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Evolutionary game analysis of company collaborative strategy in cloud manufacturing platform environment

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A B S T R A C T

The collaboration between manufacturing companies and demand companies is the focus of effective operation of cloud manufacturing platform. The evolutionary game model of manufacturing company, demand company and cloud platform was established, and the strategy stability of the three parties was analyzed in this paper. Based on Lyapunov discrimination method, the equilibrium points of the system were explored, and the simulation was applied to analyze the influence of key factors in the evolution process by MATLAB2021a. The results show that: (1) The evolution of company collaborative cooperation strategies in the cloud platform environment is staged; (2) The collaborative subsidy to the manufacturing company and the demand company by the cloud platform, the collaborative effort degree of the manufacturing company and the demand company, the value-added profits of the manufacturing company, the penalties and profits of the manufacturing company's speculation behavior, the loss of information leakage of demand company, and the government's subsidy for cloud platform supervision are important factors that affect the strategies of each subject; (3) The establishment of the cloud platform supervision mechanism can promote collaboration between the manufacturing company and the demand company. The results of the study can provide a beneficial strategic decision guidance for the development of the cloud manufacturing platform.

A R T I C L E   I N F O

Keywords:
Cloud manufacturing platform;
Manufacturing company;
Collaborative cooperation;
Evolutionary game;
Simulation;
MATLAB programming platform

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1. Introduction

With the integration of Internet of Things and Internet of services with manufacturing, the production systems of the fourth industrial revolution are undergoing renovation [1]. The cloud manufacturing is becoming a service-oriented manufacturing mode for the development of advanced manufacturing [2]. With the good communication channels and expanded communication fields, the cloud manufacturing platform transforms the companies on the platform from a relatively closed self-centered and self-organization system to an open innovation system with cooperation, which is an effective implementation of the strategy of "Internet + Manufacturing". In the cloud platform, capacity sharing changes the traditional manufacturing mode, breaks the balance of the original production system, and transforms the roles of companies and users from the traditional separation mode of producer and consumer to the co-creators of products, improving the technical performance and reducing the purchase price [3]. The relationship between supplier and demander has changed from simple value exchange to value co-creation.

Shared manufacturing based on the cloud platform has attracted the attention of relevant scholars and industrialists [4], but the development of cloud platform is still in the exploratory stage, and how to develop cloud manufacturing platform is still a common concern of platform operators and users. However, in the process of cloud platform application, some problems restricting companies' cloud adoption are gradually exposed [5]. While company collaboration is facilitated, large-scale resource sharing implemented in cloud platforms may widen the credibility gap [6]. In the process of cooperation, the situation of "free-riding" in which one partner only benefits and does not invest often occurs [7]. This reduces the effectiveness of the cloud platform to create value for companies and is not conducive to the promotion of shared innovative ideas in the system, which requires certain supervision. Facing the market environment in which the scale of companies entering the cloud platform is gradually expanding, it is necessary to make an in-depth analysis on the strategies to promote the collaborative cooperation of companies in the cloud platform.

Therefore, from the perspective of cooperation and supervision of the cloud platform, this study systematically analyzes the promotion effect of the subsidy and penalty mechanism of the cloud platform and the efforts of manufacturing company and demand company on company collaboration with the evolutionary game method, which can provide some guidance for the prosperous sharing economy and the healthy development of cloud manufacturing platform.

2. Literature review

The existing researches on cloud platform mainly focus on the business model of cloud platform, the relationship between the supply and the demand in cloud platform and the supervision of cloud platform.

The cloud platform integrates sharing with the internet, expanding small-scale sharing based on strong ties to large-scale sharing based on weak ties. Therefore, the sharing based on the cloud platform breaks through the traditional sharing behavior and becomes a more macroeconomic sharing. In the sharing economy, the cloud platform plays the role of digital media to match supply and demand. Some scholars have proposed that platform services based on the network environment will gradually become the mainstream mode of the modern service industry. Compared with traditional business mode, cloud platforms can assist buyers and sellers to match and connect faster, provide a more economical mode to increase customer value, create competitive advantage and transform business processes to increase industry profits [8], which is more consistent with the concept of sustainable development. The cloud manufacturing can realize customization and modularization of resources in the cloud platform [9], and the multi-user-oriented manufacturing service distribution [2]. Many scholars have discussed the mode of cloud manufacturing. Woo *et al.* [10] believed that intelligent cloud manufacturing platform can improve the utilization efficiency of resources in platform network sharing and provide manufacturing services on demand. Barenji *et al.* [11] found that various departments in the platform can use joint design to achieve effective communication across regions and reach perfect cooperative target by using the method of the case study. Zhang *et al.* [12] proposed that the machine system based on cloud platform can customize the architecture of intelligent manufacturing of products. Li *et al.* [13] thought that industrial robots were the service objects of the internet platform deriving from the industrial mode of "government procurement and leasing". Xu *et al.* [14] and Wu and Zhang [15] proposed the design scheme of the comprehensive platform for information services provided by supply chain participants based on the ethereum block-chain for intelligent manufacturing. Xiao *et al.* [16] suggested a service resource matching method by combining the characteristics of manufacturing service task on cloud platform, such as relevance, synergy and diversity. The construction and mode of cloud manufacturing platforms have attracted more and more scholars' attention.

Based on big data and artificial intelligence, the digital cloud platform focuses on the resource sharing of bilateral participants and is an effective carrier to achieve value creation of resource sharing service system. In the cloud platform, the main subject of supply and demand can give full play to the effective utilization of resources[17], form complementary advantages, reduce energy consumption[18], and play a guiding role in innovation. The services of cloud platforms have the characteristics of network externality, and integration, functionality and derivation of scientific and technological resources [19]. The researches on cloud platforms have found that the network effects generated by cloud platforms improve the competitive advantages and profits of the platforms [20], and the active cooperation of service providers can create higher benefits for both parties. Upgrading of manufacturing networks through the cloud platform has become the mode adopted by many manufacturing companies, which is also the reason that drives them to join the cloud manufacturing platform [21]. At the same time, product design, manufacturing network [22], competitive pressures, manager's influence, compatibility and applicability all play the critical roles in the cloud platform operation [9]. Collaboration is the key to the success of cloud platforms [23]. Ren *et al.* [24] suggested the service composition method because of synergies in allusion to social synergy characteristics of manufacturing services, and described five relationships of service networks. Company collaboration in the cloud platform is a complex system engineering [25]. How to effectively promote this synergistic relationship is still in the exploratory stage.

While the cloud manufacturing platform brings many conveniences to the development of the manufacturing industry, it also produces certain negative effects. For example, intelligent manufacturing requires the sharing of data and information, which not only leads to the risk of information exchange [26], but also brings issues such as the security of cloud platform data and information [11] and the complexity of trust relationships between cooperating subjects [27], making it difficult to ensure the credibility and responsibility of cross-company production activities [28]. Some scholars have proposed that the complexity of service upgrade would initiate cognitive bias behavior of organizational participants to jeopardize the accomplish of serviceization within the organization [29]. With the increase in the number of cloud manufacturing platform products, platform services focus more on communication and coordination between service providers and consumers, while incentive and punishment mechanisms are not well established [30]. All these make it difficult for platform supervision to promote its healthy development. Scholars have realized the necessity of effective monitoring of cloud platforms [30], and proposed some monitoring methods such as consensus mechanism of service capability proof [5]. Even if the existing supervision methods are not perfect and need to be further explored, it has been recognized by scholars that company coordination still needs to be managed, which the platform is responsible for [31, 32], and one of the autonomous cycles of the platform is believed to allow self-supervision of the coordination process [33].

3. Model building

3.1 Model description and assumption

In cloud manufacturing environment, a variety of manufacturing resources are organized by the platform to enhance the competitiveness of supply chain and realizes on-demand matching between resource demanders and suppliers based on unified management and operation, and finally completes the full life cycle of manufacturing. In this study, a collaborative cooperation multi-agent game model of cloud platform, manufacturing company and demand company is constructed. The logical relationship of the subjects in cloud manufacturing platform is shown in Fig. 1.

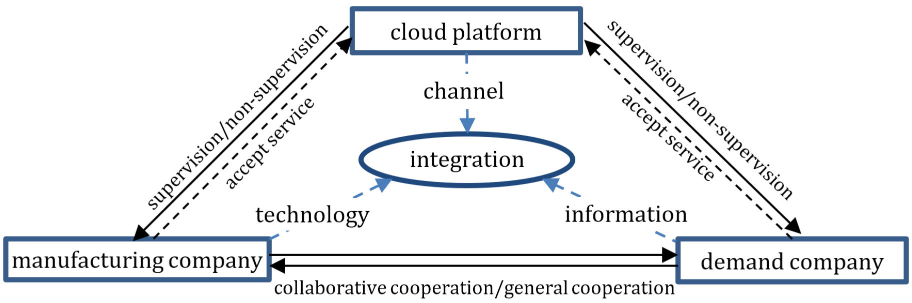

Fig. 1 Logical relationship of game model in the cloud platform environment

For the purpose of studying behavioral strategies of three-party game subjects of cloud platform, manufacturing company and demand company, the following assumptions are proposed.

Assumption 1: There are three participants in the evolutionary game model, namely the cloud platform, the manufacturing company and the demand company, and they take the maximization of their respective benefits as the goal in decision-making. Due to the characteristics of bounded rational subjects, each subject achieves the optimal strategy with keeping learning in the process and adjusts the strategy based on the strategic choice of the other parties and their benefits. The game process is repeated and dynamic. The proportion of manufacturing company collaborative cooperation is indicated as x, and the proportion of general cooperation is indicated as $1 - x$; the proportion of demand company collaborative cooperation is indicated as y, and the proportion of general cooperation is indicated as $1 - y$; the proportion of cloud platform supervision is indicated as z, and the proportion of non-supervision is indicated as $1 - z$; where $0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1$.

Assumption 2: The government actively promotes cloud manufacturing platform, and will subsidize platform supervision and the collaborative cooperation behavior of manufacturing company and demand company. The payoff of the normal operation of the cloud platform without supervision is E. When implementing the supervision of companies on the platform, the regulatory cost of cloud platform is C_P, and government subsidy for the cloud platform is S_P. If both manufacturing company and demand company choose the collaborative cooperation strategy, it will bring the value-added benefits F_P to the cloud platform.

Assumption 3: When cloud platform chooses the supervision strategy, if manufacturing company or the demand company chooses to collaboratively cooperate, the degree of collaborative effort of the manufacturing company is set as α $(0 < \alpha \leq 1)$, and the degree of collaborative effort of the demand company is set as β $(0 < \beta \leq 1)$. The cloud platform provides subsidies to manufacturing company and demand company on behalf of the government, and the subsidies are proportional to the effort of the company, denoted as αS_M and βS_C respectively.

Assumption 4: When both manufacturing company and demand company choose to collaborative cooperation, they can obtain value-added collaborative profits. The value-added profit of collaborative cooperation of manufacturing company is W_M, and that of demand company is W_C. The amount of the collaborative cooperation profit is proportional to the effort of the company, and the value-added collaborative profits of manufacturing company is αW_M and the value-added collaborative profits of demand company is βW_C.

Assumption 5: When the manufacturing company chooses collaborative cooperation and the demand company chooses general cooperation, due to the hardware upgrades carried out by the manufacturing company, even if the demand company does not collaborate cooperate with it, the manufacturing company will have a certain additional profit T. The value-added profit of the manufacturing company is proportional to its effort, so it can be described as αT. At this time, the demand company cannot obtain additional profits.

Assumption 6: When the manufacturing company chooses general cooperation and the demand company chooses collaborative cooperation, because of collaboratively cooperating by providing information, the information leakage loss of the demand company may occur, denoted as V. The loss of demand company is proportional to its collaborative effort, and the loss amount is expressed as βV. At this time, the general cooperation as "free-rider" behavior can bring the speculative profit Q to the manufacturing company, and the amount of the speculative profit is proportional to the effort of the demand company, which is expressed as βQ. The punishment mechanism in cooperation can effectively curb the occurrence of "free-rider" behavior. Therefore, the manufacturing company should be punished with the penalty *to* compensate the collaborative cooperation of the demand company, which is expressed as L_M.

Assumption 7: When both manufacturing company and demand company choose general cooperation, the parties can only obtain the payoffs of general cooperation, which are expressed as R_M and R_C respectively.

On the basis of the above descriptions and assumptions, the strategy game payoff matrix of the three-party is acquired, as illustrated in Table 1.

Table 1 Payoff matrix of three-party subjects

Strategy choice		Demand company	Cloud platform: Supervision (z)	Cloud platform: Non-supervision ($1-z$)
Manufacturing company	Collaborative cooperation (x)	Collaborative cooperation (y)	$\alpha W_M + \alpha S_M + R_M$ $\beta W_C + \beta S_C + R_C$ $E - C_P + S_P + F_P - \alpha S_M - \beta S_C$	$\alpha W_M + R_M$ $\beta W_C + R_C$ $E + F_P$
		General cooperation ($1-y$)	$\alpha S_M + R_M + \alpha T$ R_C $E - C_P + S_P - \alpha S_M$	$R_M + \alpha T$ R_C E
	General cooperation ($1-x$)	Collaborative cooperation (y)	$R_M - L_M + \beta Q$ $\beta W_C + R_C - \beta V + L_M$ $E - C_P + S_P - \beta S_C$	$R_M + \beta Q$ $R_C - \beta V$ E
		General cooperation ($1-y$)	R_M R_C $E - C_P + S_P$	R_M R_C E

3.2 Model analysis

The stability and evolution path of three subjects strategies are explored by the stability theory of differential equations, and two conditions should be satisfied for the stable point of replication dynamic equation: $F(x) = 0$, and $\frac{dF(x)}{dx} < 0$.

Replication dynamic analysis of manufacturing company strategy

The expected payoff of manufacturing company carrying out collaborative cooperation strategy is set as U_{11}, and the expected payoff of manufacturing company carrying out general cooperation strategy is set as U_{12}, which are defined as follows:

$$U_{11} = yz(\alpha W_M + \alpha S_M + R_M) + (1-y)z(\alpha S_M + R_M + \alpha T) + y(1-z)(\alpha W_M + R_M) + (1-y)(1-z)(R_M + \alpha T) \quad (1)$$

$$U_{12} = yz(R_M - L_M + \beta Q) + (1-y)zR_M + y(1-z)R_M + (1-y)(1-z)R_M \quad (2)$$

$$U_1 = xU_{11} + (1-x)U_{12} \quad (3)$$

The replication dynamic equation of manufacturing company strategy is as follows:

$$\begin{aligned} F(x) = \frac{dx}{dt} &= x(U_{11} - U_1) = x(1-x)(U_{11} - U_{12}) \\ &= x(1-x)(y(\alpha W_M - \alpha T - \beta Q) + z\alpha S_M + yzL_M + \alpha T) \end{aligned} \quad (4)$$

$$F'(x) = \frac{dF(x)}{dx} = (1-2x)(y(\alpha W_M - \alpha T - \beta Q) + z\alpha S_M + yzL_M + \alpha T) \quad (5)$$

Assume $W(z) = y(\alpha W_M - \alpha T - \beta Q) + z\alpha S_M + yzL_M + \alpha T$, when $z_0 = \frac{(y-1)\alpha T - y(\alpha W_M - \beta Q)}{\alpha S_M + yL_M}$, proposition 1 is established.

Proposition 1: when $0 < z < z_0 < 1$, the evolutionary stable state of x tends to 0, the stable strategy of the manufacturing company is general cooperation. When $0 < z_0 < z < 1$, the evolutionary stable state of x tends to 1, the stable strategy of the manufacturing company is collaborative cooperation.

Proof: $W(z)$ increases monotonically over the interval. When $z = z_0$, $W(z) = 0$, $F(x) = 0$, and $F_x'(x) = 0$, so $x \in [0,1]$ is in the stable state, and there is no fixed stable strategy in the interval; When $0 < z < z_0 < 1$, $W(z) < 0$, $F_x(0) = 0$, and $F_x'(0) < 0$, so $x = 0$ has stability; When $0 < z_0 < z < 1$, $W(z) > 0$, $F_x(1) = 0$, and $F_x'(1) < 0$, so $x = 1$ has stability.

The phase diagram of the manufacturing company strategy choice is obtained according to the above analysis, as illustrated in Fig. 2.

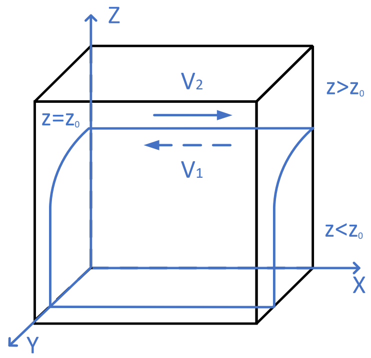

Fig. 2 Phase diagram of the manufacturing company strategy choice

Inference 1: When the values of S_M, W_M, L_M and T raise while other parameters keep constant, manufacturing company will approach collaborative cooperation strategy. In common, when the values of β and Q raise, manufacturing company will approach general cooperation strategy.

Proof: Since $z_0 = \frac{(y-1)\alpha T - y(\alpha W_M - \beta Q)}{\alpha S_M + y L_M}$, the value of z_0 will fall with the raising of the values of S_M, W_M, L_M and T, and the volume of V_2 changes inversely with the value of z_0. The enlarge of V_2 shows that the manufacturing company is more inclined to the cooperative cooperation strategy. The value of z_0 will raise with the raising of the values of β and Q, and the volume of V_1 changes the same as the value of z_0. The enlarge of V_1 shows that the manufacturing company is more inclined to the general strategy. It presents that the proportion of manufacturing company choosing collaborative cooperation is directly proportional to the subsidies for the collaborative cooperation of the manufacturing company, the value-added profits of the manufacturing company when the two sides collaborative cooperate, the speculative penalty of the general cooperation and the additional profit of collaborative cooperation of the manufacturing company, and inversely proportional to the degree of collaborative effort of the demand company and the speculative profit of the general cooperation of the manufacturing company.

Replication dynamic analysis of the demand company strategy

The expected payoff of demand company carrying out collaborative cooperation strategy is set as U_{21}, and the expected payoff of demand company carrying out general cooperation strategy is set as U_{22}, which are defined as follows:

$$\begin{aligned} U_{21} = {} & xz(\beta W_C + \beta S_C + R_C) + x(1-z)(\beta W_C + R_C) + (1-x)z(\beta W_C + R_C - \beta V + L_M) \\ & + (1-x)(1-z)(R_C - \beta V) \end{aligned} \tag{6}$$

$$U_{22} = xzR_C + x(1-z)R_C + (1-x)zR_C + (1-x)(1-z)R_C \tag{7}$$

$$U_2 = yU_{21} + (1-y)U_{22} \tag{8}$$

The replication dynamic equation of demand company strategy is as follows:

$$\begin{aligned} F(y) = \frac{dy}{dt} = y(U_{21} - U_2) = y(1-y)(U_{21} - U_{22}) \\ = y(1-y)(x(\beta W_C + \beta V) + z\beta S_C - \beta V + (1-x)zL_M) \end{aligned} \tag{9}$$

$$F'(y) = \frac{dF(y)}{dy} = (1-2y)(x(\beta W_C + \beta V) + z\beta S_C - \beta V + (1-x)zL_M) \tag{10}$$

Assume $W(x) = x(\beta W_C + \beta V) + z\beta S_C - \beta V + (1-x)zL_M$, when $x_0 = \frac{\beta V - z\beta S_C - zL_M}{\beta W_C + \beta V - zL_M}$, proposition 2 is established.

Proposition 2: When $0 < x < x_0 < 1$, the evolutionary stable point state of y tends to 0, the stable strategy of the demand company is general cooperation. When $0 < x_0 < x < 1$, the evolutionary stable state of y tends to 1, the stable strategy of the demand company is collaborative cooperation.

Proof: $W(x)$ increases monotonically over the interval. When $x = x_0$, $W(x) = 0$, $F(y) = 0$, and $F_y'(y) = 0$, so $y \in [0,1]$ is in the stable state, and there is no fixed stable strategy in the interval; When $0 < x < x_0 < 1$, $W(x) < 0$, $F_y(0) = 0$, and $F_y'(0) < 0$, so $y = 0$ has stability; When $0 < x_0 < x < 1$, $W(x) > 0$, $F_y(1) = 0$, and $F_y'(1) < 0$, so $y = 1$ has stability.

The phase diagram of the demand company strategy choice is obtained according to the above analysis, as illustrated in Fig. 3.

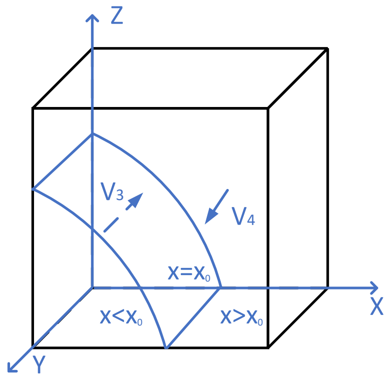

Fig. 3 Phase diagram of the demand company strategy choice

Inference 2: When the values of W_C, S_C and L_M raise while other parameters keep constant, the demand company will approach collaborative cooperation strategy. In common, when the value of V raises, the demand company will approach general cooperation strategy.

Proof: Since $x_0 = \frac{\beta V - z\beta S_C - zL_M}{\beta W_C + \beta V - zL_M}$, the value of x_0 will fall with the raising of the values of S_C, W_C and L_M, and the volume of V_4 changes inversely with the value of x_0. The enlarge of V_4 shows that the demand company is more inclined to the collaborative cooperation strategy. The value of x_0 will raise with the raising of the value of V, and the volume of V_3 changes the same as the value of x_0, The enlarge of V_3 shows that the demand company is more inclined to the general cooperation strategy. It presents that the proportion of demand company implementing collaborative cooperation is directly proportional to the subsidies for the collaborative cooperation of the demand company, the value-added profits of the demand company when the two sides collaborative cooperate, and the speculative penalty for the general cooperation of the manufacturing company, inversely proportional to the loss of information leakage of the collaborative cooperation of the demand company.

Replication dynamic stability analysis of the cloud platform strategy

The expected payoff of cloud platform carrying out supervision strategy is set as U_{31}, and the expected payoff of cloud platform carrying out non-supervision strategy is set as U_{32}, which are defined as follows:

$$\begin{aligned} U_{31} = xy(E - C_P + S_P + F_P - \alpha S_M - \beta S_C) + x(1-y)(E - C_P + S_P - \alpha S_M) \\ + (1-x)y(E - C_P + S_P - \beta S_C) + (1-x)(1-y)(E - C_P + S_P) \end{aligned} \quad (11)$$

$$U_{32} = xy(E + F_P) + x(1-y)E + (1-x)yE + (1-x)(1-y)E \quad (12)$$

$$U_3 = zU_{31} + (1-z)U_{32} \quad (13)$$

The replication dynamic equation of cloud platform strategy is as follows:

$$F(z) = \frac{dz}{dt} = z(U_{31} - 3) = z(1-z)(U_{31} - U_{32}) = z(1-z)(S_P - y\beta S_C - x\alpha S_M - C_P) \quad (14)$$

$$F'(z) = \frac{dF(z)}{dz} = (1-2z)(S_P - y\beta S_C - x\alpha S_M - C_P) \quad (15)$$

Assume $W(y) = S_P - y\beta S_C - x\alpha S_M - C_P$, when $y_0 = \frac{S_P - x\alpha S_M - C_P}{\beta S_C}$, proposition 3 is established.

Proposition 3: when $0 < y < y_0 < 1$, the evolutionary stable state of z tends to 1, the stable strategy of the cloud platform is supervision. When $0 < y_0 < y < 1$, the evolutionary stable state of z tends to 0, the stable strategy of the cloud platform is non-supervision.

Proof: $W(y)$ decreases monotonically over the interval. When $y = y_0$, $W(y) = 0$, $F(z) = 0$, and $F_z'(z) = 0$, so $z \in [0,1]$ is in the stable state, and there is no fixed stable strategy in the interval; When $0 < y < y_0 < 1$, $W(y) > 0$, $F_z(1) = 0$, and $F_z'(1) < 0$, so $z = 1$ has stability; When $0 < y_0 < y < 1$, $W(y) < 0$, $F_z(0) = 0$, and $F_z'(0) < 0$, so $z = 0$ has stability.

The phase diagram of the cloud platform strategy choice is obtained according to the above analysis, as illustrated in Fig. 4.

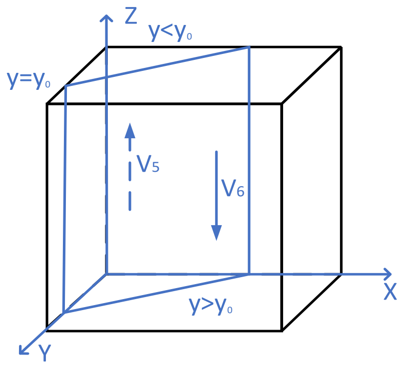

Fig. 4 Phase diagram of the cloud platform strategy choice

Inference 3: When the value of S_P raises while other parameters keep constant, the cloud platform will approach supervision strategy. In common, when the values of α, β, S_C, S_M and C_P raise, the cloud platform will approach non-supervision strategy.

Proof: Since $y_0 = \frac{S_P - x\alpha S_M - C_P}{\beta S_C}$, the value of y_0 will raise with the raising of the value of S_P, and the volume of V_5 changes the same as the value of y_0. The enlarge of V_5 shows that the cloud platform is more inclined to supervision strategy. The value of y_0 will fall with the raising of the values of α, β, S_C, S_M and C_P, and the volume of V_6 changes inversely with the value of y_0. The enlarge of V_6 shows that the cloud platform is more inclined to non-supervision strategy increases. It presents that the proportion of cloud platform implementing collaborative cooperation is directly proportional to the government subsidy for the supervision of the cloud platform, and inversely proportional to the degree of collaborative effort of the manufacturing company and the demand company, the subsidies provided by the cloud platform for the collaborative cooperation of the manufacturing company and the demand company and the regulatory cost of the cloud platform.

4. Results and discussion

4.1 Strategy stability analysis of the strategies in evolutionary games

In order to analyze the asymptotic stability of the strategies in evolutionary games, according to Lyapunov method, the eigenvalues of the Jacobian matrix are determined based on the replication dynamic equation of the subject. When the eigenvalues are negative, the equilibrium point is asymptotically stable. The Jacobian matrix of the replication dynamic system is expressed as Eq. 16. The eigenvalues of Jacobian matrix are indicated in Appendix A.

$$J = \begin{bmatrix} F_x'(x) & F_y'(x) & F_z'(x) \\ F_x'(y) & F_y'(y) & F_z'(y) \\ F_x'(z) & F_y'(z) & F_z'(z) \end{bmatrix} \tag{16}$$

The system equilibrium points of three-party evolutionary game are inditacted in Table 2.

Table 2 Strategy stability analysis of evolutionary game system

Equilibrium point	Eigenvalue	Symbol	Stability
E1(0,0,0)	$\alpha T, -\beta V, S_P - C_P$	(+, -, X)	unstable
E2(0,0,1)	$\alpha S_M + \alpha T, \beta S_C - \beta V + L_M, -(S_P - C_P)$	(+, X, X)	unstable
E3(0,1,0)	$\alpha W_M - \beta Q, \beta V, S_P - \beta S_C - C_P$	(X, +, X)	unstable
E4(1,0,0)	$-\alpha T, \beta W_C, S_P - \alpha S_M - C_P$	(-, +, X)	unstable
E5(0,1,1)	$\alpha W_M + \alpha S_M + L_M - \beta Q, -(\beta S_C + L_M - \beta V), -(S_P - \beta S_C - C_P)$	(X, X, X)	ESS in condition I
E6(1,0,1)	$-(\alpha S_M + \alpha T), \beta W_C + \beta S_C, -(S_P - \alpha S_M - C_P)$	(-, +, X)	unstable
E7(1,1,0)	$-(\alpha W_M - \beta Q), -\beta W_C, S_P - \beta S_C - \alpha S_M - C_P$	(X, -, X)	ESS in condition III
E8(1,1,1)	$-(\alpha W_M - \beta Q + \alpha S_M + L_M), -(\beta W_C + \beta S_C), -(S_P - \beta S_C - \alpha S_M - C_P)$	(X, -, X)	ESS in condition II

Note: X denotes uncertain of symbol, ESS denotes the evolutionary stable strategy.
Condition I：$\alpha(S_M + W_M) < \beta Q - L_M, \beta S_C + L_M > \beta V, S_P > \beta S_C + C_P$
Condition II：$\alpha(S_M + W_M) > \beta Q - L_M, S_P > \beta S_C + \alpha S_M + C_P$
Condition III：$\alpha W_M > \beta Q, S_P < \beta S_C + \alpha S_M + C_P$

When $\alpha(S_M + W_M) < \beta Q - L_M, \beta S_C + L_M > \beta V, S_P > \beta S_C + C_P$, if the difference between the speculative profit and the speculative penalty when the manufacturing company chooses general cooperation is more than the sum of the additional profit of the collaborative cooperation and the cooperative subsidy of the cloud platform, then the manufacturing company tends to choose the general cooperation strategy. When the sum of the platform subsidy for the demand company and the speculative punishment of the manufacturing company is more than the information leakage risk loss of the demand company, then the demand company tends to choose the collaborative cooperation strategy. If the government's subsidy for cloud platform supervision is more than the sum of the cloud platform regulatory cost and the subsidy for the demand company, the cloud platform tends to choose supervision strategy. As a result, the stable evolution strategy of the three-party subjects is E5(general cooperation, collaborative cooperation, supervision).

When $\alpha(S_M + W_M) > \beta Q - L_M$ and $S_P > \beta S_C + \alpha S_M + C_P$, on the basis of condition I, if the sum of the synergistic subsidy and synergistic benefit of the manufacturing company is more than the difference between the speculative profit and the speculative penalty of the manufacturing company, the manufacturing company tends to choose the collaborative cooperation. If the government's subsidies for cloud platform supervision are still more than the sum of the regulatory costs of cloud platform and the subsidies for manufacturing company and demand company, the cloud platform will continue to choose the supervision strategy. When the manufacturing company chooses collaborative collaboration and the cloud platform chooses supervision, the value-added profits of the demand company's collaborative cooperation are greater, so the collaborative cooperation strategies are chosen. Therefore, the stable evolution strategy of the three-party subjects is E8 (collaborative cooperation, collaborative cooperation, supervision).

When $\alpha W_M > \beta Q$, and $S_P < \beta S_C + \alpha S_M + C_P$, on the basis of condition II, if the manufacturing company and the demand company improve their collaborative efforts, the sum of the regulatory cost and the subsidies for the manufacturing company and demand company of the cloud platform is more than the government's subsidies for cloud platform supervision, the cloud platform tends to non-supervision strategy. If the value-added profits of the manufacturing company's collaborative cooperation are more than the profits of the manufacturing company's speculative behavior, the value-added profits of the demand company are larger, and the manufacturing company and the demand company also tend to adopt the collaborative cooperation strategy. Therefore, the stable evolution strategy of the three-party subjects is E7(collaborative cooperation, collaborative cooperation, non-supervision).

4.2 Numerical simulation analysis

To test strategic stability of three-party evolutionary game, the model parameters are assigned values based on the real situation, and MATLAB2021a is used for numerical simulation.

Equilibrium steady state of the model

When condition I is met, the model parameters are assigned as followings: C_P = 30, S_P = 50, W_M = 30, S_M = 20, α = 0.1, Q = 25, T = 15, L_M = 5, W_C = 30, S_C = 20, β = 0.5, V = 26; when condition II is met, S_M = 40, α = 0.2, and other parameters are the same with condition I; when condition III is met, α = 0.6, β = 0.6, S_C = 40, and other parameters are the same with condition II. The evolution results of the data simulation over time are shown in Fig. 5.

According to Fig. 5, in the early stage of the establishment of the cloud platform, the profits of collaborative cooperation are less than the speculative profits of general cooperation for the manufacturing company. Therefore, driven by the interests, the manufacturing company will gradually stabilize in the general cooperation strategy. When the manufacturing company generally cooperates, if the government's supervision subsidy is more than the supervision investment for the cloud platform, the cloud platform will stabilize in the supervision strategy. So the evolutionary game system will be stable in the strategy combination E5 (0,1,1). As the supervision mechanism of the cloud platform is gradually established, with the increase of subsidies obtained by manufacturing company for collaborative cooperation, the level of collaborative effort of company will increase, and manufacturing company will be stable in collaborative cooperation strategy, so the evolutionary game system is stable in the strategy combination E8 (1,1,1). In the improvement stage of cloud platform, with the increase of collaborative subsidies for the demand company, the degree of collaborative effort between manufacturing company and demand company is further increased, the proportion of cloud platform supervision is reduced, and finally stabilized in the non-supervision strategy, so the evolutionary game system will be stable in the strategy combination E7 (1,1,0). This means that as long as both the manufacturing company and the demand company have a long-term development concept and can recognize the benefits brought by collaboration, the cloud platform can make the two parties collaborate without supervision.

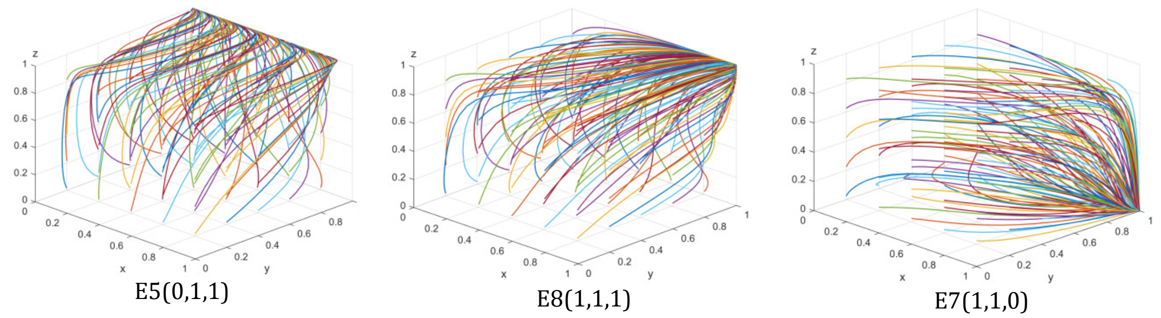

Fig. 5 System evolution stability at equilibrium points

The influence of the subsidies and the value-added profits for the collaborative cooperation of the manufacturing company

On the basis of condition I, if S_M = {20, 30, 50, 60}, and the simulation results of three-party evolutionary game are indicated in Fig. 6a. If W_M = {30, 45, 60, 80}, the simulation results of the three-party evolutionary game are indicated in Fig. 6b.

According to Fig. 6a, with the raising of the subsidy of cloud platform for manufacturing company, the proportion of the manufacturing company to choose collaborative cooperation increases. The strategy of the manufacturing company will shift from general cooperation to collaborative cooperation, and the critical value of changing the strategy is S_M = 45. Due to the change of manufacturing company's strategy, the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8 (collaborative cooperation, collaborative cooperation, supervision). According to Fig. 6b, with the increase of the value-added profits of manufacturing company in collaborative cooperation, the proportion of manufacturing company choosing collaborative cooperation increases. The strategy of the manufacturing company will shift from general cooperation to collaborative cooperation, and the critical value for changing the strategy is W_M = 55. Due to the change of manufacturing company's strategy, the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8 (collaborative cooperation, collaborative cooperation, supervision).

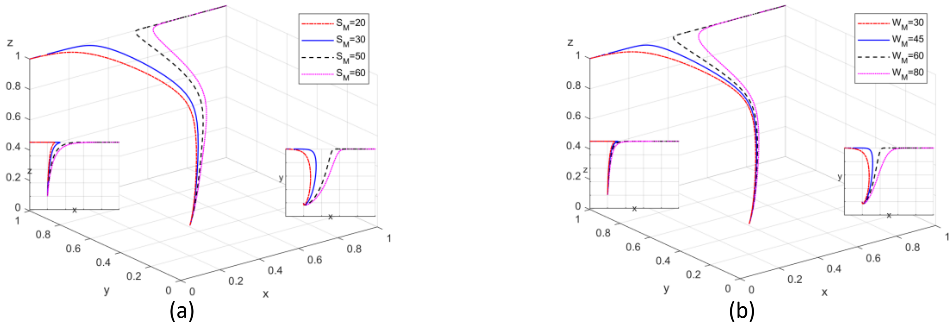

Fig. 6 Influence of the subsidies and the value-added profits for the collaborative cooperation of manufacturing company on strategy evolution

The influence of the degree of collaborative effort of the manufacturing company and the demand company

On the basis of condition I, if $\alpha = \{0.10, 0.13, 0.20, 0.35, 0.55, 0.65\}$, and the simulation results of three-party evolutionary game are indicated in Fig. 7a. If $\beta = \{0.2, 0.3, 0.41, 0.5, 0.85, 0.95\}$, the simulation results of three-party evolutionary game are indicated in Fig. 7b.

According to Fig. 7a, with the increase of the collaborative efforts of the manufacturing company, three evolutionary stable states may appear in the system. The critical value of changing the strategy of manufacturing company is $\alpha_1 = 0.15$, and the critical value of changing the strategy of the cloud platform is $\alpha_2 = 0.5$. When $0.15 < \alpha < 0.5$, the proportion of the manufacturing company choosing collaborative cooperation increases with the increase of α. The strategy of the manufacturing company will shift from general cooperation to collaborative cooperation, the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8(collaborative cooperation, collaborative cooperation, supervision). When $\alpha > 0.5$, the proportion of the cloud platform choosing supervision decreases with the increase of α. The strategy of the cloud platform will change from supervision to non-supervision, and the evolution strategy combination will change from E8(collaborative cooperation, collaborative cooperation, supervision) to E7 (collaborative cooperation, collaborative cooperation, non-supervision).

According to Fig. 7b, with the change of the degree of collaborative effort of the demand company, two evolutionary stable states and an unstable state may appear in the system. The critical value of changing the strategy of manufacturing company is $\beta_1 = 0.4$, and the critical value of changing the strategy of demand company is $\beta_2 = 0.83$. When $0.4 < \beta < 0.83$, the proportion of manufacturing company choosing collaborative cooperation increases with the increase of β. The strategy of the manufacturing company will change from general cooperation to collaborative cooperation, and the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8 (collaborative cooperation, collaborative cooperation, supervision). When $\beta > 0.83$, the proportion of the demand company will decrease with the increase of β. The strategy of the demand company will tend to the unstable state, and the evolution strategy combination will be also in an unstable state.

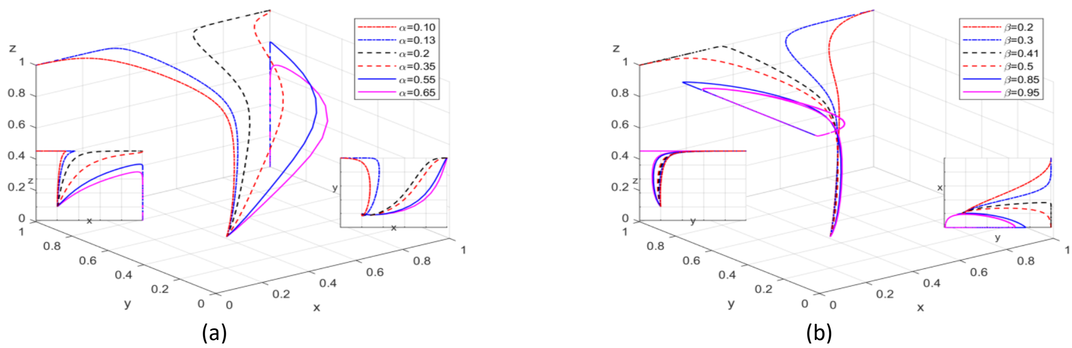

Fig. 7 The influence of the degree of collaborative effort of the manufacturing company and demand company on strategy evolution

The influence of the speculative penalty and profit of the general cooperation of the manufacturing company

On the basis of condition I, if L_M = {5, 7, 10, 15}, and the simulation results of three-party evolutionary game are indicated in Fig. 8a. If Q = {10, 15, 21, 25}, the simulation results of three-party evolutionary game are indicated in Fig. 8b.

According to Fig. 8a, with the increase of the speculative penalty of manufacturing company, the proportion of manufacturing company to choose collaborative cooperation increases. The strategy of the manufacturing company will shift from general cooperation to collaborative cooperation, and the critical value of changing the strategy is L_M = 7.5. Due to the change of manufacturing company's strategy, the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8 (collaborative cooperation, collaborative cooperation, supervision). According to Fig. 8b, with the decrease of the speculative profits of manufacturing company, the proportion of manufacturing company to choose collaborative cooperation increases. The strategy of the manufacturing company will shift from general cooperation to collaborative cooperation, and the critical value of changing the strategy is Q = 20. Due to the change of manufacturing company's strategy, the evolution strategy combination will change from E5 (general cooperation, collaborative cooperation, supervision) to E8 (collaborative cooperation, collaborative cooperation, supervision).

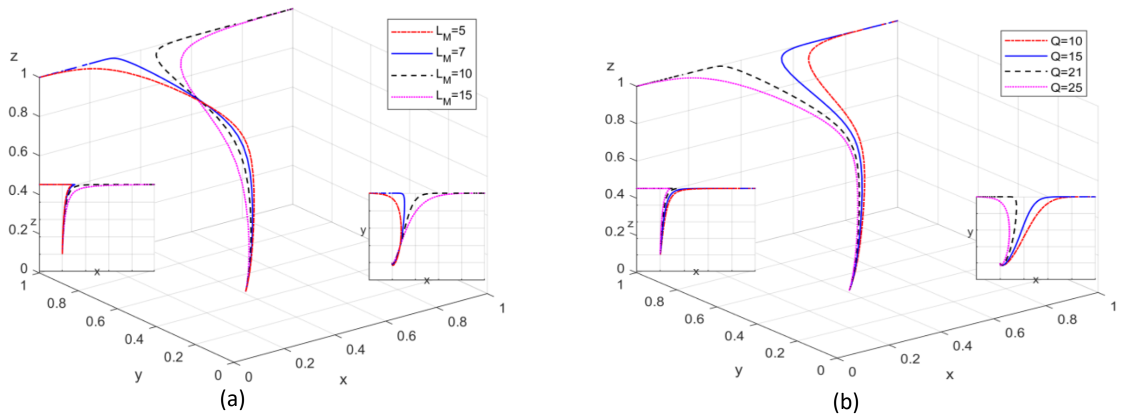

Fig. 8 The influence of the speculative penalty and profit of the general cooperation of the manufacturing company on strategy evolution

The influence of the loss of information leakage and the subsidies for the collaborative cooperation of the demand company

On the basis of condition II, if V = {15, 26, 40, 60}, and the simulation results of three-party evolutionary game are indicated in Fig. 9a. If S_C = {10, 20, 30, 35}, the simulation results of three-party evolutionary game are indicated in Fig. 9b.

According to Fig. 9a, with the increase of the information leakage loss of demand company, the proportion of manufacturing company to choose collaborative cooperation increases, the proportion of cloud platform to choose supervision increases, and the proportion of demand company to choose collaborative cooperation decreases. The evolution strategy combination will tend to E8 (collaborative cooperation, collaborative cooperation, supervision). According to Fig. 9b, the strategies of the cloud platform and the manufacturing company will be affected by the collaborative subsidies of the demand company. The critical value of changing the strategy is S_C = 24. When $S_C < 24$, with the increase of collaborative subsidies of demand company, the proportion of manufacturing company and demand company to choose collaborative cooperation increases, and the proportion of cloud platform to choose supervision increases. The evolution strategy combination will tend to E8 (collaborative cooperation, collaborative cooperation, supervision). When $S_C > 24$, with the increase of collaborative subsidies of demand company, the proportion of cloud platform supervision and the manufacturing company collaborative cooperation decreases, the cloud platform and the manufacturing company cannot evolve to a stable state, and the system cannot evolve to a stable state.

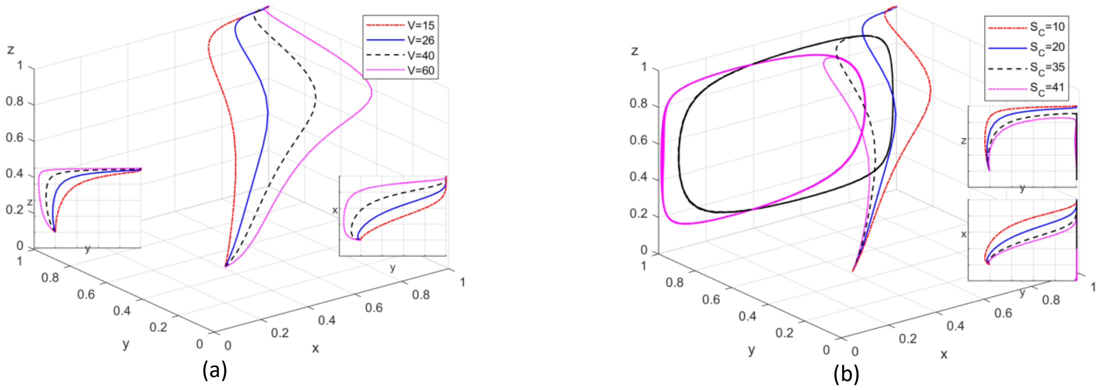

Fig. 9 The influence of the loss of information leakage and the subsidies for the collaborative cooperation of the demand company on strategy evolution

The influence of the government subsidy for the cloud platform supervision

On the basis of condition III, if S_P = {50, 70, 80, 90}, and the simulation results of three-party evolutionary game are indicated in Fig. 10.

According to Fig. 10, when the government subsidies for cloud platform supervision decrease, the proportion of the platform to choose supervising decreases. The strategy of the cloud platform will shift from supervision to non-supervision, and the critical value of changing the strategy is S_P = 78. Due to the change of cloud platform's strategy, the evolution strategy combination will change from E8 (collaborative cooperation, collaborative cooperation, supervision) to E7 (collaborative cooperation, collaborative cooperation, non-supervision).

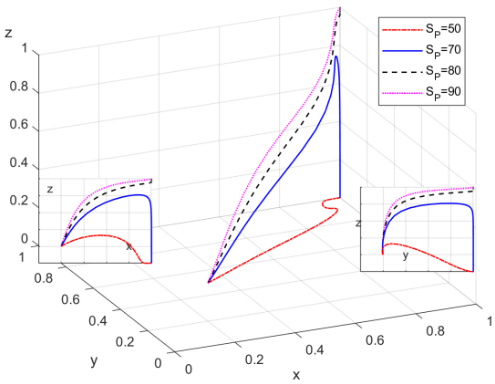

Fig. 10 The influence of the government subsidy for the cloud platform supervision on strategy evolution

5. Conclusion

This study constructed a three-party collaborative evolutionary game model with the cloud platform, the manufacturing company and the demand company, and the main conclusions are as follows:

- The strategy combination evolution of company collaborative cooperation in the cloud platform environment is staged. In the initial stage of cloud platform, since the manufacturing company can obtain free-riding profits in the process of cooperation, it tends to general cooperation strategy. However, with the support of platform subsidies, reward and punishment, the demand company can obtain better profits by sharing information and inclined to choose collaborative cooperation, and the platform tends to supervision due to government subsidies, so the system will be stable in the strategy combination of E5 (general cooperation, collaborative cooperation, supervision). With the increase of penalty costs and synergy profits of manufacturing company, the manufacturing company also tends to choose collaborative cooperation. Therefore, in the mid stage of cloud platform, the system will be stable in the strategy combination of E8(collaborative cooperation, collaborative cooperation, supervision) depending on the supervision measures of the platform. When the cloud platform runs smoothly, manufacturing company and demand company can take advantage of the platform to integrate resources, the degree of company collaborative effort gradually increases, and the platform tends to implement non-supervision strategy. The platform has reached mature stage, in which the spontaneous collaboration of manufacturing company and demand company can form the effective operation of the cloud platform.

- The collaborative subsidy to manufacturing company, the value-added profit of the manufacturing company, the degree of collaborative effort of the manufacturing company and the demand company, and the penalty and profits of the manufacturing company's speculation are the important factors that affect the cooperation strategy of the manufacturing company. By appropriately increasing the subsidy to manufacturing company, the value-added profit of manufacturing company, the penalty for free-riding speculation of manufacturing company, and reducing the speculative profit of manufacturing company, and promoting the degree of collaborative effort of manufacturing company, the strategy of the manufacturing company will be changed from general cooperation to collaborative cooperation.
- The collaborative subsidy to demand company, the degree of collaborative efforts of demand company, the loss of information leakage of demand company, and the speculation penalty of manufacturing company are important factors that affect the cooperation strategy of demand company. With the increase of collaborative subsidy of demand company, the appropriate improvement of the level of collaborative efforts of demand company, the reduction of information leakage loss of demand company and the increase of speculative penalty of manufacturing company, the proportion of demand company to collaborative cooperation increases, and demand company gradually stabilizes in collaborative cooperation strategy.
- The degree of collaborative efforts of manufacturing company and demand company and the government's subsidy for cloud platform supervision are important factors that affect the platform supervision strategy. When the degrees of collaborative effort of manufacturing company and demand company are low, raising the government's regulatory subsidy for cloud platform can gradually increase the proportion of cloud platform supervision and cloud platform stabilize in the supervision strategy. However, as the degrees of collaborative efforts of manufacturing company and demand company increase, and the government's subsidy for cloud platform supervision reduces, the strategy of cloud platform can be changed from supervision to non-supervision.

Acknowledgement

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Appendix A

Jacobian matrix of replicated dynamical systems:

$$J=\begin{bmatrix}(1-2x)(y(\alpha W_M-\alpha T-\beta Q)+z\alpha S_M+yzL_M+\alpha T) & x(1-x)(\alpha W_M-\alpha T-\beta Q+zL_M) & x(1-x)(\alpha S_M+yL_M)\\ y(1-y)(\beta W_C+\beta V-zL_M) & (1-2y)(x(\beta W_C+\beta V)+z\beta S_C-\beta V+(1-x)zL_M) & y(1-y)(\beta S_C+(1-x)L_M\\ z(1-z)(-\alpha S_M) & z(1-z)(-\beta S_C) & (1-2z)(S_P-y\beta S_C-x\alpha S_M-C_P)\end{bmatrix}$$