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Knowledge Input or Not in the Dynamic Cooperation Behavior of Top Management Teams? From the Perspective of Knowledge Flow

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ABSTRACT Top management teams (TMTs) play an important role in enterprises. How to improve the cooperation of TMTs in the process of the mixed ownership reform of state-owned enterprise is a new era theme and currently a key objective in China. In this paper, we use evolutionary game theory to research the dynamic behavior of TMTs from the perspective of knowledge input and knowledge flow. We construct the evolutionary game model from the dimensions of knowledge input, knowledge flow, cooperation costs, government reward, and government penalty firstly, then we explore the strategy selection on knowledge input or not in the cooperation of TMTs between state-owned enterprise and private enterprise. Finally, we discuss the model's local stability and perform a simulation analysis of the factors that can influence the stability of the model. The results show that the final strategy choices of TMTs between two parties are related to not only the initial payment matrix constructed but also the selection of the initial parameters of the partners: Under different situations, the strategy evolution result will be stable at (input, not input), (not input, input) and (input, input). Increasing the degree of knowledge flow, government reward, and government penalty and reducing the cooperation costs between state-owned enterprise and private enterprise can promote the TMTs' cooperation in the process of the mixed ownership reform. Based on the conclusions, we put forward relevant suggestions for enterprises and the government. We hope that this research can provide some sustainable solutions to improve the cooperation of the TMTs between state-owned and private enterprise.

INDEX TERMS Mixed ownership reform, top management teams, state-owned enterprise, knowledge flow, cooperative behaviour, evolutionary game.

I. INTRODUCTION

At present, China's economic development has entered a new normal and its economic growth has gradually shifted from high-speed growth to medium high-speed growth. Due to the driven of consumption, investment, and innovation, the overall economic structure is also optimized and upgraded. In the development of the national economy, state-owned enterprise have played an important role and their reform has always been valued by the party and the state. In November 2013, the "Decision of the Central Committee of the Communist Party of China on Comprehensively Deepening the Reform of Some Major Issues" adopted at the Third Plenary Session of the 18th CPC Central Committee and clearly stated that it is necessary to actively develop the idea of mixed ownership, which means that the reform of state-owned enterprise in

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China will focus on the reform of mixed ownership. The reform of mixed ownership is not only the theme of the new era but also the only way to develop a high-quality economy in the future. In the reform, the purpose of the mixed reform is to realize the transformation from ''management enterprise'' to ''management capital'' [1] and finally let state-owned enterprise become real market entities [2].

In the process of the mixed reform, ''mixing'' is the premise of ''combination'', and ''combination'' is ''cooperative interaction''. However, in the practice of the mixed reform of many state-owned enterprises, the mixed reform has the form of ''mixed'' but does not present substantive reform. With the continuous introduction and implementation of the national mixed reform policy, the current mixed reform of state-owned enterprise has entered the deepening period. At this time, the further advancement of the mixed reform requires a system of mutual integration and the design of scientific institutions among the stakeholders. At present, Chinese academic circles mainly focus on ''how to mix''. Li [3] held that deepening the reform of state-owned enterprise first required exploration of the dual-track system, which gave power to the group's subsidiaries, such as by empowering the board of directors to appoint and remove, determine remuneration, and set equity incentives. On the other hand, executives nominated by non-state shareholders may overturn the management authority and salary limits prescribed by the administrative department. Xiang [4] considered that it was important to balance the distribution of interests between the state-owned enterprise executive team and the private enterprise executive team in the process of mixed ownership reform. Qi and Zhang [5] considered that the ideal path for state-owned enterprise reform in monopoly industries was effective competition among a number of enterprises and that the mixed ownership reform should follow the path of co-governance between state-owned enterprise and private enterprise.

In the process of the mixed ownership reform of state-owned enterprise, the ownership structure will be changed from a single ownership structure to a mixed-ownership structure. State-owned enterprise will introduce private enterprise' executives and let them hold shares, and the two groups will run the business together; at this time, the cooperation of TMTs will play an important role. If the teams cannot cooperate successfully, the enterprise's economy will be stagnant. According to bounded rationality, TMTs will choose a rational strategy according to their profit; consequently, cooperation is a dynamic and evolutionary process. Therefore, how to maintain TMTs' cooperation under the mixed ownership reform is a valuable research.

As far as the TMTs are concerned, some scholars have discussed the concept of TMTs from different aspects. Richard and James [6] first proposed the concept of TMTs according to the ''advantageous alliance'' theory. However, the theory does not make a clear definition of TMTs. After that, James [7] did some researches on the top management team in 1984, they put forward the theory of the senior management echelon. In addition, based on the study of demographic characteristics, Hambrick and Mason [8] made an important extension of this theory, they proposed high-order theory, which was a new field of research dedicated to top management teams. In high-order theory, TMTs are the decision-makers of the system, and their decision-making is affected by their own experience and values. Furthermore, some scholars also define TMTs according to the rights and responsibilities of TMTs members [9], making significant decisions that affect the performance of the enterprise [10]; the top five positions in an enterprise with the highest salary [11], and with high education achievements can generate more innovative ideas in the workplace [12]. Combined with the above definitions and our understanding, TMTs in this paper refer to managers who play an important role in the decision-making process of enterprises. Based on the above definitions of TMTs, scholars have carried out relevant researches around the TMTs, such as TMTs' incentives and major shareholder supervision [13]; TMTs' personality characteristics, incentive mechanisms, equity, and their relationship with strategic risk exposure [14]; the relationship between transformational leadership and the TMTs [15]; TMTs' product innovation and educational diversity [16]; team conflict and top management teams' creativity [17]; relationship between firms' top management teams (TMTs) and internationalization complexity [18].

However, scholars have done a lot of researches around the TMTs, few scholars have studied the dynamic cooperation behavior among top management teams from the perspective of evolutionary game theory at the micro level, furthermore, fewer scholars study the dynamic cooperative behavior between state-owned executives and private executives from the perspective of knowledge flow. In fact, knowledge flow is very important to the cooperation between two parties, in the process of the cooperation, knowledge as a carrier can transmit two parties' information and improve the innovation, it has a profound impact on cooperation, so how to maintain the cooperation between TMTs from the perspective of knowledge flow is important to the mixed ownership reform. As we all know, knowledge as a kind of structured experience, textual information, and expert opinions, it plays an important role in the process of enterprise cooperation. Knowledge reasonable flow and sharing can achieve deep cooperation innovation for enterprises. In terms of knowledge, it can be divided into explicit knowledge and tacit knowledge, the explicit knowledge includes text, pictures, videos.etc which can be seen, while tacit knowledge includes experience, opinions, and other knowledge form which can't be seen. At present, scholars have carried out some researches on the relationship among the cooperation, innovation, and knowledge flow. Jiang *et al.* [19] proposed that partner trustworthiness had a positive role in the knowledge acquisitioncan and had different effects on the knowledge leakage under different alliance regimes; Cheong *et al.* [20] researched the relationship between knowledge flow and the purpose of expatriate assignments and found that different enterprises had different knowledge flow strategies; Gaur *et al.* [21] explored the cross-border flow of knowledge and proposed a comprehensive knowledge management framework; Rupietta and Backes-Gellner [22] explored the occurrence of superior incremental innovation performance based on the a knowledge creation (KC) system which was integrated by knowledge stock and flow; Lo [23] used a multidimensional knowledge-flow model to explore the knowledge flow across different stakeholders in an organization; Zhao *et al.* [24] established a dynamic system evolution model and analyzed the relationship between knowledge absorption capacity, knowledge potential, and knowledge transfer capacity under different incentives intensities, they found that incentive mechanism could promote the evolution of strategic alliance innovation; Li *et al.* [25] explored the relationship among knowledge flow of multimedia information, alliances and clusters, they found that similarity, complementarity and spillage of knowledge were conducive to the formation of the alliance; Zhou and Wu [26] used the dynamic model of knowledge flow in a complex network to explore the transmission rate of the knowledge in the network, they considered that the average degree of the network, the number of enterprises involved in the transfer, and the effective transmission rate of the knowledge had significant influences on the efficiency of the knowledge flow; in addition, other scholars explored the knowledge flow in teams [27], workplace [28], [29], citations of articles [30], universities [31] and supply chain [32]. Above existing studies explored the knowledge flow from different perspectives and levels based on the static perspective mostly, few scholars explore the phenomenon of knowledge flow in the process of senior executives' cooperation.

Furthermore, the mixed reform of state-owned enterprise has merged the interests of multi-party investors and business entities with differences in management concepts, behavioral habits, and communication methods, and the new system has led to TMTs heterogeneity. In the context of heterogeneity, the cooperation among different subjects is dynamic, uncertain, and complex. Therefore, how to coordinate the relationship between state-owned shareholders and non-state-owned shareholders from a dynamic perspective has become a real problem that needs to be solved urgently. This moment, as a dynamic method to explore the evolution law of population, evolutionary game theory can effectively simulate the development law of heterogeneous population. Evolutionary game theory has a long history since it is put forward and it has been applied to explain many dynamic evolution phenomenon, such as human cooperative behavior [33], the evolutionary choice of nature [34], and social games [35] etc. Specifically speaking, in terms of human behavior, Scatà *et al.* [36] used social network and game theory to investigate the evolution of human cooperation based on the perspective of the homophily, and they explained the phenomenon of the "birds of a feather flock together"; Liu and Chen [37] explored the prosocial exclusion and the antisocial exclusion in the human cooperation; Dong *et al.* [38] considered that self-interest, the behavior of others, the reaction to rewards, and the reaction to punishment can effect the cooperation of human behavior; furthermore, some scholars have studied human cooperative behavior from reputation mechanism [39] and moral hazard [40], [41]. In terms of the evolutionary choice of nature, Brown [42] considered that game theory not only could be applied to matrix games and social games, it also could be applied to speciation, macroevolution and perhaps even to cancer; Sample and Allen [43] studied the weak selection and large population size in the evolutionary game theory. In terms of social games, Feng *et al.* [44] explored the behavioral motivation that leads drivers to illegally occupy the motorway emergency lane; Song and Zhang [45] explored the collaborative innovation processes between industry and university based on evolutionary games; moreover, some scholars also used the evolutionary game theory to explore the information sharing behavior [46], regional cooperative governance [47], government supervision [48], ect social behavior. In addition, from the perspective of evolutionary participants, scholars also have studied three-party and multi-party games. The above scholars use the evolutionary game theory to explore the many social behaviors from many perspectives, these studies provide some enlightenment for the follow-up scholars, however, few scholars use the evolutionary game theory to carry out relevant researches on knowledge input and knowledge flow between senior executives' cooperative behaviors.

Based on this, in order to fill in the gap that knowledge input and knowledge flow in senior executives' cooperative behaviors, this paper uses the evolutionary game theory to explore the dynamic cooperation behavior of top management teams in the process of the mixed ownership reform from the perspective of knowledge flow. By establishing a dynamic model and carrying out related analysis, we can intuitively understand the behavior choices between state-owned and private enterprise. In addition, the study aims to expand the collaborative innovation research of TMTs between state-owned and private enterprise, enrich the connotation of the state-owned enterprise governance mechanism, and make it more effective to guide the practice of state-owned enterprise.

II. RESEARCH HYPOTHESIS AND MODEL CONSTRUCTION

A. BASIC ASSUMPTIONS AND MODEL CONSTRUCTION

Hypothesis 1: In the process of the mixed ownership reform, it is assumed that TMTs of state-owned enterprise and private enterprise carry out cooperative activities constantly, and they have two strategic choices: Knowledge input and knowledge not input. Assume that in the initial stage of the game, when the TMTs of state-owned enterprise choose the input strategy, the probability is x, when they choose the not input strategy, the probability is $1 - x$; when the TMTs of private enterprise choose the input strategy, the probability is y, when they choose the not input strategy, the probability is $1 - y$.

TABLE 1. The evolutionary game payment matrix payment matrix of the TMTs between the state-owned and private enterprise.

		private enterprise's TMTs B	
		input(y)	not input $(1-y)$
state owned enterprise's TMTs A	input (x)	$(\alpha\pi + r_1 - c_1, (1-\alpha)\pi + r_2 - c_2)$	$(A - c_1 + r_1, \beta_1 c_1 - p_2)$
	not input $(1-x)$	$(\beta_2 c_2 - p_1, B - c_2 + r_2)$	$(0, 0)$

Hypothesis 2: When two parties sign a cooperation agreement and if the cooperation is successful, the TMTs of state-owned and private enterprise need to input some knowledge resources, also these resources can be called the cooperation cost in the cooperation activities. The input cost of state-owned enterprise TMTs is recorded as c_1. The input cost of private enterprise TMTs is recorded as c_2. If state-owned enterprise TMTs and the private enterprise both adopt input strategies, they can not only take advantage of the complementary advantages of the team but also achieve excess profit π; in this case, the excess profit coefficient of the state-owned enterprise is α, and the excess profit coefficient of the private enterprise is $1-\alpha$.

Hypothesis 3: In the process of the cooperation between the TMTs of state-owned enterprise and private enterprise, both sides would input some knowledge to sustain the cooperation, in this period, the knowledge will turn into the cooperation or innovation achievements between two sides. Specially, because of the moral hazard and the bounded rationality, people always want to maximize their own profit, and don't care the partner's. This moment, if one party inputs the knowledge but the other doesn't, the knowledge will flow to the party who not inputting from the party who inputting, so the party who not inputting the knowledge will obtain the some profit, these profit is coming from the transformation of flowing knowledge. In the cooperation between the TMTs of state-owned enterprise and private enterprise, we assume the knowledge flow coefficient of state-owned enterprise is β_1 and private enterprise is β_2. So if the state-owned enterprise chooses the input strategy, the private enterprise chooses the not input strategy, the private enterprise will obtain the external profit $\beta_1 c_1$. In the same way, the state-owned enterprise will obtain the external profit $\beta_2 c_2$. Furthermore, the literature [49] pointed that the knowledge flow degree of state-owned enterprise is larger than the private enterprise generally, so we assume knowledge flow coefficient of the state-owned enterprise is larger than the private enterprise, that is $\beta_1 > \beta_2$.

Hypothesis 4: In the process of the mixed ownership reform, in order to improve the implementations of mixed ownership reform smoothly, some rewards and punishments would be taken by the governments. In the process of cooperation between the two parties, if the two parties establish a cooperative consensus and reach cooperative willingness, the government will give a certain reward r_1 to state-owned enterprise and r_2 to private enterprise; if one of the parties terminates the knowledge input, it will have to pay a certain penalty p to the government. Here, we assume the penalty of state-owned enterprise is p_1 and private enterprise is p_2.

Hypothesis 5: When the TMTs of state-owned enterprise and the private enterprise don't cooperate mutually and both choose the not input strategy, the two sides can't obtain the income. At this time, the profit obtained by the state-owned enterprise and private enterprise are recorded as 0. If each of them chooses the input strategy, the other chooses the not input strategy, the one who inputting knowledge will obtain the normal profit. In our model, we assume that if the state-owned enterprise input knowledge, but the private enterprise don't input the knowledge, so the state-owned enterprise will obtain the profit A; for the same reason, the private enterprise will obtain the profit B. In addition, in the process of cooperation, in order to promote cooperation, it is assumed that the profit generated by the partners who both choosing the input strategy is larger than the one of them choosing the input strategy, that is $\alpha\pi > A$, $(1-\alpha)\pi > B$; usually speaking, the profit obtained is larger than the cost, that is $\alpha\pi > A > c_1$, $(1-\alpha)\pi > B > c_2$.

Based on the above assumptions, we can construct the evolutionary game payment matrix of the TMTs between the state-owned and private enterprise, it is shown in Table 1.

B. EVOLUTIONARY GAME MODEL

The replication dynamics are dynamic differential equations that can describe the frequency of a particular strategy being used in a population [50], and it can be expressed as:

$$\frac{d_{x_i}}{d_t} = x_i[(u_{s_i}, x) - u(x, x)] \tag{1}$$

In the above formula, x_i is a pure strategy, s_i is the ratio or probability in a population, and (u_{s_i}, x) is the fitness when using a pure strategy, which indicates average fitness. Among them, $\frac{dx_i}{dt}$ refers to the speed of the state-owned enterprise TMTs' probability of selecting the input strategy over time. If the value of $\frac{dx_i}{dt}$ greater than zero, it indicates that the probability of the choosing the input strategy increases over time. Conversely, if the value of $\frac{dx_i}{dt}$ is less than zero, the probability of the choosing the input strategy decreases over time.

According to the payment matrix, the expected profit of state-owned enterprise TMTs when they select the input strategy is $U_{S_1}^A$.

$$U_{S_1}^A = y(\alpha\pi + r_1 - c_1) + (1-y)(A - c_1 + r_1) \tag{2}$$

The expected profit of state-owned enterprise TMTs when they select the not input strategy is $U_{S_2}^A$.

$$U_{S_2}^A = y(\beta_2 c_2 - p_1) \tag{3}$$

The average expected profit of state-owned enterprise TMTs when they select the input and not input

TABLE 2. Jacobian matrix at each equilibrium point *Tr J* and *Det J*.

Equilibrium point	$Det\ J$	$Tr\ J$
$E(0,0)$	$(A-c_1+r_1)(B-c_2+r_2)$	$(A-c_1+r_1)+(B-c_2+r_2)$
$S(0,1)$	$-(B-c_2+r_2)(\alpha\pi-\beta_2c_2+p_1-c_1+r_1)$	$(\alpha\pi-\beta_2c_2+p_1-c_1+r_1)$ $-(B-c_2+r_2)$
$N(1,0)$	$-[(1-\alpha)\pi-\beta_1c_1+p_2-c_2+r_2](A-c_1+r_1)$	$(A-c_1+r_1)$ $-[(1-\alpha)\pi-\beta_1c_1+p_2-c_2+r_2]$
$D(1,1)$	$(\alpha\pi-\beta_2c_2+p_1-c_1+r_1)[(1-\alpha)\pi-\beta_1c_1+p_2-c_2+r_2]$	$-(\alpha\pi-\beta_2c_2+p_1-c_1+r_1)$ $-[(1-\alpha)\pi-\beta_1c_1+p_2-c_2+r_2]$
$P(x,y)$	$-(c_1-r_1-A)(c_2-r_2-B)[1-\frac{c_2-r_2-B}{(1-\alpha)\pi-B-\beta_1c_1+p_2}][1-\frac{c_1-r_1-A}{\alpha\pi-A-\beta_2c_2+p_1}]$	0

strategies is $\bar{U^A}$.

$$\bar{U^A} = x[y(\alpha\pi + r_1 - c_1) + (1-y)(A - c_1 + r_1)] + (1-x)[y(\beta_2 c_2 - p_1)] \quad (4)$$

According to the replication dynamic formula, the replication dynamic equation of state-owned enterprise TMTs can be marked as $F_A(x,y)$.

$$\begin{aligned} F_A(x,y) &= \frac{d_x}{d_t} = x(U^A_{S_1} - \bar{U^A}) \\ &= x(1-x)[y(\alpha\pi - A - \beta_2 c_2 + p_1) \\ &\quad + A - c_1 + r_1] \end{aligned} \quad (5)$$

According to the payment matrix, the expected profit of private enterprise TMTs when they select the input strategy is $U^B_{S_1}$.

$$U^B_{S_1} = x[(1-\alpha)\pi + r_2 - c_2)] + (1-x)(B - c_2 + r_2) \quad (6)$$

The expected profit of private enterprise TMTs when they choose the not input strategy is $U^B_{S_2}$.

$$U^B_{S_2} = x(\beta_1 c_1 - p_2) \quad (7)$$

The average expected profit of private enterprise TMTs when they choose the input and not input strategy is $\bar{U^B}$.

$$\bar{U^B} = y[x((1-\alpha)\pi + r_2 - c_2) + (1-x)(B - c_2 + r_2)] + (1-y)[x(\beta_1 c_1 - p_2)] \quad (8)$$

Similarly, the replication dynamic equation of the private enterprise TMTs can be marked as $F_B(x,y)$.

$$\begin{aligned} F_B(x,y) &= \frac{d_y}{d_t} = y(U^B_{S_1} - \bar{U^B}) \\ &= y(1-y)\{x[(1-\alpha)\pi - B - \beta_1 c_1 + p_2] \\ &\quad + B + r_2 - c_2\} \end{aligned} \quad (9)$$

Letting $\frac{d_x}{d_t} = 0$, $\frac{d_y}{d_t} = 0$, we can obtain five equilibrium points: $E(0,0)$, $S(0,1)$, $N(1,0)$, $D(1,1)$,

$$P\left(\frac{c_2 - r_2 - B}{(1-\alpha)\pi - B - \beta_1 c_1 + p_2}, \frac{c_1 - r_1 - A}{\alpha\pi - A - \beta_2 c_2 + p_1}\right).$$

III. EVOLUTIONARY STABILITY ANALYSIS

The local stability analysis of Jacobian is as follows:

$$J = \begin{bmatrix} \frac{\partial F_A(x,y)}{\partial x} & \frac{\partial F_A(x,y)}{\partial y} \\ \frac{\partial F_B(x,y)}{\partial x} & \frac{\partial F_B(x,y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[y(\alpha\pi - A - \beta_2 c_2 + p_1) + A - c_1 + r_1] \\ x(1-x)(\alpha\pi - A - \beta_2 c_2 + p_1) \\ y(1-y)[(1-\alpha)\pi - B - \beta_1 c_1 + p_2] \\ (1-2y)\{x[(1-\alpha)\pi - B - \beta_1 c_1 + p_2] + B + r_2 - c_2\} \end{bmatrix} \quad (10)$$

The determinant of the Jacobian matrix J is marked as $Del\ J$.

$$\begin{aligned} Del\ J &= (1-2x)(1-2y)[y(\alpha\pi - A - \beta_2 c_2 + p_1) \\ &\quad + A - c_1 + r_1]\{x[(1-\alpha)\pi - B - \beta_1 c_1 + p_2] \\ &\quad + B + r_2 - c_2\} - x(1-x)y(1-y)(\alpha\pi - A \\ &\quad - \beta_2 c_2 + p_1)[(1-\alpha)\pi - B - \beta_1 c_1 + p_2] \end{aligned} \quad (11)$$

The trace of the Jacobian matrix J is marked as $Tr\ J$.

$$\begin{aligned} Tr\ J &= (1-2x)[y(\alpha\pi - A - \beta_2 c_2 + p_1) + A \\ &\quad - c_1 + r_1] + (1-2y)\{x[(1-\alpha)\pi - B \\ &\quad - \beta_1 c_1 + p_2] + B + r_2 - c_2\} \end{aligned} \quad (12)$$

Calculate the values of the determinants and traces of the equilibrium points in the Jacobian matrix. The results are shown in Table 2.

According to Table 2, we can calculate the value of the diameter and the trace of the Jacobian matrix J and judge their symbols at the five points. According to the value of the probability x and y, we need to consider two situations in the process of the calculation.

(1) if $(1-\alpha)\pi - B - \beta_1 c_1 + p_2 < c_2 - r_2 - B < 0$, $\alpha\pi - A - \beta_2 c_2 + p_1 < c_1 - r_1 - A < 0$, at this time, two parties will choose the contrary strategy, if the state-owned enterprise chooses the input strategy, the private enterprise will chooses the not input strategy. Similarly, if the state-owned enterprise chooses the not input strategy, the private enterprise will choose the input strategy. Under the above conditions, the system's stability results are shown in Table 3.

As shown in Table 3, among the above five equilibrium points, $S(0,1)$ and $N(1,0)$ are *ESS* stable points, $E(0,0)$ and $D(1,1)$ are unstable points, and $P(x,y)$ is the saddle points.

TABLE 3. Stability of Jacobian matrix at each equilibrium point under situation 1.

Equilibrium point	$Det\ J$	$Tr\ J$	Stability
$E(0,0)$	$+$	$+$	$Unstable$
$S(0,1)$	$+$	$-$	ESS
$N(1,0)$	$+$	$-$	ESS
$D(1,1)$	$+$	$+$	$Unstable$
$P(x,y)$	$-$	0	$Saddle\ point$

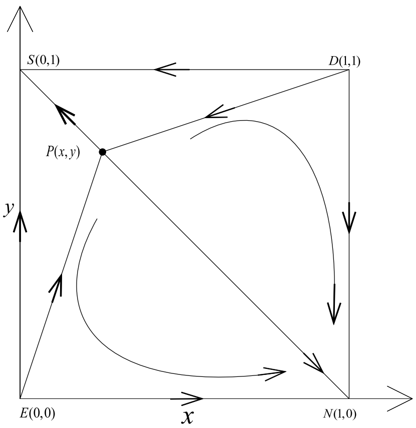

FIGURE 1. The path evolution diagram when $x < \frac{1}{2}, y > \frac{1}{2}$.

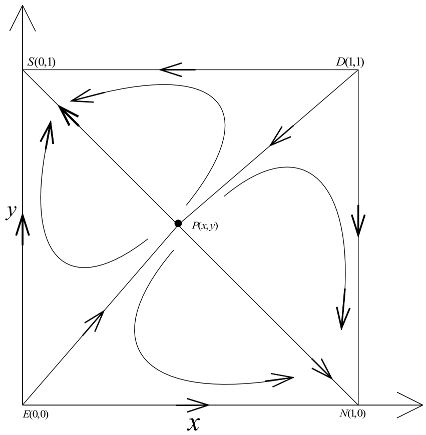

FIGURE 2. The path evolution diagram when $x = \frac{1}{2}, y = \frac{1}{2}$.

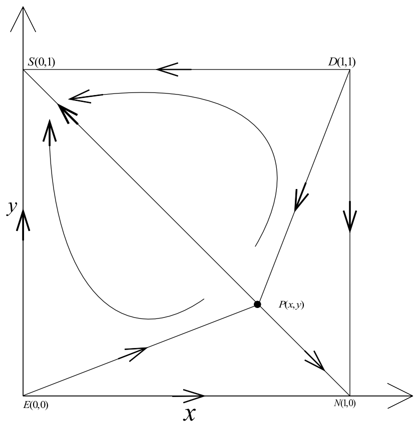

FIGURE 3. The path evolution diagram when $x > \frac{1}{2}, y < \frac{1}{2}$.

In order to observe the evolution process more intuitively, an evolution path diagram is shown in Figure 1, Figure 2, and Figure 3. Among them, Figure 1 depicts the situation when $x < \frac{1}{2}$, $y > \frac{1}{2}$; Figure 2 depicts the situation when $x = \frac{1}{2}$, $y = \frac{1}{2}$; Figure 3 depicts the situation when $x > \frac{1}{2}$, $y < \frac{1}{2}$. In each figure, the horizontal axis represents the probability of the input strategy selected by the state-owned enterprise and the vertical axis represents the probability of the input strategy selected by the private enterprise.

As shown in Figure 1, when $x < \frac{1}{2}$ and $y > \frac{1}{2}$, the area of the quadrilateral *EPDN* is larger than the area of the quadrilateral *EPDS*. This moment, the final strategy of state-owned enterprise is the input strategy and the final strategy of private enterprise is the not input strategy. The stable point of the system moves to $N(1, 0)$, that is, the (input, not input) is the final stable strategy between two parties.

As shown in Figure 2, when $x = \frac{1}{2}$ and $y = \frac{1}{2}$, the area of the quadrilateral *EPDS* is equal to the area of the quadrilateral *EPDN*. At present, two parties' final strategy may be the input or the not input strategy and the stable point may move to $S(0, 1)$ or $N(1, 0)$, that is, the final stable strategy is not sure.

As shown in Figure 3, when $x > \frac{1}{2}$ and $y > \frac{1}{2}$, the area of the quadrilateral *EPDN* is smaller than the area of the quadrilateral *EPDS*. Now, the final strategy of state-owned enterprise is the not input strategy and the final strategy of private enterprise is the input strategy. The final stable point of the system will move to $S(0, 1)$, that is, the (not input, input) is the final stable strategy between two parties.

(2) if $c_2 - r_2 - B < (1-\alpha)\pi - B - \beta_1 c_1 + p_2$, $c_1 - r_1 - A < \alpha\pi - A - \beta_2 c_2 + p_2$. This moment, two parties' final strategy is the input strategy, and the equilibrium point of the system will stabilize at the $D(1, 1)$, the system's stability results are shown in Table 4.

TABLE 4. Stability of Jacobian matrix at each equilibrium point under situation 2.

Equilibrium point	$Det\ J$	$Tr\ J$	Stability
$E(0,0)$	$+$	$+$	$Unstable$
$S(0,1)$	$-$	$Uncertain$	$Saddle\ point$
$N(1,0)$	$-$	$Uncertain$	$Saddle\ point$
$D(1,1)$	$+$	$-$	ESS

As shown in Table 4, we can see that there are 4 equilibrium points, among them, there is one unstable point $E(0, 0)$, two saddle points $S(0, 1)$ and $N(1, 0)$, and one stable point $D(1, 1)$. In this case, the evolution path diagram is shown in Figure 4.

As shown in Figure 4, we can see that the unstable point $E(0, 0)$ will move to the stable point $D(1, 1)$ in the path of *ESD* or *END*, it means that when two parties choose the not input strategy initially, as time goes on, the strategy will transform from the not input strategy to the input strategy finally.

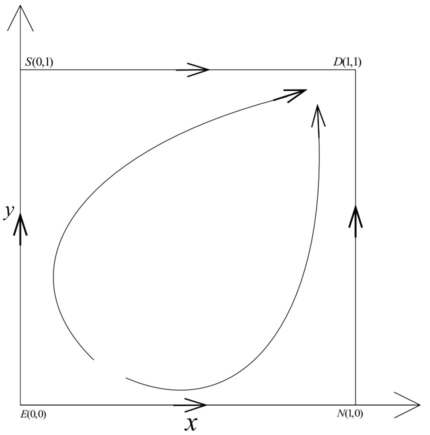

FIGURE 4. Path evolution diagram of the cooperative partner under situation 2.

IV. NUMERICAL SIMULATION AND RESULT ANALYSIS

Furthermore, in order to explore the evolutionary path of the cooperation between the state-owned enterprise TMTs and the private enterprise TMTs, this paper selects relevant parameters and uses MATLAB 2018 software to carry out numerical simulation and analysis under the background of the mixed ownership reform. We carried two part related numerical simulations: One is the cooperative path evolution simulation and the other is the simulation of the influence of payment parameters on the evolution of system stability.

A. COOPERATIVE PATH EVOLUTION SIMULATION

In this section, we select some parameters to do the simulation of the system's path evolution under the situation 1 and situation 2. In situation 1, it can be divided into three stages according to the values of x and y: $x < \frac{1}{2}, y > \frac{1}{2}; x = \frac{1}{2}, y = \frac{1}{2}; x > \frac{1}{2}, y < \frac{1}{2}$. At this time, keeping $c_1 = 0.4$, $c_2 = 0.4$, $r_1 = 0.1$, $r_2 = 0.04$, $p_1 = 0.1$, $p_2 = 0.1$, $b_1 = 0.9$, $b_2 = 0.8$, $A = 0.5$, $B = 0.5$, $\pi = 0.8$ unchanged, and setting the profit coefficient of the state-owned enterprise $\alpha = 0.6$, $\alpha = 0.4$, and $\alpha = 0.3$ accordingly. With the change of parameters, the value of the x and y can meet the condition $x < \frac{1}{2}, y > \frac{1}{2}; x = \frac{1}{2}, y = \frac{1}{2}; x > \frac{1}{2}, y < \frac{1}{2}$ correspondingly, the value of the x and y are $x = 0.3128$, $x = 0.8333$; $x = 0.5$, $y = 0.5$; $x = 0.7000$, $y = 0.4167$. In situation 2, there are 4 equilibrium points and x and y will not be between (0, 1), this moment, setting $c_1 = 0.4$, $c_2 = 0.4$, $r_1 = 0.1$, $r_2 = 0.04$, $p_1 = 0.4$, $p_2 = 0.3$, $b_1 = 0.9$, $b_2 = 0.8$, $A = 0.5$, $B = 0.5$, $\pi = 0.8$, $\alpha = 0.4$, we can obtain $x = 1.75$, $y = 2$. The specific simulation result of the system's path evolution under the situation 1 and situation 2 is shown in Figure 5.

As shown in Figure 5, we can understand the evolution process of system path intuitively, among them, the Figure 5(a), Figure 5(b), and Figure 5(c) are the simulation results of the situation 1, the Figure 5(d) is the simulation result of the situation 2. In Figure 5 (a), there are 5 equilibrium points, the initial value of x is less than $\frac{1}{2}$, the initial value of y is more than $\frac{1}{2}$, the system's path will move from $S(0, 1)$ to $N(1, 0)$, it means that state-owned enterprise will choose input strategy and private enterprise will choose not input strategy; in Figure 5(b), when the initial value $x = \frac{1}{2}, y = \frac{1}{2}$, the path of the system perhaps move to $S(0, 1)$ or $N(1, 0)$, this moment, the system's path evolution has the uncertain result; in Figure 5(c), when the initial value $x > \frac{1}{2}, y < \frac{1}{2}$, the path of the system will move to $S(0, 1)$, at this time, the state-owned enterprise will choose the not input strategy and the private enterprise will choose the input strategy; in Figure 5(d), there are 4 equilibrium points, the path of the system will move from $E(0, 0)$ to $D(1, 1)$, the strategy of state-owned enterprise and private enterprise is input.

B. SIMULATION OF THE INFLUENCE OF PAYMENT PARAMETERS ON EVOLUTION SYSTEM STABILITY

In the context of the mixed ownership reform, there are many factors that can affect the process of dynamic cooperation between state-owned enterprise and private enterprise. To explore the factors that have a certain impact on the cooperative process between two parties, relevant numerical simulations are carried out. We select four factors: Knowledge flow coefficient β, input cost c, government reward r, and government penalty p. When $x < \frac{1}{2}, y > \frac{1}{2}$, the initial ratio of the state-owned enterprise TMTs and the private enterprise TMTs is set to 0.40 and 0.60, respectively. When $x < \frac{1}{2}, y > \frac{1}{2}$, the initial ratio of the state-owned enterprise TMTs and the private enterprise TMTs is set to 0.60. and 0.45 respectively. The specific results are as follows.

1) KNOWLEDGE FLOW COEFFICIENT β

Before simulation, we set the parameters as follows: $c_1 = 0.4$, $c_2 = 0.4$, $r_1 = 0.1$, $r_2 = 0.1$, $p_1 = 0.1$, $p_2 = 0.1$, $A = 0.5$, $B = 0.5$, $\alpha = 0.6$, $\pi = 0.8$. Keeping the above parameters fixed, we increase the knowledge flow coefficient of state-owned enterprise β_1 from 0.9 to 0.98 and knowledge flow coefficient of private enterprise β_2 from 0.8 to 0.88. Based on the above parameters, we explore the impact of knowledge flow on the dynamic cooperative behavior between two parties. The specific result is shown in Figure 6.

In Figure 6(a), when the knowledge flow coefficient of state-owned enterprise β_1 increases from 0.9 to 0.98, we can see that the proportion of the input strategy of the state-owned TMTs gradually increases from 0.4 to 1. When the knowledge flow coefficient β_1 increases further, the state-owned enterprise TMTs' evolution steps tend to shorten, it indicates that the degree of knowledge flow of state-owned enterprise TMTs has the positive effect on the cooperation between two parties; in Figure 6(b), when the knowledge flow coefficient of private enterprise β_2 increases from 0.8 to 0.88, the private enterprise TMTs' evolution steps tend to extended, it also indicates that the greater knowledge flow will slow down the proportion of not input strategy. According to above results, we can find that the greater degree of knowledge flow is helpful to the knowledge input between state-owned enterprise and private enterprise TMTs.

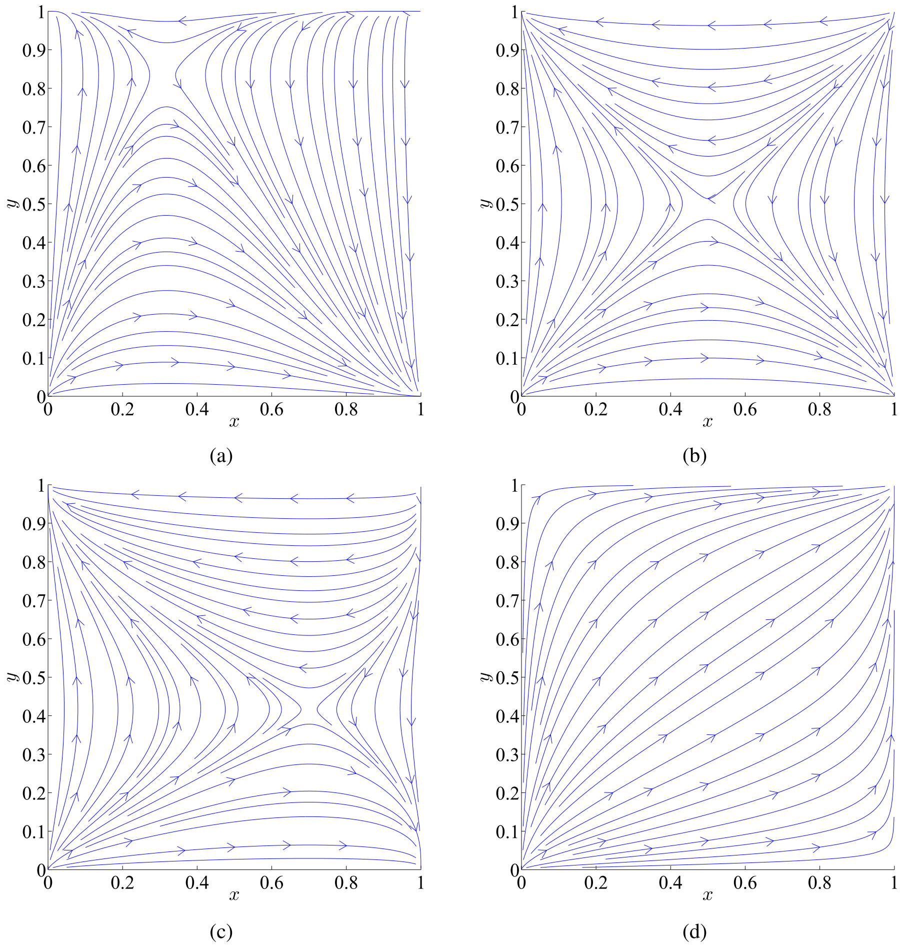

FIGURE 5. The system's path evolution simulation result under the situation 1 and situation 2. (a), (b), and (c) belong to situation 1; (d) belongs to situation 2. (a) $x = 0.3182$, $y = 0.8333$; (b) $x = 0.5$, $y = 0.5$; (c) $x = 0.7000$, $y = 0.4167$; (d) $x = 1.7500$, $y = 2.0000$.

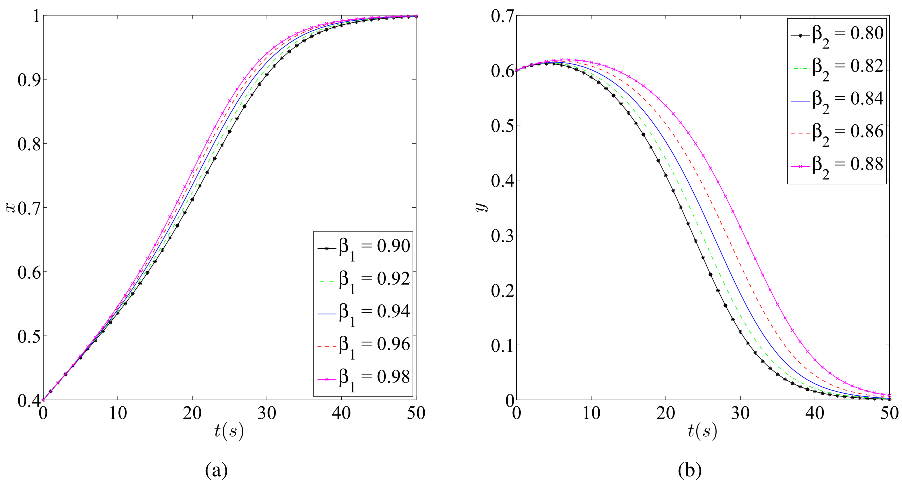

FIGURE 6. Strategy selection process of the state-owned enterprise and the private enterprise when increase the knowledge flow coefficient β. (a) increase the knowledge flow coefficient of state-owned enterprise TMTs β_1 from 0.9 to 0.98; (b) increase the knowledge flow coefficient of private enterprise β_2 from 0.8 to 0.88.

2) INPUT COST *c*

We set the parameters $r_1 = 0.1$, $r_2 = 0.1$, $\beta_1 = 0.9$, $\beta_2 = 0.8$, $p_1 = 0.1$, $p_2 = 0.1$, $A = 0.5$, $B = 0.5$, $\alpha = 0.6$, $\pi = 0.8$ and keep the input cost of state-owned enterprise c_1 and private enterprise c_2 increasing from 0.4 to 0.48 gradually. Based on the above parameters, we explore the impact of input

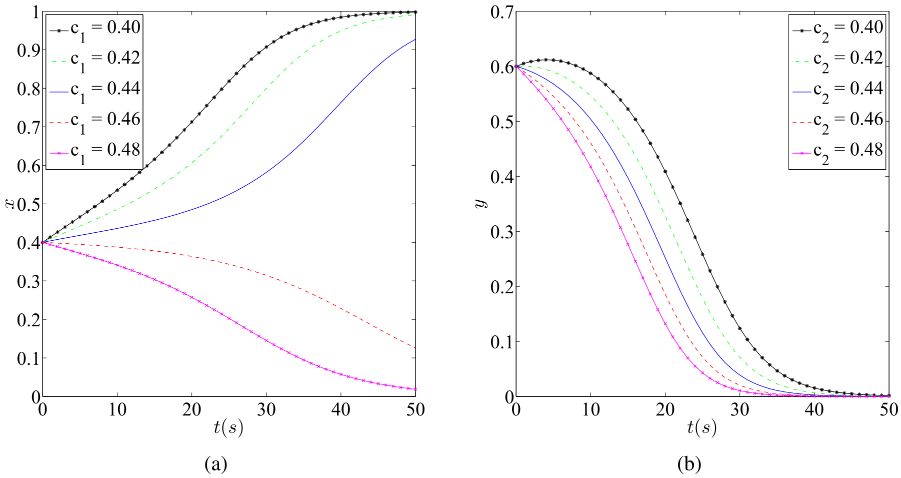

FIGURE 7. Strategy selection process of the state-owned enterprise and the private enterprise when increase the input cost c. (a) increase the input cost of state-owned enterprise TMTs c_1 from 0.4 to 0.48; (b) increase the input cost of private enterprise c_2 from 0.4 to 0.48.

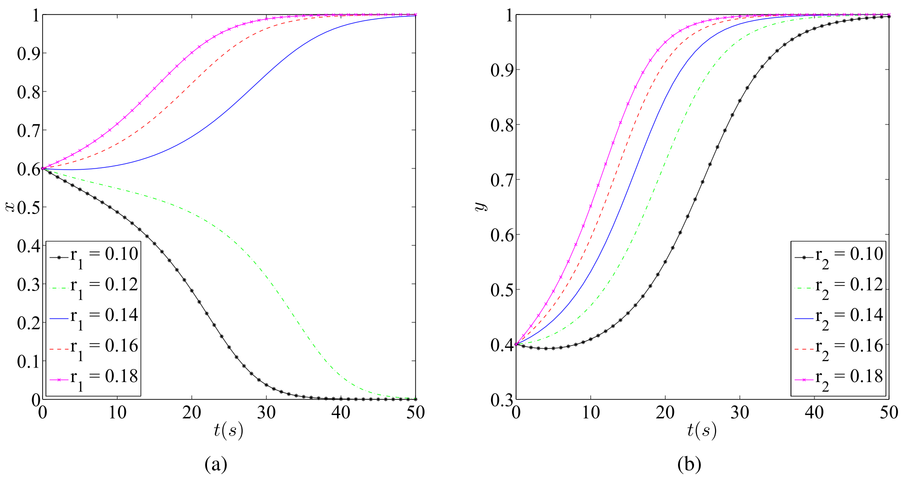

FIGURE 8. Strategy selection process of the state-owned enterprise and the private enterprise when increase the government reward r. (a) increase the government reward of state-owned enterprise TMTs r_1 from 0.1 to 0.18; (b) increase the government reward of private enterprise r_2 from 0.1 to 0.18.

cost on the cooperation between state-owned enterprise and private enterprise. The specific result is shown in Figure 7.

As shown in Figure 7(a), when input cost of state-owned enterprise c_1 increases from 0.40 to 0.48, the strategy of the state-owned enterprise will transform from the input to the not input strategy, it means that the larger input cost will be not conducive to the cooperation between state-owned enterprise and private enterprise. In Figure 7(b), as for the private enterprise, we will also notice that the larger input cost will hinder the cooperation between two parties. Specially, when $c_1 = c_2 = 0.4$, the state-owned enterprise will choose the input strategy, while the private enterprise will choose the not input strategy, this moment, decrease the input cost of the private enterprise will improve the cooperation more effectively.

3) GOVERNMENT REWARD *r*

We set the parameters $c_1 = 0.4$, $c_2 = 0.4$, $\beta_1 = 0.9$, $\beta_2 = 0.8$, $p_1 = 0.1$, $p_2 = 0.1$, $A = 0.5$, $B = 0.5$, $\alpha = 0.2$, $\pi = 0.5$ and keep the government reward on the state-owned enterprise and private enterprise r_1 and r_2 increasing from 0.1 to 0.18, based on the above parameters, we explore the government reward's effect on the cooperation between state-owned enterprise and private enterprise. The specific result is shown in Figure 8.

As shown in Figure 8(a), when increase the government reward on the state-owned enterprise from 0.10 to 0.18, the state-owned enterprise' strategy will transform from not input to the input strategy, it means that the larger government reward will improve the cooperation between state-owned enterprise and private enterprise. In Figure 8(b), when increase the government reward on the private enterprise from 0.10 to 0.18, the system's evolutionary steps will shorten from 50 to 30, it also indicates that the government reward on the private enterprise will improve the cooperation. Furthermore, when $r_1 = r_2 = 0.10$, the state-owned enterprise will choose the not input strategy, while the private enterprise chooses the input strategy. From this, we can know

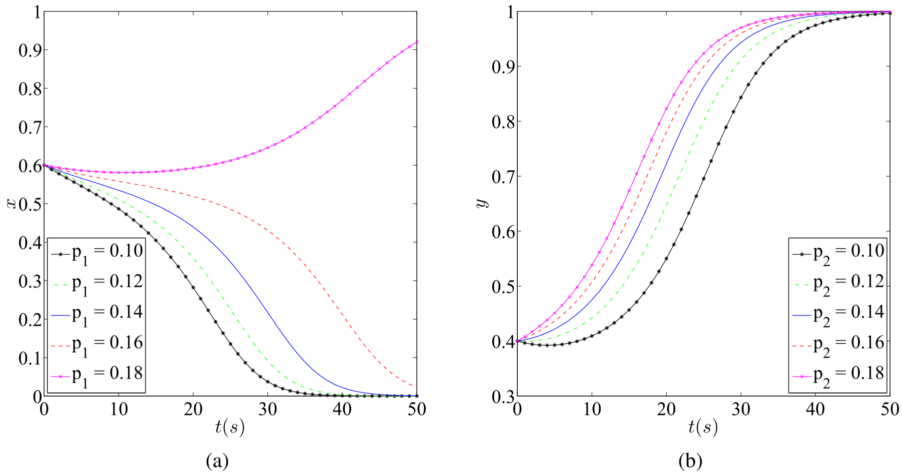

FIGURE 9. Strategy selection process of the state-owned enterprise and the private enterprise when increase the government penalty p. (a) increase the government penalty of state-owned enterprise TMTs p_1 from 0.1 to 0.18; (b) increase the government penalty of private enterprise p_2 from 0.1 to 0.18.

that increase government reward on the private enterprise can improve the cooperation more effectively.

4) GOVERNMENT PENALTY p

We set the parameters $c_1 = 0.4, c_2 = 0.4, r_1 = 0.1, r_2 = 0.1, \beta_1 = 0.9, \beta_2 = 0.8, A = 0.5, B = 0.5, \alpha = 0.2, \pi = 0.5$ and increase the government penalty of state-owned and private enterprise p_1 and p_2 from 0.1 to 0.18. Based the above parameters, we explore the government penalty's effect on the cooperation between state-owned enterprise and private enterprise. The specific simulation result is shown in Figure 9.

As shown in Figure 9(a), when the government liquidated damages of state-owned enterprise TMTs p_1 increases from 0.1 to 0.18, the strategy of state-owned enterprise will transform from not input to input strategy, it indicates that the larger government penalty of state-owned enterprise will be conducive to the cooperation between two parties. In Figure 9(b), when the government penalty of private enterprise TMTs p_2 increases from 0.1 to 0.18, the system's evolutionary result will tend to the input strategy, furthermore, with the increase of p_2, the evolutionary steps will shorten form 50 to 40. In addition, when $p_1 = p_2 = 0.1$, the state-owned enterprise chooses the not input strategy while the private enterprise chooses the input strategy, it indicates that increasing government penalty on the private enterprise can boost the cooperation more effectively.

V. CONCLUSION

Under the background of the mixed ownership reform, we make some assumptions based on the cooperation of TMTs between state-owned enterprise and private enterprise in real life firstly. Then, we use the evolutionary game theory and duplicate dynamic equation to explore the dynamic cooperative behaviors of state-owned enterprise TMTs and private enterprise TMTs based on the perspective of knowledge input and knowledge flow. Finally, the rationality of the model is verified by numerical simulation. Through the above research, there are some interesting conclusions: (1) From the perspective of knowledge input and knowledge flow, knowledge input or not input is the strategy can be selected by the TMTs of state-owned enterprise and the private enterprise in their cooperation. The final strategy choices are related to the model construction and the parameter setting of the initial payment matrix: There are different game results under the different situations, when the conditions meet the situation 1, (input, not input) or (not input, input) is the final strategy between two parties; when the conditions meet the situation 2, the game is the win-win situation, this moment, (input, input) is the final strategy between TMTs of state-owned enterprise and private enterprise. (2) Within a certain range, the knowledge flow coefficient, input cost, government reward, and government penalty have different effects in the cooperation between TMTs of state-owned enterprise and private enterprise. The larger knowledge flow coefficient, government reward, and government penalty have positive effects in the cooperation between two parties, the input cost has a negative effect in the cooperation. (3) For private enterprise, because of the lesser knowledge flow coefficient, private enterprises face more difficulties in the process of cooperation, therefore, improving the knowledge flow coefficient and increasing the government reward and government penalty for TMTs of private enterprise can promote the cooperation between two parties more effectively.

In order to improve the cooperation between state-owned enterprise and the private enterprise, we put forward relevant opinions and suggestions to relevant departments based on the above researches and the results, the suggestions are as follows: (1) Increase the degree of knowledge flow, encourage mutual communication between TMTs of state-owned enterprise and private enterprise. Under the background of mixed ownership reform, state-owned enterprise and private enterprises should carry out the cooperation and innovation activities between two parties, such as regular communication and fellowship, personnel exchanges and mutual visits, and various activities which can improve the cooperation. In this way, can two parties establish the basis of cooperation, deepen the connotation of cooperation, and strengthen cooperation in system, experience and knowledge.

(2) Decrease the knowledge input cost and threshold of cooperation, build a good cooperation environment. In the process of the cooperation, both sides should lower the entry threshold, broaden the scope of cooperation, and build a flexible and free cooperation environment. Two parties should explore the knowledge flow mechanism, such as the mutual utilization of human resources, establishing common development goals, and building a collaborative atmosphere that encourages innovation and fault tolerance. Only in this way, could the respective advantages of state-owned enterprise and private enterprise be combined and the mixed ownership reform's performance be visible.

(3) Increase the penalty and reward level of government, build a reasonable mechanism of rewards and punishments, and improve the the knowledge flow of state-owned and private executives. Government should increase the penalty if either party breaks the contract in the process of cooperation and increase the incentives if the TMTs of mixed ownership enterprise can input knowledge mutually and carry out cooperative activities. This moment, the government should take various kinds of incentive measures, especially, it's necessary to consider the characteristics of senior executives, the government should give material and spiritual rewards to encourage TMTs to input and exchange knowledge mutually. Furthermore, increase the penalty of knowledge plagiarism and moral hazard behaviour, encourage people to collaborate with each other, and build a good team atmosphere. In this way, can the fair and just cooperation atmosphere be built easily.

In general, this paper uses the evolutionary game theory to explore the knowledge input and knowledge flow between TMTs of state-owned enterprise and private enterprise under the background of the mixed ownership reform. We put forward some suggestions to the related government based on the research and hope our suggestions could provide some substantial help to the current reform. In the future, the above model and methods can be used other fields, such as the cooperation between schools and enterprises, cooperation within the research team, and local government cooperation and innovation, etc. Also, other factors can be combined to explore cooperation between state-owned enterprise and private enterprise TMTs in the future.

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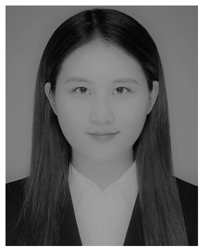

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