As a result, inquiry market will form a steady-state equilibrium of low-price collusion. In this case, blindly increasing the penalties for illegal quotations or reducing the culling rate cannot fundamentally solve the problem of low-price collusion since it cannot shift SD's strategy from light into tough. LIIs and SMIIs can still form stable strategies of rapacious quotation and imitative quotation respectively through cognitive iteration.

Conclusions and policy implications

From the perspective of strategic interactions, this paper introduces evolutionary game method to analyze the theoretical mechanism, institutional condition and regulatory governance of phenomenon of low-price collusion in SIBC's inquiry market, and comes up with the following conclusions. First, low-price collusion rooted in light supervision condition in SIBC, which means SD's benefits of tough supervision is even lower than minimum benefit of light supervision. Under this condition, SD will be laid-back and choose light supervision, LIIs and SMIIs will choose rapacious quotation and imitative quotation in response and low-price collusion will gradually form in SIBC's inquiry market. Second, high-price culling rule will become a booster for low-price collusion and accelerate SMIIs' evolutionary process to imitative quotation, which means it may not be compatible with market-based inquiry of SIBC. Third, increasing penalties for illegal quotation is not an effective approach for regulatory governance under light supervision condition. Fourth, institutional investors' choices of quotation strategies are more volatile and highly susceptible to supervision behaviors of SD when facing exogenous uncertainty and the keys to solving low-price collusion are shifting supervision condition from light into tough through increasing incremental benefits of tough supervision and providing institutional investors with a stable and predictable supervision policy.

We make the following policy recommendations based on the above conclusions (Table 5). For SIBC's inquiry market system, what most necessary is to form an effective incentive and punishment mechanism and shift supervision condition from light into tough. On the one hand, the government should reduce SD's costs of tough supervision through measures such as extensively adopting Regtech in supervision of

Table 5 Summary of policy recommendations

Implementation scope	Guideline	Specific sub-measure
Inquiry market system	Reduce SD's costs of tough supervision	Extensively adopting Regtech in supervision
		Strengthening cross-departmental cooperation in law enforcement
		Increasing training for SD's officials
	Increase SD's incentives of tough supervision	Take the supervision or punishment intensity of illegal quotations as a key performance indicator or plus point of SD
		Link the satisfaction of the financing companies with the rewards of SD
	Modify high-price culling rule	Shift high-price culling rule into extreme price culling rule
		Dynamically adjust culling rate according to the distribution or concentration of quotations
External systems	Deterring potential violators	Clarify the identification criteria and punishment measures of illegal quotations in the form of law
	Increase the exposure of illegal quotation	Establish a coordinated oversight system for society, the media and industry associations
	Stabilize investors' expectations to supervision policy	Establish a communication and feedback mechanism between market participants and SD

illegal quotations, strengthening cross-departmental cooperation in law enforcement, and increasing training for SD's officials. On the other hand, incentive mechanisms for SD through administrative or market channels are supposed to be more introduced. The superior may take the supervision or punishment intensity of illegal quotations as a key performance indicator or plus point of SD and increase its rewards when it excels on these indicators. Also, it's appropriate to link the satisfaction of the financing companies with the rewards of SD. Additionally, the policymakers may shift high-price culling rule into extreme-price culling rule and dynamically adjust culling rate according to the distribution or concentration of institutional investors' quotations to encourage SMIIs to quote independently and reasonably.

Some changes should cooperatively be made outside of SIBC's inquiry market system. First, the legal department may clarify the identification criteria and punishment measures of illegal quotations in the form of law for the purpose of deterring potential violators in SBIC's inquiry market. Second, a coordinated oversight system for society, the media and industry associations should be established to increase the exposure of illegal quotation. Finally, SD should establish a communication and feedback mechanism with market participants to better clarify regulatory policies and stabilize institutional investor expectations.

As Chinese Vice Premier Liu He said, system building, non-intervention, and zero tolerance are a unified organism. The reform of the registration system for the inquiry market should not only stop at the stage of restoring the pricing power to the market and enhancing market vitality (non-intervention), but should also fundamentally establish quotation mechanism and supervision mechanism that are compatible with market-based pricing (system building), and ensure that SD conducts continuous, effective and normalized supervision of institution investors (zero tolerance). Only by fully realizing the organic unification of system building, non-intervention, and zero tolerance, resource allocation and price discovery functions of SIBC can be fully utilized, and the problem of low-price collusion in SIBC can be eliminated.

Appendix 1: Statistics on the actual allocation rate of SIBC

According to Wind database, we counted the monthly average of the actual allocation rate of SIBC's inquiry market from July 2019 to December 2021 and got the time series plot shown in Fig. 17. It can be found that except for the first half year after the running of SBIC, the actual distribution rate at other times is relatively stable. Especially from January 2021 to July 2021, it basically remained at a level around 2.5%. And the research object of this article, low-price collusion, also mainly occurred in this time period.

Appendix 2: Replicator dynamic equation

According to the idea of evolutionary game, if the benefits of adopting a pure strategy is higher than the average benefits of the whole population in a round of games, the pure strategy will be selected by more individuals in the next round, so that the proportion of individuals adopting the pure strategy in the population will continue to increase until reaching an

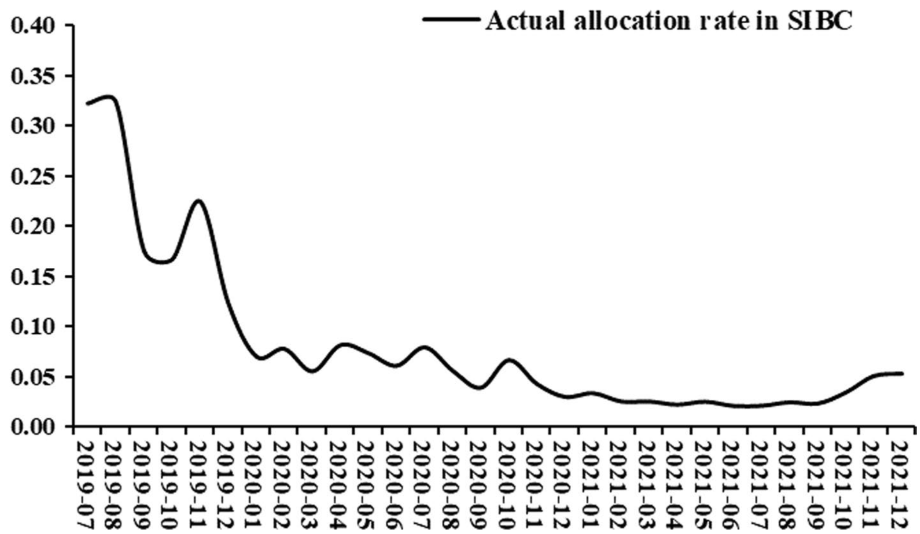

Fig. 17 monthly average of the actual allocation rate in SIBC's inquiry market

equilibrium state. Let E_{11} and E_{12} be the benefits of LIIs who adopt rapacious quotation and fair quotation strategies respectively, and let E_1 be the average benefits of LIIs.

$$E_{11}=\alpha n[p_L-\overline{p}(x)]-zM_1 \tag{25}$$

$$E_{12}=\frac{\alpha np_1[p_L-\overline{p}(x)]}{p_2} \tag{26}$$

$$E_1=xE_{11}+(1-x)E_{12} \tag{27}$$

Then the replicator dynamic equation for the strategy choice of LIIs is:

$$\begin{aligned}U_1(x)&=\frac{dx}{dt}=(E_{11}-E_1)x\\&=x(1-x)\{\frac{\alpha n[p_L-\bar{p}(x)](p_2-p_1)}{p_2}-zM_1\}\end{aligned} \tag{28}$$

Let E_{21} and E_{22} be the benefits of SMIIs who adopt imitative quotation and independent quotation strategies respectively, and let E_2 be the average benefits of SMIIs.

$$E_{21}=\alpha\eta n(p_L-\overline{p}(x))-zM_2 \tag{29}$$

$$E_{22}=\frac{\alpha\eta np_1(1-k)[p_L-\overline{p}(x)]}{p_3} \tag{30}$$

$$E_2=yE_{21}+(1-y)E_{22} \tag{31}$$

Then the replicator dynamic equation for the strategy choice of SMIIs is:

$$\begin{aligned} U_2(y) &= \frac{dy}{dt} = (E_{21} - E_2)y \\ &= y(1-y)\{\frac{\alpha\eta n[p_L - \overline{p}(x)][p_3 - (1-k)p_1]}{p_3} - zM_2\} \end{aligned} \tag{32}$$

Let E_{31} and E_{32} be the benefits of SD who adopt tough supervision and light supervision strategies respectively, and let E_3 be the average benefits of SD.

$$E_{31}{=}I_1 - C \tag{33}$$

$$E_{32}{=}I_2 - \frac{\lambda(x+y)}{2}N \tag{34}$$

$$E_3{=}zE_{31}{+}(1-z)E_{32} \tag{35}$$

Then the replicator dynamic equation for the strategy choice of SD is:

$$\begin{aligned} U_3(z) &= \frac{dz}{dt} = (E_{31} - E_3)z \\ &= z(1-z)[I_1 - C - I_2 + \frac{\lambda(x+y)N}{2}] \end{aligned} \tag{36}$$

Appendix 3: Proof of marginal condition in part 3

Lemma 1: A stochastic differential equation is given by Eq. (37).

$$dx(t) = f(t, x(t))dt + g(t, x(t))d\omega(t), x(t_0) = x_0 \tag{37}$$

Assume that there exists a positive, continuous function $V(t, x)$ and positive constants c_1,c_2, such that:

$$c_1|x|^p \le V(t, x) \le c_2|x|^p, t \ge 0 \tag{38}$$

When there exists a positive constant γ, for

$$LV(t, x) \le -\gamma V(t, x) \tag{39}$$

where

$$LV(t, x){=}V_t(t, x) + V_x(t, x)f(t, x) + g^2(t, x)V_{xx}(t, x)/2 \tag{40}$$

This implies Eq. (37) exists the global exponential stability in p-th mean, and that

$$E|x(t, x_0)|^p \le c_2|x_0|^p e^{-\gamma t}/c_1, t \ge 0 \tag{41}$$

And when there exists a positive constant γ, for

$$LV(t, x) \ge \gamma V(t, x) \tag{42}$$

where

$$LV(t, x){=}V_t(t, x) + V_x(t, x)f(t, x) + g^2(t, x)V_{xx}(t, x)/2 \tag{43}$$

This implies Eq. (37) doesn't exist the global exponential stability in p-th mean, and that

$$E|x(t,x_0)|^p \geq c_2|x_0|^p e^{-\gamma t}/c_1, t \geq 0 \tag{44}$$

The proofs of Lemma 1 can be seen in Baker & Buckwar (2005).

For Eq. (16) ~ (18), suppose $V(t,x)=x$, $V(t,y)=y$ and $V(t,z)=z$,$0 \leq x,y,z \leq 1$, $c_1=c_2=1$,$p=1$ and γ=1. It's easy to find that

$$LV(t,x)=f(t,x)=x[\frac{\alpha n(p_L-\overline{p}(x))(p_2-p_1)}{p_2}-zM_1] \tag{45}$$

$$LV(t,y)=f(t,y)=y\{\frac{\alpha\eta n(p_L-\overline{p}(x))[p_3-(1-k)p_1]}{p_3}-zM_2\} \tag{46}$$

$$LV(t,z)=f(t,z)=z[I_1-C-I_2+\frac{\lambda(x+y)N}{2}] \tag{47}$$

If Eq. (16) ~ (18) exist the zero-solution exponential stability, then

$$x[\frac{\alpha n(p_L-\overline{p}(x))(p_2-p_1)}{p_2}-zM_1] \leq -x \tag{48}$$

$$y\{\frac{\alpha\eta n(p_L-\overline{p}(x))[p_3-(1-k)p_1]}{p_3}-zM_2\} \leq -y \tag{49}$$

$$z[I_1-C-I_2+\frac{\lambda(x+y)N}{2}] \leq -z \tag{50}$$

As $0 \leq x,y,z \leq 1$, Inequality (47) ~ (49) imply that

$$\frac{\alpha n(p_L-\overline{p}(x))(p_2-p_1)}{p_2} \leq zM_1-1 \tag{51}$$

$$\frac{\alpha\eta n(p_L-\overline{p}(x))[p_3-(1-k)p_1]}{p_3} \leq zM_2-1 \tag{52}$$

$$I_1-C-I_2+\frac{\lambda(x+y)N}{2} \leq -1 \tag{53}$$

That is

$$z \geq \frac{\alpha n(p_L-\overline{p}(x))(p_2-p_1)+p_2}{M_1p_2} \tag{54}$$

$$z \geq \frac{\alpha\eta n(p_L-\overline{p}(x))[p_3-(1-k)p_1]+p_3}{M_2p_3} \tag{55}$$

$$I_1 - C - I_2 + 1 \leq \frac{\lambda(x+y)N}{2} \tag{56}$$

As $0 \leq x, y, z \leq 1$, it's obvious that

$$\frac{\alpha n(p_L - \overline{p}(x))(p_2 - p_1)}{M_1 p_2} \leq \frac{\alpha n(p_L - p_1 + m)(p_2 - p_1)}{M_1 p_2} \tag{57}$$

$$\frac{\alpha \eta n(p_L - \overline{p}(x))[p_3 - (1-k)p_1] + p_3}{M_2 p_3} \leq \frac{\alpha \eta n(p_L - p_1 + m)[p_3 - (1-k)p_1]}{M_2 p_3} \tag{58}$$

$$\frac{\lambda(x+y)N}{2} \leq \lambda N \tag{59}$$

Therefore, the necessary conditions for zero-solution exponential stability of Eq. (16) ~ (18) are:

$$z(t) \geq [p_2 + \alpha n(p_L - p_1 + m)(p_2 - p_1)] \big/ M_1 p_2 \tag{60}$$

$$z(t) \geq [p_3 + \alpha \eta n(p_L - p_1 + m)(p_3 - (1-k)p_1)] \big/ M_2 p_3 \tag{61}$$

$$(I_1 - C) - (I_2 - \lambda N) \leq -1 \tag{62}$$

In the same way, we can get the necessary conditions that Eq. (16) ~ (18) don't exist zero-solution exponential stability.

$$z(t) \leq [-p_2 + \alpha n(p_L - p_1)(p_2 - p_1)] \big/ M_1 p_2 \tag{63}$$

$$z(t) \leq [-p_3 + \alpha \eta n(p_L - p_1)(p_3 - (1-k)p_1)] \big/ M_2 p_3 \tag{64}$$

$$(I_1 - C) - I_2 \geq 1 \tag{65}$$

Appendix 4: Determination of simulation data

We count real data of the stocks listed on SIBC in July 2021, and thirteen stocks were identified to be used to determine the simulation data after excluding outliers. And the samples and raw data are from the Wind database. The rules for calculation are as follows: (1) We consider closing price of new stock after 30 days of listing as p_L and regard the arithmetic average of all quotations as p_1; (2) We consider the highest, second highest quotes and as p_3 and p_2 respectively; (3) We consider the ratio of maximum subscription to minimum subscription as η and regard maximum subscription as n whose unit is ten thousand; (4) The calculation rules for $\overline{p}(x)$, α, e and pe are consistent with their actual meaning, and pe preserves integers when calculating. The real values of these parameters are shown in Table 6 where the unit of α is one percent and the unit of n is ten thousand specially.

Typically, we take the mean of each parameter as a reference for determination of simulation data. Considering the simplicity of the calculation, we finally take the following values as simulation data: $p_L = 60$, $p_1 = 20, p_2 = 35, p_3 = 55, \overline{p}(x) = 18, \eta = 0.25$,

Table 6 Data of selected stocks relevant to quotation process

Stock symbol	p_L	p_1	p_2	p_3	$\overline{p}(x)$	η	n	α	e	pe
688,071.SH	33.03	13.78	21.83	23.88	13.73	0.56	500	0.02	0.55	40
688,148.SH	34.34	4.83	15.88	17.05	4.58	0.11	3040	0.03	0.11	47
688,296.SH	44.20	12.56	24.86	27.36	12.46	0.25	850	0.02	0.67	59
688,303.SH	72.00	21.79	37.21	38.00	21.49	0.01	8000	0.05	0.54	46
688,501.SH	16.48	10.59	12.05	16.20	10.57	0.49	780	0.02	0.44	39
688,509.SH	5.66	1.99	2.77	28.12	1.97	0.08	6,000	0.02	0.07	34
688,511.SH	53.38	28.54	52.50	52.77	28.09	0.18	600	0.02	1.36	46
688,670.SH	80.90	55.53	95.21	267.00	55.18	0.15	670	0.03	1.76	44
688,718.SH	28.46	5.87	10.50	14.74	5.85	0.51	1290	0.02	0.24	40
688,768.SH	102.00	18.38	42.10	42.73	18.23	0.40	500	0.01	0.92	35
688,778.SH	106.22	24.62	33.95	55.73	24.50	0.07	1900	0.02	0.97	47
688,793.SH	106.51	27.53	57.13	57.67	27.40	0.27	450	0.02	1.02	45
688,800.SH	80.65	15.40	46.05	99.00	15.02	0.20	800	0.02	0.61	45
Average	58.76	18.57	34.77	56.94	18.39	0.25	1952	0.02	0.71	44

$n = 2000$, $\alpha = 0.02\%$, $e = 0.5$ and $pe = 40$. We simply regard x as 0.5 in July 2021, hence $m = (p_1 - \overline{p}(x))/x = 4$. And we notice that SFC's regulation with culling rate of high-price not less than 10% is still in force in July 2021, so we set $K = 0.1$ simply. Hence, we can calculate maximum incremental benefits of LIIs and SMIIs with illegal quotations are 75,429 and 29,600 respectively. Since China's Securities Law provides that whoever disrupts or manipulates the securities market shall be fined not less than one time but not more than ten times the illegal benefits, we take 2 times to calculate the penalty for illegal quotation and we can get $M_1 = 150,858$ and $M_2 = 59,200$. To guarantee convenience of our calculation, we further set $M_1 = 18$ and $M_2 = 6$ with a unit of ten thousand yuan. By reviewing the CSRC's 2021 information announcement, we found that the CSRC's annual regulatory expenditure budget was 46.1448 million yuan, handling a total of 609 cases, with an average budget of 75.77 thousand yuan per case. Therefore, we set $C = 8$ with a unit that is the same as M_1 and M_2. Noticing that Inequality (19)~(22) always hold under both simulation data and real data, we can find our assumptions of model is realistic.

Since the information such as normal salaries, performance incentives, and internal penalties of SFC is not disclosed to the public, we cannot accurately measure the actual values of I_1, I_2 and N on a single regulatory project. And sensitivity of exposure ratio to the proportion of illegal quotation is also difficult to measure. Referring to Huang and Yu (2022), we simply set $I_2 = 5$, $N = 10$ and $\lambda = 0.5$ while the units of I_2 and N are ten thousand yuan. Finally, we set $\sigma = 1$ by convention.

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Author contributions

XL carried out the research papers' modeling, numerical simulation and analysis, and drafted the manuscript. ZC, theoretical discussion, modeling guidance and support, and editing. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests

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