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Evolutionary game model for the behavior of private sectors in elderly healthcare public–private partnership under the condition of information asymmetry

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Abstract

Chinese elderly healthcare services face problems of poor service quality, difficulty in eliminating hidden quality risks, and inadequate government supervision, primarily due to information asymmetry and insufficient supervision among providers, users, and regulatory bodies. The study addresses two key questions: How does information asymmetry influence private sector strategies in elderly healthcare public–private partnership (PPP), and what regulatory models can overcome the potential shortcomings? The study examines the influence of information asymmetry, particularly on "experience" and "credence," crucial for governance and service quality in elderly healthcare PPPs in China. By developing the novel methodology of evolutionary game theory and employing MATLAB simulations, this study analyzes private sector behavior under two distinct regulatory models. The research findings reveal a significant disparity, under the traditional "single" model; private sectors often prioritize low-quality services driven by self-interest or inadequate penalties, while the collaborative model incentivizes them to deliver higher-quality services influenced by factors such as public participation, reputational incentives, and penalties. Therefore, the paper proposed a multi-faceted regulatory model based on strengthening third-party evaluation mechanisms, encouraging public participation, and refining reward and penalty systems. This proposed model will not only significantly contribute to regulatory effectiveness and quality services within elderly healthcare PPP projects, but will also serve as a reference point for government decision-makers responsible for quality services within PPP projects.

Keywords Information asymmetry, Elderly healthcare PPP project, The third-party evaluation, Public participation, Reputation incentive, Evolutionary game

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Introduction

In recent years, a series of incidents in nursing homes across China such as falls, food poisoning, suicides, fires, and structural collapses have raised serious concerns about the quality of elderly healthcare services [1]. These events have exposed significant issues in the quality of elderly healthcare services, such as inadequate safety measures, unaddressed hidden risks, insufficient government oversight, and a lack of effective regulatory frameworks [2, 3]. The underlying cause of these issues is information asymmetry, where the private sector, elderly users, and government regulators are often disadvantaged in accessing crucial information, leading to poor decision-making and suboptimal service outcomes [4].

In line with China's market-oriented reforms in elderly healthcare, public–private partnership (PPP) projects have emerged as a key mechanism for collaboration between the private sector and government. These projects are vital for enhancing service quality, fostering innovation, and ensuring the long-term sustainability of elderly healthcare services, directly impacting the well-being of the aging population [5]. However, during the operational phase of these PPP projects, the government faces considerable challenges due to information asymmetry. Regulatory agencies often face significant constraints in data, resources, and capacity, hindering their ability to effectively monitor private sector performance and enforce regulations that ensure high standards of care [6]. Constraints on regulatory resources including limited funding, insufficient workforce, inadequate inspection capacity, and poor service quality monitoring result in ineffective oversight, ultimately diminishing the government's ability to enforce regulatory frameworks and guarantee quality care [7].

Moreover, some local governments prioritize infrastructure development while neglecting their regulatory responsibilities, resulting in a "zero-regulation" or "completely unregulated" state [8–10]. This lack of oversight fosters opportunistic behavior by private sector actors, who may exploit the "experience goods" and "trust goods" characteristics of elderly healthcare services [11]. With an information advantage and strong profit incentives, private providers may cut corners on service quality, disregarding both contractual obligations and regulatory frameworks. This not only diminishes service standards but also jeopardizes the welfare of elderly citizens and undermines the broader social good, turning elderly healthcare PPP projects into mechanisms for financial and social capital extraction [12].

In response to these challenges, this study seeks to investigate the behavioral strategies employed by private sector participants in elderly healthcare PPP projects, focusing on the role of information asymmetry and its impact on regulatory models. By employing an evolutionary game theory (EGT) model, this paper explores the interactions between the government and the private sector within these partnerships, offering insights into how strategic decisions evolve under conditions of information asymmetry. EGT is particularly suitable for this context, as it models the dynamic interactions between actors whose strategies evolve in response to changing incentives and external pressures. Unlike traditional static models, EGT allows for the exploration of long-term strategic equilibria and examines the effects of regulatory interventions on the private sector's behavior.

Theoretical review and research gap

Elderly healthcare PPP projects serve as a bridge between private sector entities providing services and elderly users receiving these services. In this context, the private sector often possesses a significant information advantage, creating a situation of information asymmetry [13]. This asymmetry plays a crucial role in shaping the quality of care provided and presents considerable challenges for regulatory oversight.

In the context of information asymmetry, Nelson [14] and Darby et al. [15] classify products and services into three categories: search goods, experience goods, and trust goods. Search goods are those that consumers can evaluate before purchase; experience goods require users to assess quality only after usage; and trust goods are those for which users find it difficult to evaluate quality even after consumption. In the case of elderly healthcare services, these services primarily fall into the categories of experience goods and trust goods. Elderly users, who often face significant information disadvantages, cannot fully assess the quality of care provided in elderly healthcare PPP projects before or even after consumption. Quality evaluations, therefore, rely heavily on actual usage, and for those without sufficient knowledge or experience, the ability to assess service quality remains limited [16].

The special nature of trust goods in elderly healthcare services introduces unique challenges for the private sector. Elderly users may be emotionally subjective in their assessments of service quality, making it difficult for the private sector to build a credible reputation based solely on self-reported service quality. This results in market failure, where low-quality services may crowd out higher-quality alternatives [17]. To address this issue, involving a third-party, professional, and credible evaluation agency becomes crucial. This third party, trusted by elderly consumers, can assess and publicly report the quality of services offered by elderly healthcare PPP projects. Regular publication of these reports ensures transparency and can help mitigate the information asymmetry between

the private sector and elderly users. The government plays an instrumental role by setting minimum quality standards for services, tying subsidies to third-party evaluations, and offering rewards and penalties based on the quality outcomes of these evaluations. These measures effectively transform trust goods into experience goods by providing users with more concrete information about service quality [18, 19].

While regulating minimum quality standards under information asymmetry can enhance the quality of goods and services, leading to increased sales and overall industry welfare [20, 21], it also creates a situation where low-quality services can drive out higher-quality ones, particularly in the elderly care sector. This issue highlights the need for a reputation mechanism to stimulate market behavior and address the failures of quality regulation [22–24]. Adam Smith's early emphasis on reputation underscored its vital role in ensuring the smooth execution of contracts [25]. Numerous scholars have extended the concept of reputation incentives from individuals to broader groups and societies, applying it in diverse fields such as finance, insurance, food safety, healthcare, environmental policy, and PPP [26–28]. Reputation incentives have, therefore, become an effective mechanism for overcoming the limitations of quality regulation induced by information asymmetry, actively engaging the public in the process [29].

The role of public participation is particularly crucial in the operational performance of PPP projects. Increased public engagement enhances the regulatory effectiveness and operational success of these projects [30]. In the regulatory and governance framework of elderly care PPP projects, public participation has a direct effect on the quality regulation of elderly care services [31]. In practice, private sector entities and third-party evaluators can report non-compliance, thereby reducing government regulatory costs while improving quality monitoring [2]. Therefore, public participation is a critical component in ensuring the success of quality regulation within elderly healthcare PPP projects. Public participation is crucial within the regulatory framework of elderly healthcare PPP projects, as it directly enhances the efficacy of quality regulation.

However, existing literature often overlooks the information asymmetry inherent in the experience goods and trust goods characteristics of elderly healthcare services. Furthermore, there is a lack of comparative studies on different regulatory models in the operation of elderly healthcare PPP projects. The main difference between this paper and the previous studies is shown in Table 1.

This study addresses key gaps in the literature by investigating the opportunistic behavior of the private sector in elderly healthcare PPP projects under conditions of information asymmetry. Using an evolutionary game theory (EGT) approach, it models the interactions among private sector entities, government, and public participants. The novelty of this approach lies in its ability to simulate strategic decision-making under asymmetric information, offering insights into the dynamics of opportunistic behavior and regulatory responses.

Furthermore, the research develops a novel framework combining EGT and MATLAB simulations to compare the private sector's behavioral strategies under two distinct regulatory models. By identifying the limitations of traditional frameworks, it proposes a multifaceted regulatory approach aimed at enhancing effectiveness and service quality in elderly healthcare PPP projects. This framework provides valuable insights for governments in designing more robust regulatory models, with Fig. 1 illustrating the theoretical framework applied in this study.

Table 1 Differences between previous literature and this research

Intervention for the behavior of private sectors in elderly healthcare PPP under the condition of information asymmetry	Existing Literature	This Study
Specifically targets elderly healthcare in China, addressing the critical issue of information asymmetry between service providers, users, and regulatory bodies, which affects service quality and governance.		√
Primarily utilizes principal-agent theory, contract theory, and basic game theory models	√	
Evolutionary game theory to model dynamic strategies of private sector actors under information asymmetry.		√
Information asymmetry is central, particularly related to "experience" and "credence" factors in healthcare services.		√
Mainly relies on static models, economic optimization, or simplified agent-based models	√	
Uses MATLAB simulations with evolutionary game theory to simulate dynamic interactions and outcomes over time.		√
Proposes a multifaceted regulatory model, including third-party evaluations, public participation, and refined reward/penalty systems.		√
Directly addresses service quality risks, particularly in elderly healthcare, influenced by the collaboration between private sector and government.		√

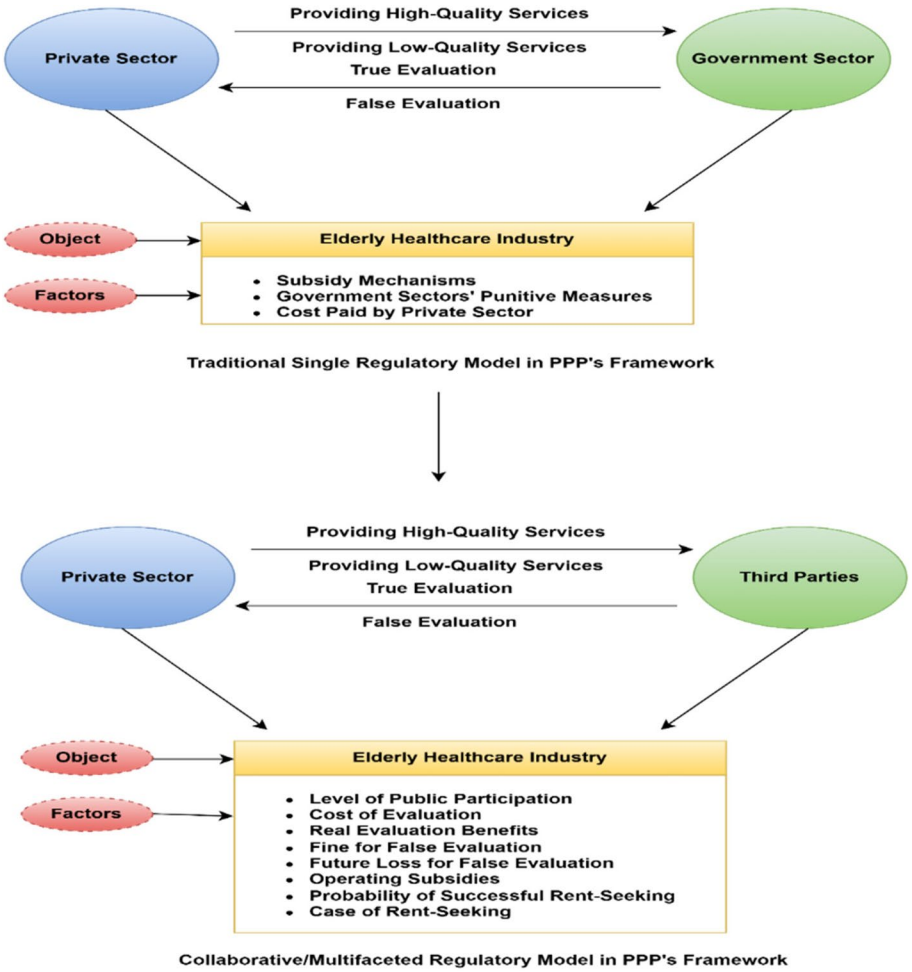

Fig. 1 Theoretical framework

The remainder section of the paper is structured as follows. "Analyzing the evolutionary game between private sectors and government sectors in the traditional 'single' supervision mode" section analyzes the evolutionary game between the private sector and the government sector in the traditional "single" supervision mode. "Analyzing the evolutionary game between private sectors and third parties in the multiple collaborative supervision mode" section analyzes the evolutionary game between the private sector and the third Party in the multiple collaborative supervision mode. "Conclusions and related recommendations" section provides a conclusion with policy implications for the government based on the empirical results of the applied models and provides suggestions to further enhance the service quality of PPP projects.

Analyzing the evolutionary game between private sectors and government sectors in the traditional 'single' supervision mode

It is assumed that elderly healthcare PPP projects provide health services for the elderly through the Build-Operate-Transfer (BOT) and Operations & Maintenance (O&M) models. Government sectors entrust the local Working Commission on Aging or Civil Affairs Bureau as the government regulation department to maintain the market order of the PPP framework in the elderly healthcare industry, construct the required service quality standard system, and build a fair elderly healthcare service security system. In addition, their role is to supervise and manage the operation of the project and to ensure the maximization of public welfare. On the other hand, the private sector is responsible for the operation of PPP projects in the

elderly healthcare industry and obtains returns through user fees, operating subsidies, etc. In the traditional "single" regulatory model, private sectors and government sectors are the main players in the game.

Constructing hypotheses and building the evolutionary model

Hypothesis 1

In the case of information asymmetry, both private sectors and government sectors are bounded rationality, regardless of the differences between the two parties themselves. Government sectors pursue their interests while seeking to maximize the interests of society as a whole, and private sectors pursue the maximization of profits and shareholders' rights. Therefore, they constantly fine-tune their strategies throughout the game until they find the optimal approach.

Hypothesis 2

Based on market prices or under the equivalent charging standards set by the government, private sector's strategy space is defined as $P=(PH, PL)$, where PH (providing high-quality services) represents that the service quality is higher than the minimum quality standard in the public–private contract in elderly healthcare PPP projects. Similarly, PL (providing low-quality services) represents that the service quality is lower than the minimum quality standard in the public–private contract in the elderly healthcare PPP project. Moreover, government sectors have two options i.e. active regulation and negative regulation. Government sectors' strategy space is defined as $R=(AR, NR)$. Here, AR (active regulation) shows that government sectors vigorously supervise the operating and service quality of PPP projects for the elderly to sidestep private sector violations and NR (negative regulation) specifies that government sectors do not apply any punishment mechanism to private sectors with low-quality services.

Hypothesis 3

The probability that private sectors choose the strategy of PH is $x(0 \leq x \leq 1)$, while the probability of choosing the strategy of PL is $1-x$. Similarly, the probability of government sectors adopting the AR strategy is $z(0 \leq z \leq 1)$ while the probability of adopting the NR strategy is $1-z$.

Hypothesis 4

Based on the public–private contract, the fixed benchmark benefit that private sectors can achieve through user fees is assumed as R_s, whereas the operating subsidy that can be obtained through performance evaluation is assumed as R_e. The cost for private sector to choose the strategy of PH is assumed as C_H (for example, the provision of service facilities is higher than the minimum standard in the public–private contract and the number of professional nursing staff employed exceeds the minimum standard in the public–private contract, etc.). The cost of private sector choosing the strategy of PL is assumed as C_L (for example, the service facilities equipped are lower than the minimum standard in the public–private contract, and the number of professional nursing personnel employed is less than the minimum standard in the public–private contract, etc.). So, we can conclude that in case $C_H > C_L$, it means following the standards and better performance. On the contrary, if $C_H < C_L$, it means that private sectors provide low-quality services, and it will be charged by the government under the active supervision of government sectors, represented as F_s, and cannot obtain operation subsidies as well, which is represented as R_e.

Hypothesis 5

When government sectors actively supervise, they can obtain benefits represented as R_g (such as allowances, subsidies, and bonuses from superior departments to encourage supervision and public recognition) but need to pay costs represented as C_g. When government sectors passively supervise, it will neither generate regulatory costs nor gain regulatory benefits. To properly understand and simplify the model, it is understood that if government sectors actively supervise, the problem of low-quality services in private sectors will be investigated and dealt with, and operating subsidies to private sectors will be canceled. On the contrary, if government sectors passively supervise, the problem of low-quality services in private sectors will not be investigated and thus, it will persist, however, the operating subsidies to private sectors will continue.

To provide a clear understanding of each parameter in the above assumptions, Table 2 presents a comprehensive description of these parameters. Based on the aforementioned hypotheses, Table 3 illustrates the payoff matrix

Table 2 Explanation of the meaning of the game model parameter symbols

Symbol	Description
R_s	Fixed Benchmark Benefit from User Fees
R_e	Operating Subsidy through Performance Evaluation
C_H	Cost for Providing High-quality Services
C_L	Cost for Providing Low-quality Services
F_s	Fine for Low-Quality Service under Government Supervision
R_g	Benefit of Active Supervision by Government
C_g	Cost of Active Supervision by Government

Table 3 The payoff matrix of the evolutionary game between private sectors and government sectors in the traditional "single" supervision mode

Private sectors	Government sectors	
	AR (z)	***NR*** $(1-z)$
PH (x)	$R_s + R_e - C_H, R_g - C_g$	$R_s + R_e - C_H, 0$
PL $(1-x)$	$R_s - C_L - F_s, R_g - C_g$	$R_s + R_e - C_L, 0$

of the evolutionary game between the private sector and government sector under the traditional "single" supervision mode.

Model analysis

In practice, elderly healthcare PPP projects have a long operating cycle. In addition, government sectors often must pay higher costs of supervision than private sectors owing to the asymmetry of information, the complexity of the organization of elderly healthcare PPP projects, and the high degree of concealment of rent-seeking behavior. Therefore, it can be seen from the payment matrix in Table 1 that if there is no other mechanism to constrain the strategic selection behavior of both parties, as long as $R_s + R_e - C_H < R_s - C_L - F_s$, that is, $R_e + F_s < C_H - C_L$, private sectors may have opportunistic behavior, that is, choose the strategy of *PL*. For government sectors, however, as long as $R_g - C_g < 0$, or in other words, $R_g < C_g$, government sectors will choose the strategy of *NR*. Therefore, if elderly healthcare PPP projects are adopted by the traditional "single" administrative supervision mode, they will not only be inefficient and costly but also cannot form an effective disclosure mechanism for the information on the quality of elderly healthcare services. When government regulation fails or there are loopholes in regulation (rent-seeking collusion), it is difficult to rely only on government sectors' punitive measures and subsidy mechanisms to urge private sectors to improve the service quality of elderly healthcare.

The practice has also repeatedly proved that this traditional "single" administrative supervision mode is doomed to fail, even after four major regulatory system adjustments, China's elderly healthcare service quality administrative supervision system has been increasingly perfect. If it is directly applied to the supervision of elderly healthcare PPP projects, it will also lead to "government failure" and "market failure" in the face of multiple elderly healthcare PPP project organizations and endless illegal means. Reflecting on the failure of the supervision mode of health care institutions in China, it can be implied that China overemphasizes the leading role of the government in the supervision of elderly healthcare quality. However, it ignores the role of third-party professional evaluation institutions (referred to as third parties) and the public (including elderly users, public welfare organizations, and news media) in the supervision of the elderly healthcare quality.

Analyzing the evolutionary game between private sectors and third parties in the multiple collaborative supervision mode

To address more effectively the problem of opportunistic behavior in private sectors caused by information asymmetry, government sectors can entrust third parties to directly supervise and evaluate the quality of services provided by private sectors. In this scenario, government sectors become discreet minimum quality regulators and supervisors. The public can also participate in the supervision of elderly healthcare PPP projects directly (with third parties participating in the evaluation) or indirectly (through reporting) to help eradicate the passive supervision phenomenon caused by insufficient regulatory resources (regulatory funds, staff, etc.) of government sectors. Moreover, according to the reputation of private sectors and third parties in public, future cooperation opportunities with a higher (poorer) reputation can be increased (decreased). In addition, public participation, reputation incentives, and government supervision can be introduced into the game model as variables affecting the choice of strategies of both parties. At the same time, the government subsidy system has a role to play and can be implemented according to third parties' evaluation results of the services provided by private sectors, thus forming an evolutionary game relationship between private sectors and third parties in the multiple collaborative supervision mode. Therefore, private sectors and third parties are the main participants in the game in the multiple collaborative supervision mode.

Model hypothesis and construction

Hypothesis 6

As for the information asymmetry game, even differences between players are not considered. Trusting the government, third parties assess and monitor the quality of care for the elderly offered by private sectors in elderly healthcare PPP projects. Third parties' strategy space is defined as *E=(TE, FE)*. In this case, *TE* stands for true evaluation, which means that third parties hire professional evaluators, and use advanced techniques in assessment. They have uniform criteria industry-wide to reject rent-seeking from private actors and issue an accurate report; while *FE* means false evaluation which serves as reducing to amateur nonalignment of standards practices mentioned above, accepting rent-seeking from private sectors and issuing irregular reports, etc. The probability that

third parties choose the *TE* strategy is y $(0 \leq y \leq 1)$. The probability of choosing the *FE* strategy is 1-y.

Hypothesis 7

The government is responsible for supervising and spot-checking the behavior of third parties and private sectors. The probability of regulation and spot-checking is set as $\beta(0 \leq \beta \leq 1)$. Under the participation mechanism established by the government, the public supervises the service behavior of private sectors and the third-party evaluation behavior according to the law, and the level of public participation is set as λ $(0 \leq \lambda \leq 1)$.

Hypothesis 8

Third parties can obtain evaluation benefits represented as R_t, and the cost of *TE* (true evaluation) is set as C_t (such as adopting unified evaluation standards and advanced evaluation techniques, employing professional evaluators, and issuing real evaluation reports, and so on.). If the cost of *FE* (false evaluation) is C_f (such as not adopting unified evaluation standards and advanced evaluation technology, employing amateurs to do evaluation work, issuing FE reports, and so on). It means that $C_t > C_f$ will be the set scenario. The third-party real evaluation can gain public trust and a good reputation, and the future benefits will increase and therefore is symbolized as T_1 (for example, the public trusts the evaluation results, the government-entrusted evaluation business increases, and so on). On the other hand, third-party false evaluations will be fined which is symbolized as F_t, for example when found by random inspections by government departments. Similarly, when the public finds out and reports it, it is the same as being fined by the government represented as F_t. At the same time, due to the decline of public reputation, future loss will be considered and is represented as T_2 (for example, people's trust in their evaluation results will decrease, and the amount of evaluation business entrusted by the government will decrease, and so on).

Hypothesis 9

According to the third-party evaluation results, private sectors that provide high-quality services can obtain operating subsidies, which are set as R_e. Consequently, private sectors will have a good reputation among the public for providing high-quality services, and the future benefits will increase which is designated as S_1 (such as a reduction in the vacancy rate of elderly beds or the government adding new cooperation projects and so on). In addition, private sectors with only up-to-standard services cannot receive operating subsidies, which is symbolized as R_e, no fines will be imposed. However, private sectors that provide low-quality services will not receive any subsidies but the government will punish them as well, which is set F_s. Hence, due to poor reputation among the public, future losses will be considered which is designated as S_2 (such as increased vacancy rates of elderly beds, government termination, or reduction of existing cooperative projects). Furthermore, when private sectors provide low-quality services, the probability of successful rent-seeking with a third party is set as $\alpha(0 \leq \alpha \leq 1)$, and the cost of rent-seeking is set as ν, at this time $\nu < C_H - C_L$; under the behavior of rent-seeking collusion, third parties choose an *FE* strategy. Henceforth, to reduce the risk of being investigated by the government and spotted by the public, only private sectors that provide low-quality services are rated as satisfactory by third parties. Although private sectors do not receive government subsidies, they are exempt from government penalties based on evaluation results.

To provide a clear understanding of each parameter in the above assumptions, Table 4 presents a comprehensive description of these parameters. Based on the above hypotheses, the payoff matrix for constructing the evolutionary game between private sectors and third parties in the multiple collaborative supervision mode is shown in Table 5.

Table 4 Explanation of the meaning of the game model parameter symbols

Symbol	Description
β	Probability of Regulation and Spot-Checking
λ	Level of Public Participation
C_t	Cost of True Evaluation
C_f	Cost of False Evaluation
T_1	Future Benefits of True Evaluation
T_2	Future Losses from False Evaluation
F_t	Fine for False Evaluation
S_1	Future Benefits of Providing High-Quality Services
S_2	Future Losses from Providing Low-Quality Services
α	Probability of Successful Rent-Seeking with Third Party
ν	Cost of Rent-Seeking

Table 5 The payoff matrix of the evolutionary game between private sectors and third parties in the multiple collaborative supervision mode

Private sectors	Third parties	
	TE (y)	***FE*** $(1-y)$
$PH\,(x)$	$R_s - C_H + R_e + \lambda S_1$ $R_t - C_t + \lambda T_1$	$R_s - C_H + R_e + \lambda S_1$ $R_t - C_f - \lambda T_2 - (\lambda + \beta)F_t$
$PL\,(1-x)$	$R_s - C_L - \lambda S_2 - F_s$ $R_t - C_t + \lambda T_1$	$R_s - C_L - \alpha\nu - \lambda S_2 - (\lambda + \beta)F_s$ $R_t - C_f + \alpha\nu - \lambda T_2 - (\lambda + \beta)F_t$

Equilibrium analysis and stability assessment of evolutionary strategies

It is inferred from the game model matrix presented above that the projected revenue of private sectors for *PH* is:

$$E_x = y(R_s - C_H + R_e + \lambda S_1) + (1-y)(R_s - C_H + R_e + \lambda S_1) \quad (1)$$

The projected revenue of private sectors for *PL* is:

$$E_{1-x} = y(R_s - C_L - \lambda S_2 - F_s) + (1-y)[R_s - C_L - \alpha v - \lambda S_2 - (\lambda+\beta)F_s] \quad (2)$$

The average projected revenue of private sectors is:

$$\overline{E} = xE_x + (1-x)E_{1-x} \quad (3)$$

Based on the Malthusian dynamic equation [32], the replicator dynamics equation for private sectors can be derived as follows:

$$F(x) = \frac{dx}{dt} = x(1-x)[y(1-\lambda-\beta)F_s + \lambda(S_1+S_2+F_s) - (C_H - C_L - \alpha v - R_e - \beta F_s)] \quad (4)$$

Similarly, the replicator dynamics equation of third parties can be obtained as:

$$G(y) = \frac{dy}{dt} = y(1-y)[v\alpha x + \lambda(T_1+T_2+F_t) - (C_t - C_f - \beta F_t)] \quad (5)$$

The strategy evolution of private sectors and third parties can be described by the system *L* of differential equations composed of Eqs. (4) and (5).

$$J = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}$$

In the formula, B_{11}, B_{12}, B_{21}, and B_{22} are respectively:

$$B_{11} = (1-2x)[y(1-\lambda-\beta)F_s + \lambda(S_1+S_2+F_s) - (C_H - C_L - \alpha v - R_e - \beta F_s)]$$

$$B_{12} = x(1-x)(1-\lambda-\beta)F_s$$

$$B_{21} = y(1-y)\alpha v$$

$$B_{22} = (1-2y)[x\alpha v + \lambda(T_1+T_2+F_t) - (C_t - C_f - \beta F_t + \alpha v)]$$

Then, if the following two conditions are satisfied at the same time, the equilibrium point of the replication dynamic equation is the evolutionary stable strategy (ESS).

(1) $\mathrm{tr}J = B_{11} + B_{22} < 0$ (Trace condition).
(2) $\det J = B_{11}B_{22} - B_{12}B_{21} > 0$. (Jacobian determinant condition).

By combining differential equation system L with the Jacobian Matrix J, the values of B_{11}, B_{12}, B_{21}, B_{22} at the five equilibrium points can be obtained, as shown in Table 6.

In which, $M = \frac{[C_t - C_f - \beta F_t + \alpha v - \lambda(T_1+T_2+F_t)][-C_t + C_f + \beta F_t + \lambda(T_1+T_2+F_t)](1-\lambda-\beta)F_s}{(\alpha v)^2}$

$$N = \frac{[C_H - C_L - \beta F_s - \alpha v - R_e - \lambda(S_1+S_2+F_s)][(1-\lambda-\beta)F_s - C_H + C_L + \beta F_s + \alpha v + R_e + \lambda(S_1+S_2+F_s]\alpha v}{(1-\lambda-\beta)^2 F_s^2}$$

$$\begin{cases} \mathrm{F(x)} = \mathrm{d}x/dt = x(1-x)[y(1-\lambda-\beta)F_s + \lambda(S_1+S_2+F_s) - (C_H - C_L - \alpha v - R_e - \beta F_s)] \\ \mathrm{G(y)} = \mathrm{d}y/dt = y(1-y)[v\alpha x + \lambda(T_1+T_2+F_t) - (C_t - C_f - \beta F_t)] \end{cases}$$

Let a = 0 and solve four points (0,0) (0,1) (1,0) (1,1) as the pure strategy local equilibrium points of the system *L* and the point (x^*, y^*) may be the local equilibrium point of the system *L*.

When $0 < x^* = \frac{C_t - C_f - \beta F_t + \alpha v - \lambda(T_1+T_2+F_t)}{\alpha v} < 1$ and $0 < y^* = \frac{C_H - C_L - \beta F_s - \alpha v - R_e - \lambda(S_1+S_2+F_s)}{(1-\lambda-\beta)F_s} < 1$, (x^*, y^*) becomes the unique equilibrium point of the system *L*.

According to the literature [33], the Jacobian matrix composed of Eq. (4) and Eq. (5) within the differential equation system *L* is given below:

According to "the local equilibrium point solved by the dynamic equation is not the equilibrium point of the evolutionary stable strategy (ESS)" [33, 34]. It is obvious that there is $trJ < 0$ at the local equilibrium point (x^*, y^*), which does not meet the condition of the evolutionary stable strategy $trJ < 0$, so the local equilibrium point (x^*, y^*) is not the equilibrium point of the evolutionary stable strategy.

Case 1

Under the conditions of $0 < \lambda < \min\left(\frac{C_H - C_L - \beta F_s - R_e - \alpha v}{S_1+S_2+F_s}, \frac{C_t - C_f - \beta F_t + \alpha v}{T_1+T_2+F_t}\right)$, $F_s < (C_H - C_L - R_e - \alpha v)/\beta$ and, $F_t < (C_t - C_f + \alpha v)/\beta$, only when $x = 0$ and $y = 0$, there are $trJ < 0$ and $detJ > 0$, so (0,0)

Table 6 The specific values of B_{11}, B_{12}, B_{21} and B_{22} at the local equilibrium point

Balance point	B_{11}	B_{12}	B_{21}	B_{22}
(0, 0)	$\lambda(S_1+S_2+F_s)-(C_H-C_L-\alpha v-R_e-\beta F_s)$	0	0	$\lambda(T_1+T_2+F_t)-(C_t-C_f-\beta F_t+\alpha v)$
(1, 0)	$-\lambda(S_1+S_2+F_s)+(C_H-C_L-\alpha v-R_e-\beta F_s)$	0	0	$\lambda(T_1+T_2+F_t)-(C_t-C_f-\beta F_t)$
(0, 1)	$F_s+\lambda(S_1+S_2)-(C_H-C_L-\alpha v-R_e)$	0	0	$-\lambda(T_1+T_2+F_t)+(C_t-C_f-\beta F_t+\alpha v)$
(1, 1)	$-F_s-\lambda(S_1+S_2)+(C_H-C_L-\alpha v-R_e)$	0	0	$-\lambda(T_1+T_2+F_t)+(C_t-C_f-\beta F_t)$
(x^*, y^*)	0	M	N	0

is the only ESS equilibrium point of the system (detailed analysis in Table 7). As the public participation level is relatively low and the government sectors' punishment of violators is relatively light, it is not enough to make private sectors pay attention to the service quality, nor can third parties consciously perform the evaluation responsibility, so private sectors tend to choose the strategy of *PL*, while third parties tend to choose the strategy of *FE*.

Case 2

Under the conditions of $\frac{C_t-C_f-\beta F_t+\alpha v}{T_1+T_2+F_t}<\lambda<\frac{C_H-C_L-F_s-R_e-\alpha v}{S_1+S_2}$, $F_s<C_H-C_L-\alpha v-R_e$ and,$F_t<(C_t-C_f+\alpha v)/\beta$, only when $x=0$ and $y=1$, there are $trJ<0$ and $detJ>0$, so (0,1) is the only ESS equilibrium point of the system (detailed analysis in Table 7). Since government sectors impose fewer penalties on private sector that violates regulations and impose stronger penalties on third parties who violate the regulations, the level of public participation has increased at this time, which has a greater impact on the income of third parties but has a small impact on the income of private sectors. Therefore, private sectors are inclined to choose the approach of "providing low-quality services", and third parties tend to choose the strategy of *TE*.

Case 3

Under the conditions of $\frac{C_H-C_L-\beta F_s-\alpha v-R_e}{S_1+S_2+F_s}<\lambda<\frac{C_t-C_f-\beta F_t}{T_1+T_2+F_t}$, $F_s<(C_H-C_L-\alpha v-R_e)/\beta$ and $F_t<(C_t-C_f)/\beta$, only when $x=1$ and $y=0$, there are $trJ<0$ and $detJ>0$, so (1,0) is the only ESS equilibrium point of the system (detailed analysis in Table 7). Since government sectors impose fewer penalties on private sectors that violate regulations, and more severe penalties for third parties who violate the regulations, the level of public participation has increased this time, which has a greater impact on the benefits of private sectors and less impact on the benefits of third parties. Therefore, private sectors are inclined to choose the approach of "providing high-quality services", and third parties are likely to choose the approach of *FE*.

Case 4

Under the conditions of $\max\left(\frac{C_H-C_L-F_s-R_e-\alpha v}{S_1+S_2},\frac{C_t-C_f-\beta F_t}{T_1+T_2+F_t}\right)<\lambda<1$, $F_s<C_H-C_L-\alpha v-R_e$ and, $F_t<(C_t-C_f)/\beta$, only when $x=1$ and $y=1$, there are $trJ<0$ and $detJ>0$, so (1,1) is the only ESS equilibrium point of the system (detailed analysis in Table 7). Although the government sectors punishment of violators is low, public participation is strong enough to have a great impact on both private sectors and third parties, so private sectors will eventually choose the strategy of "providing high-quality services", and third parties will tend to choose the strategy of "true assessment". At this point, the supervision mechanism has come into effect, giving full play to the advantages of multiple collaborative supervision, and the quality of elderly healthcare PPP projects has been effectively controlled.

Numerical simulation analysis

Given the lack of relevant data on elderly healthcare PPP projects, this paper draws on the numerical simulation method, largely used by scholars to better describe the evolution of strategy selection of private sectors' behavior in multiple collaborative supervision modes [35–37]. According to the hypotheses, MATLAB (2016b) is used to quantitatively analyze the influence of each parameter variable on the strategy selection of the game part under

Table 7 Equilibrium analysis for cases 1–4

	Case 1			Case 2			Case 3			Case 4		
Balance point	tr*J*	det *J*	Local stability	tr*J*	det *J*	Local stability	tr*J*	det *J*	Local stability	tr*J*	det *J*	Local stability
(0, 0)	−	+	ESS	±	−	Saddle point	±	−	Saddle point	±	−	Saddle point
(1, 0)	±	−	Saddle point	−	+	ESS	±	−	Saddle point	±	−	Saddle point
(0, 1)	±	−	Saddle point	±	−	Saddle point	−	+	ESS	±	−	Saddle point
(1, 1)	±	−	Saddle point	±	−	Saddle point	±	−	Saddle point	−	+	ESS

the condition of changing different parameter values. This aim is to verify the consistency of the above model assumptions and conclusions and to simulate the evolution track of the behavior of the game subject by adjusting or controlling the key variables.

Validation of model conclusions

It is assumed that the horizontal axis represents time, the initial time of evolution is 0, and the end time is 2; the vertical axis represents the probability of both; and five different initial states of evolution are $x_1 = 0.1, y_1 = 0.2, \mathrm{x2} = 0.3, \mathrm{y2} = 0.4, x_3 = 0.5, \mathrm{y}_3 = 0.6, x_4 = 0.7, y_4 = 0.8, x_5 = 0.9, \mathrm{y}_5 = 0.9$. Suppose that simulated values of parameters in the Case 1 to 4 of evolutionary stabilization strategies are listed in Table 8.

Figure 2 illustrates that, regardless of the initial conditions, the system eventually stabilizes at point (0,0) over time. This suggests that private sectors gravitate toward the *PL* strategy, while third parties adopt the *FE* strategy, consistent with the assumptions of the game model.

Figure 3 shows that, regardless of the initial conditions, the system ultimately stabilizes at point (0,1) over time. This indicates that private sectors choose the *PL* strategy, while third parties adopt the *TE* strategy, which aligns with the assumptions of the game model.

Figure 4 shows that, regardless of the initial conditions, the system ultimately stabilizes at point (1,0) over time. This suggests that private sectors choose the *PH* strategy, while third parties opt for the *FE* strategy, consistent with the assumptions of the game model.

Figure 5 illustrates that, regardless of the initial conditions, the system ultimately stabilizes at point (1,1) over time. This indicates that private sectors adopt the *PH* strategy, while third parties choose the *TE* strategy, which is consistent with the assumptions of the game model.

Adjustment and impact analysis of key parameter variables

This paper is aimed at promoting the evolution of the game between the two sides to the ideal supervision mode, that is, private sectors provide high-quality services, and third parties truly evaluate. Therefore, the

Table 8 Simulated values of parameters in the cases 1 to 4 of evolutionary stabilization strategies

Case	λ	β	α	S_1	S_2	F_s	C_H	C_L	v	R_e	T_1	T_2	F_t	C_t	C_f	Diagram
Case1	0.01	0.2	0.3	50	70	40	100	40	40	10	60	80	60	50	20	Figure 2
Case 2	0.2	0.2	0.3	50	70	40	100	40	40	10	60	80	60	50	20	Figure 3
Case 3	0.15	0.2	0.3	50	70	80	100	40	40	10	60	80	10	50	20	Figure 4
Case 4	0.3	0.2	0.3	50	70	30	100	40	40	10	60	80	60	50	20	Figure 5

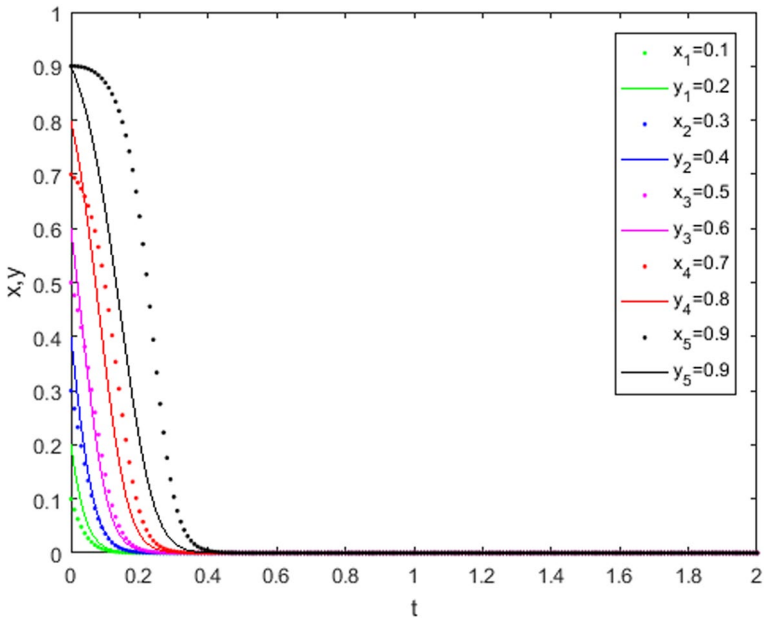

Fig. 2 Evolution track of Case1

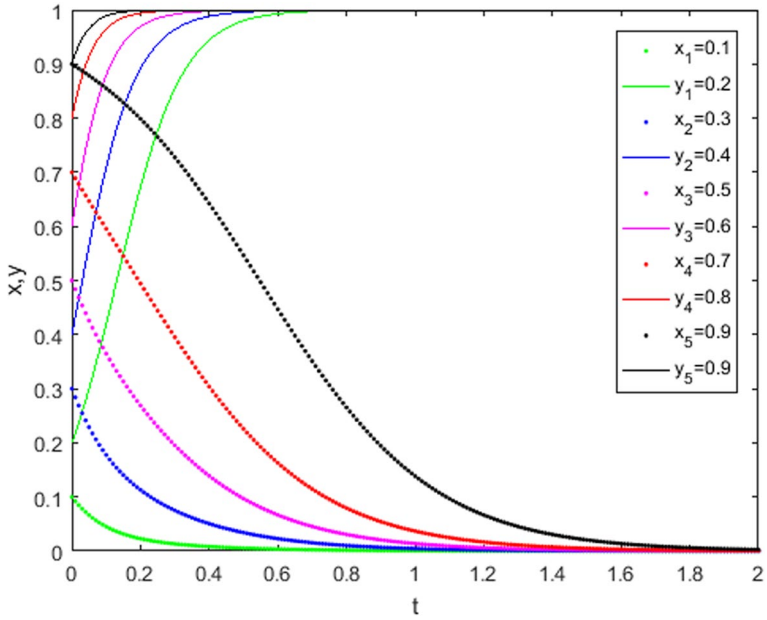

Fig. 3 Evolution track of Case2

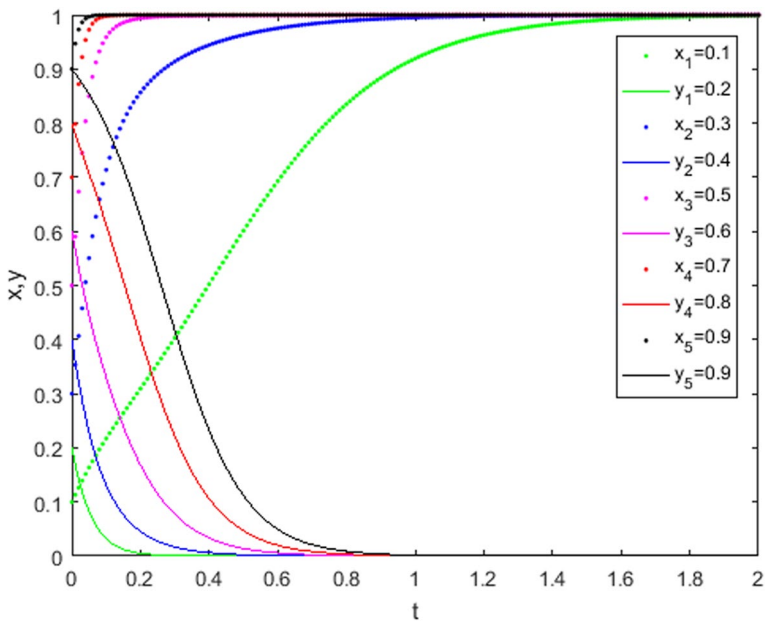

Fig. 4 Evolution track of Case3

first three cases can guide the behavior of the participants to evolve toward the desired direction by adjusting or controlling key variables. It is assumed that $x=1$, $y=1$ are the initial values of the system, the horizontal axis signifies the probability that private sectors "provide high-quality service", and the vertical axis signifies the probability that third parties "truly evaluate".

Based on the original value of Case 1, λ, β, [λ β] and [F_s F_t] were set as variables respectively in Case 5. As can be seen in Figs. 6, 7, and 9, when $\lambda > 0.1$ or $\beta > 0.65$ or $F_s > 100$ and $Ft > 120$, the system began to evolve from point $P_1(0,0)$ to point $P_4(1,1)$. It is found from Fig. 8 that when $\lambda > 0.15$, the system evolves from point $P_1(0,0)$ to point $P_4(1,1)$ despite government sectors'

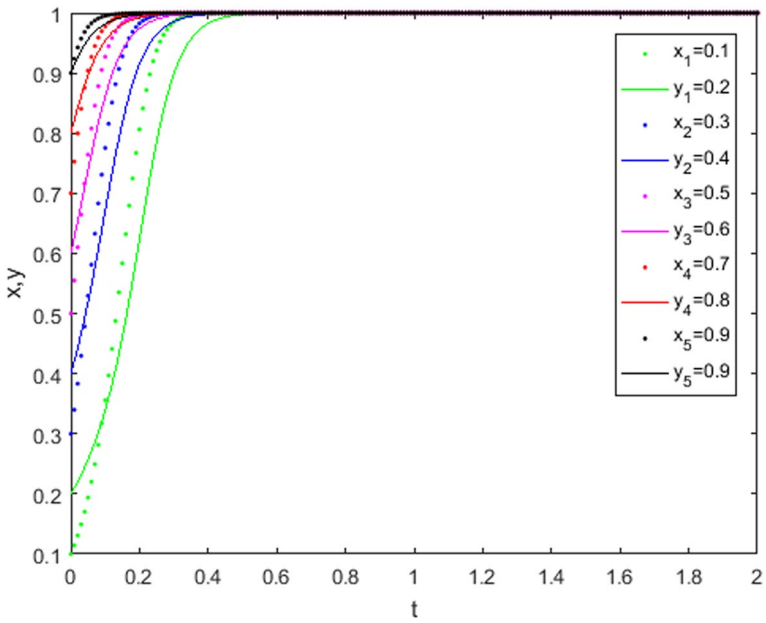

Fig. 5 Evolution track of Case4

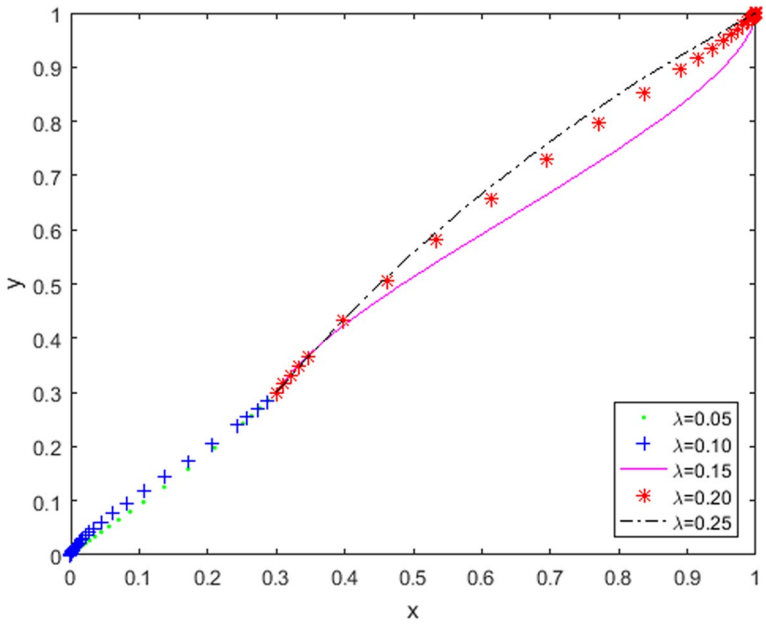

Fig. 6 Evolution tracks as λ change

supervision probability $\beta < 0.3$, and when $\lambda < 0.15$, the system evolves from point $P_4(1,1)$ to point $P_1(0,0)$ despite government sectors' supervision probability $\beta > 0.3$.

Figures 6, 7, 8 and 9 illustrate that with the improvement of the level of public participation or the improvement of the probability of government supervision and spot-check or the strengthening of punishment, the benefits of private sectors and third parties are greatly affected. Private sectors ultimately choose to provide a high-quality service strategy, while third parties finally perform the responsibility of true evaluation. The decline

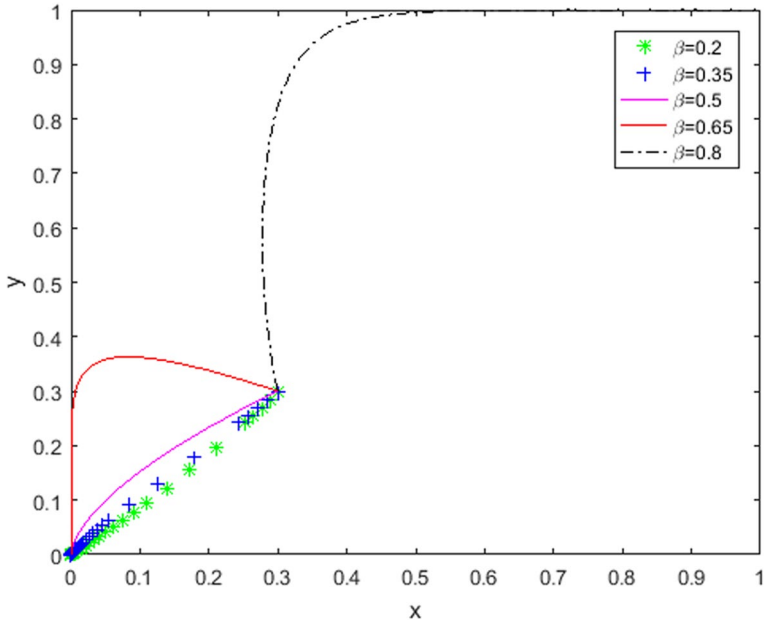

Fig. 7 Evolution tracks as β change

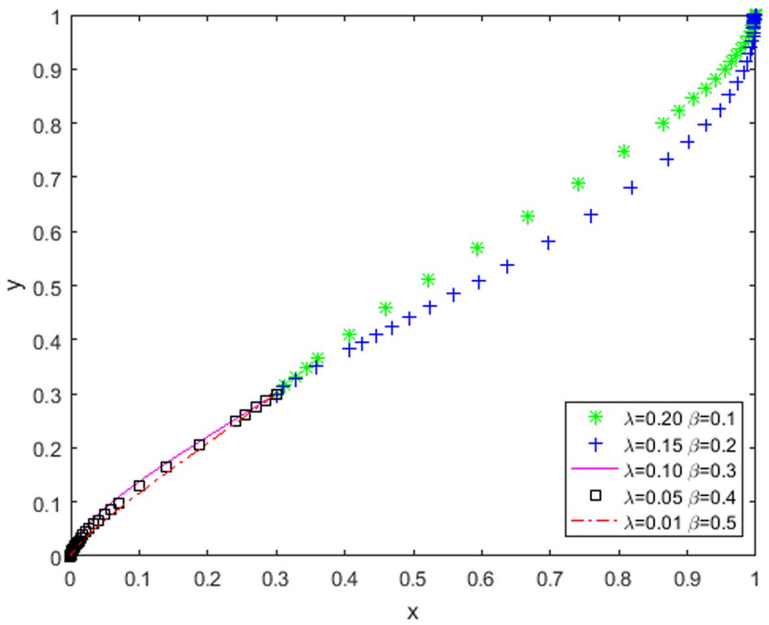

Fig. 8 Evolution tracks as λ and β change

in the level of public participation will have a larger influence on the behavior of game subjects than the increase in the probability of government supervision. When the level of public participation is low, both private sectors and third parties tend to break the rules, even if the probability of government supervision and spot checks is high. Therefore, the improvement of public participation can diminish the probability of government supervision and spot checks, which can alleviate the problem of insufficient regulatory resources of the government to some extent.

Based on the original value of Case 2, $[S_1\ S_2]$ and R_e are set as variables respectively in Case 6. As can be seen from Figs. 10 and 11 when $S_1 > 60$, $S_2 > 80$, or $R_e > 10$, the

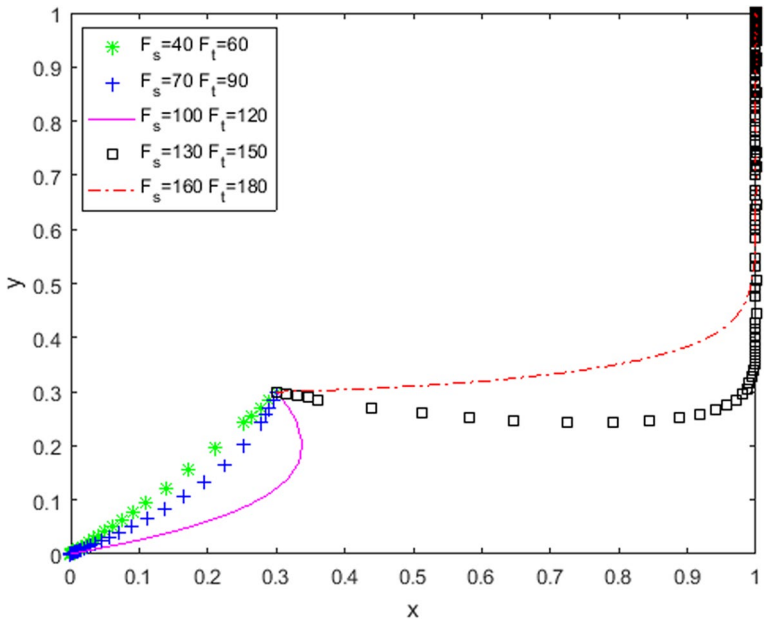

Fig. 9 Evolution tracks as F_s and F_t change

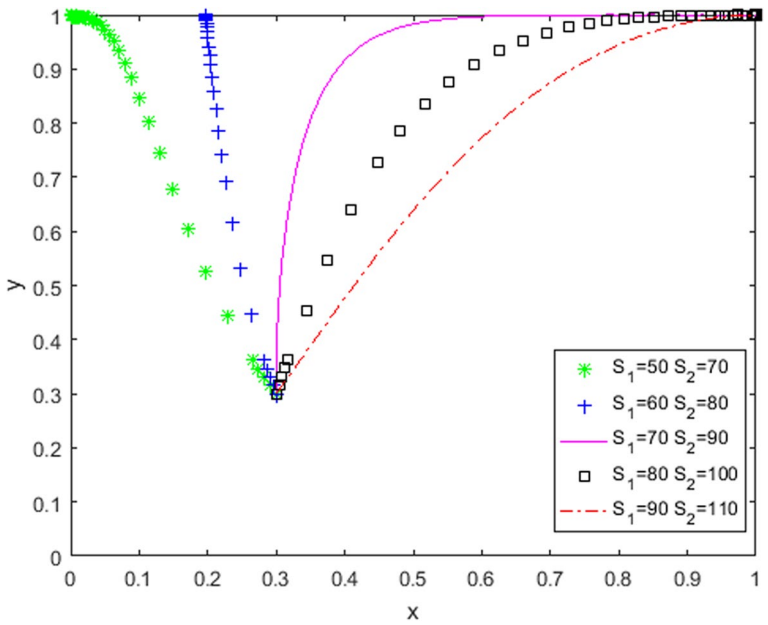

Fig. 10 Evolution tracks as S_1 and S_2 change

system began to evolve from point P_2 (0,1) to point P_4 (1,1) after MATLAB simulation.

Figures 10 and 11 illustrate that as the government strengthens reputation incentives for private sectors or increases operating subsidies, private sectors' benefits are more affected, and private sectors' behavior evolves from choosing the strategy of providing low-quality services to choosing the strategy of providing high-quality services.

Since the original value of $T_2 > 90$ in Case 2, $[T_1\ T_2]$ and C_t are set as variables respectively in Case 7. By increasing the value of T_1 and T_2 or decreasing the value of C_t, it can be seen from Figs. 12 and 13 that when $T_1 > 70$ or $C_t < 45$, the system began to evolve

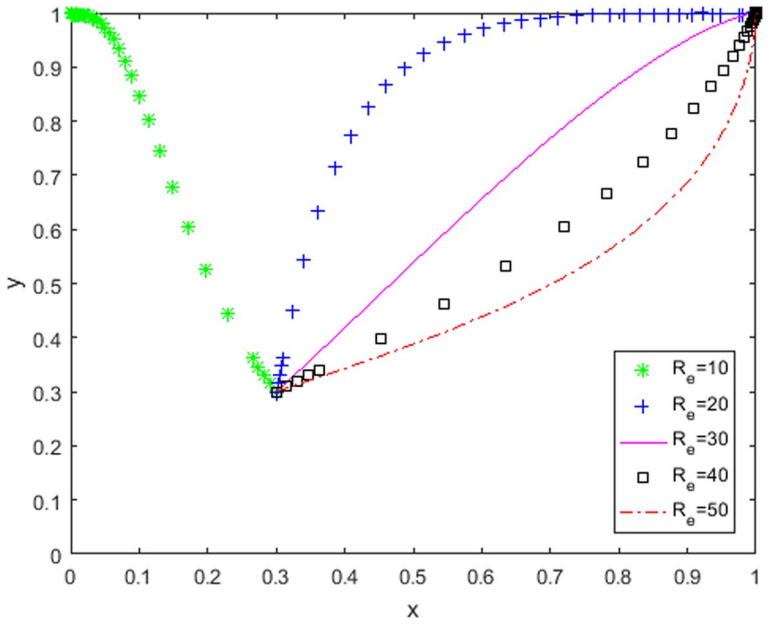

Fig. 11 Evolution tracks as R_e change

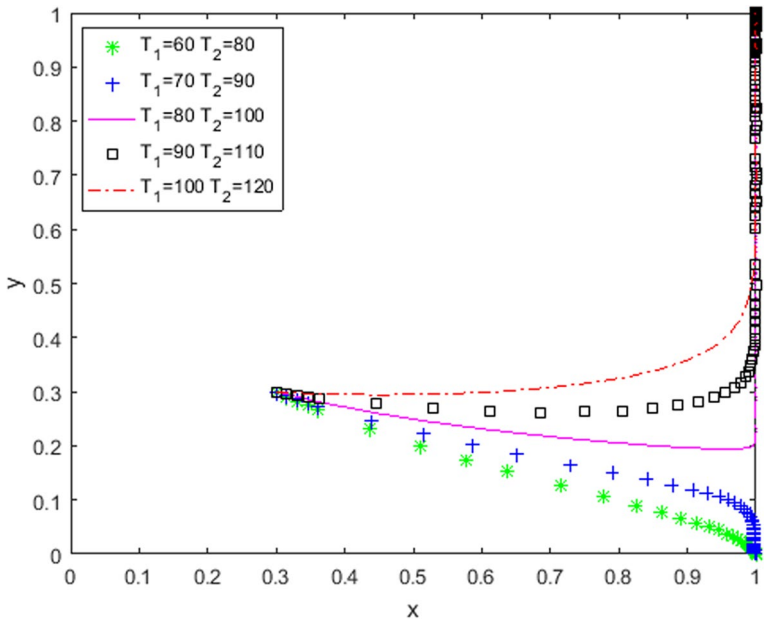

Fig. 12 Evolution tracks as T_1 and T_2 change

from point P_2 (0,1) to point P_4 (1,1) after MATLAB simulation.

Figures 12 and 13 illustrate that with the strengthening of the reputation of third parties or the reduction of the cost of third-party evaluation, third parties evolve from choosing the *FE* strategy to the *FT* strategy. Therefore, the enhancement of reputation incentives can reduce the probability of third parties violating the regulations and the reduction of the cost of third-party evaluation helps third parties to perform the evaluation responsibility and reduce the motivation of rent-seeking with private sectors, thus promoting private sectors to improve the service quality.

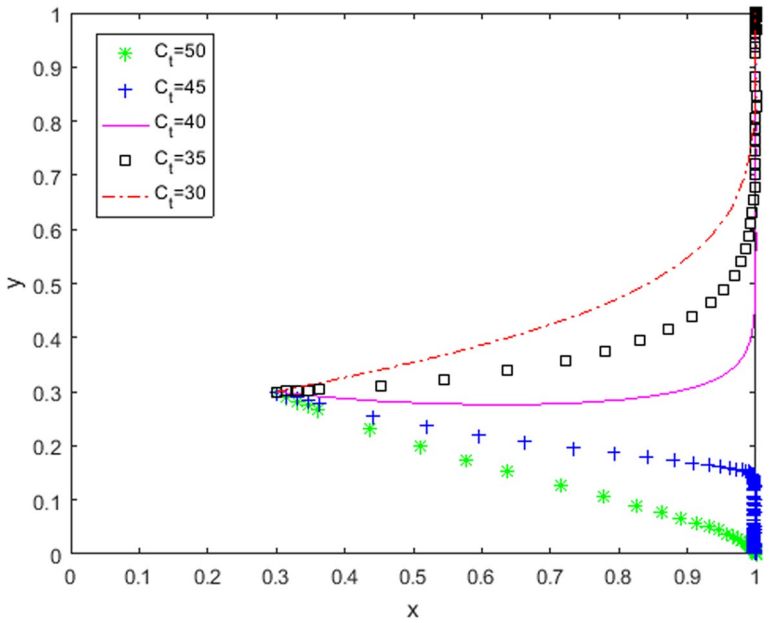

Fig. 13 Evolution tracks as C_t change

Conclusions and related recommendations

Based on game model analysis and numerical simulation, this study yield crucial results. First, the traditional "single" regulatory model of the government encounters hurdles in overcoming information asymmetry amid the regulator (government) and the ones beings regulated (private sector). It is difficult to restrain the opportunistic behavior of the private sector by solely relying on operating incentive and punishment mechanisms, which can easily lead to government failure to overcome regulatory shortcomings. Furthermore, in the multivariate collaborative regulatory model, incorporating public participation and third-party evaluation can help overcome the information asymmetry between the regulator and the regulated. Consequently, prompts the private sector to pay more attention to the quality of elderly health care services. To some extent, this model has a regulatory role akin to government departments. Reputation incentives can reduce the probability of being regulated, complemented by operating subsidy and punishment mechanisms acting as constraints. Therefore, in the context of information asymmetry and limited regulatory resources, the government might consider the impact of public participation and reputation incentives on the behavioral choice strategies of the private sector after the involvement of third-party evaluation agencies. At the same time, it is also necessary to stimulate and improve the third-party evaluation, reward, and punishment mechanisms. Likewise, it is crucial to improve public participation and reputation incentive mechanisms, thus forming a multivariate collaborative regulatory model to ensure the high-quality improvement of the project PPP. The specific recommendations are as follows:

First, the third-party evaluation system should be improved to help third parties reduce evaluation costs. Therefore, it is necessary to clarify the legal status of the third-party evaluation and make clear provisions on the principles, procedures, types, results, personnel composition, and use of funds of the third-party evaluation. Moreover, governments should ensure the independence of third-party evaluations and apply their results. Finally, it is necessary to build an information management system for elderly healthcare PPP projects, to realize the sharing of information resources, and display the types of services and charges of elderly healthcare PPP projects in various places in real time. The public evaluation function can also be opened to minimize information asymmetry between the supervisor and the supervised party. In this way, the third party can obtain detailed and valid information and reduce the cost to make an objective and true evaluation.

Second, the public participation system should be established and improved to enhance the level of public participation. Under the constraints of the punishment and the reputation incentive mechanism, the higher the level of public participation,

the greater the influence on the profit and loss of the private sector and third parties. Thus, the more it can spur and motivate the private sector and third parties to operate following regulations and reduce the burden and pressure of government regulation to a certain extent. Based on this concept, laws and regulations related to public participation should be established and further improved. Similarly, online public compliance and reporting platforms, for example, Weibo or WeChat, etc., official accounts should be created to deliver suitable and easy methods for the public to vigorously participate in monitoring or reporting violations of private sectors and third parties, to diminish the cost and any associated risk of public reporting and ultimately improve the efficiency of government regulation.

Third, reward and punishment mechanisms should be established and further improved to increase penalties for violations and operational subsidies to the private sector. Considering the geographical monopoly of the service industry responsible for elderly healthcare, it may not be appropriate to completely shut down the private sector services, as it will disrupt its normal operations. It is better to impose economic penalties such as withholding operation subsidies, and high fines and urge them to make regular rectifications. Moreover, in severe cases, the scope of business cooperation with the private sector can be reduced, or cooperation in elderly healthcare PPP projects can be banned. For the third party who violates the rules, measures such as fines, suspension of assessment qualifications or even severe steps like cancellation of cooperation may be taken to raise the cost of the third party's violation. Furthermore, the joint liability system for quality accidents may be implemented to weaken the rent-seeking motivation of the third party and the private sector.

Fourth, an information disclosure mechanism can be established to strengthen the reputation incentive mechanism. The suggested steps include; the third party's evaluation results should be regularly published on the official website of the government sector, the illegal or irregular facts of the third party, and the private sector can be disclosed promptly with the help of the news media. In this way, the strategic behaviors and decision-makings of third parties and private sectors are influenced or restrained by reputation factors, and more importantly, the role of public participation (comprised of social groups, news media, and masses, etc.) in the monitoring and supervision of elderly PPP projects is given full play.

Limitations and future directions

While this study offers valuable insights into improving elderly healthcare governance through a multifaceted regulatory model, several limitations must be acknowledged. First, the focus on the Chinese elderly healthcare context limits the generalizability of the findings to other regions with different regulatory frameworks and healthcare systems. Additionally, while evolutionary game models provide valuable insights, they may oversimplify real-world complexities, such as political pressures or contextual factors influencing decision-making. The proposed regulatory model requires empirical testing in real-world settings to assess its practicality and effectiveness.

Future research could apply the model to other sectors or countries to refine its applicability. Empirical studies using data from actual elderly healthcare PPPs would help validate the effectiveness of third-party evaluations, public participation, and reward/punishment mechanisms. Further refinement of the game-theoretic models could incorporate additional behavioral factors, such as political influences or social norms, to better reflect real-world decision-making dynamics and improve the regulatory frameworks for PPP projects in various contexts.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions
Conceptualization, X.H.Y.; writing—original draft preparation, X.H.Y., R.F.L.; software, X.H.Y., S.K.D.; writing—review and editing, S.K.D., W.L.L.; supervision, W.L.L., S.M., M.K.A.; All authors reviewed the manuscript and agreed.

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Data availability
The data used to support the findings of this study are included within the article.

Declarations

Ethics approval and consent to participate
Not Applicable.

Consent for publication
Not Applicable.

Competing interests
The authors declare no competing interests.

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