Cooperative Stability Analysis of Industry Clusters Considering the Risk of Information Sharing Based on Evolutionary Game Theory

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Abstract. Information sharing has an important impact on the stability of cooperation in industrial clusters. Considering the risk of information sharing, this paper constructs an evolutionary game model for the synergy relationship between "ordinary enterprises and core enterprises". The stability conditions of the two-party game model are determined by means of Jacobian matrix, and finally the evolutionary path of each player in the game model is verified by using MATLAB. The study shows that the loss of benefits and the cost of active information sharing are the decisive factors in the core enterprises' decision on information sharing strategy, and the evolutionary strategy of ordinary enterprises is influenced by the core enterprises. When the strategy of the core enterprises evolves to "synergy cooperation", the strategy of ordinary enterprises will also evolve to "synergy cooperation". Based on this, while improving the stability of industrial cluster cooperation, information sharing platform should be established to prevent the risk of information sharing, and incentive and constraint mechanism should be established to reduce the cost of information sharing.

Keywords: Industrial clusters · Information sharing · Evolutionary game

1 Introduction

Industrial clusters can promote the specialized division of labor and digital transformation of clusters by rapidly aggregating resources and integrating elements. The report of the Party's 20th "Congress" emphasizes the need to promote the deep integration of the digital economy and the real economy [1]. With the rapid development of the digital economy, digital transformation of industry clusters is an important path to build a strong manufacturing country and promote high-quality industrial development [2]. Different enterprises have heterogeneous resources, so the synergy and cooperation among enterprises can help accelerate the digital transformation of industry clusters. However, the complex and variable structure within industry clusters has led to the co-existence of cooperation and competition among enterprises.

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Therefore, there are risks of cooperation spillover [3], alliance costs [4], inadequate regulation [5] and other risks of information sharing in the process of enterprise cooperation. And the risk of information sharing can interfere with the willingness of enterprises to cooperate with each other, which in turn affects the stability of cooperation among enterprises in industry clusters [6]. Therefore, it is important to study the strengthening of trust mechanisms among cooperative subjects under the influence of information sharing risks to improve the stability of inter-firm cooperation within industry clusters.

Scholars have studied the factors influencing the stability of enterprise cooperation from different perspectives such as transaction cost theory [7] and cultural background [8], but with the advent of the digital economy, the importance of information sharing in enterprise cooperation has become increasingly prominent [9, 10]. Although some studies have shown that information sharing among enterprises is conducive to improving the performance of manufacturing enterprises and industrial clusters [11, 12], there are also numerous studies showing that information sharing can intensify competition among enterprises Strength [13] and bring certain risks [14, 15]. In order to effectively deal with the potential problem of information leakage in a synergy competitive environment, Jung Seung Hwan [16] considered the possibility of leakage in information sharing and constructed a game-theoretic model to study the strategic interaction of enterprises' procurement within the supply chain. Although Jung considered the problem of information leakage in information sharing, the consideration about the disadvantages of information sharing is still not comprehensive.

Even there is a wealth of established research on the stability of industrial clusters, there is not enough research on the stability of industrial clusters considering the risk of information sharing. Based on the risk of information sharing, this paper integrates the theories of industrial clusters, information sharing and evolutionary games with the current status of domestic and international research. Based on this, this paper constructs a game model for the evolution of the synergy relationship between ordinary enterprises and core enterprises, and then determines the stability conditions of the game model between the two parties through the Jacobi matrix. Finally, MATLAB is used to verify the evolutionary paths of each player in the game model and to analyze the impact of changes in the parameters of the model on the choice of competing strategies of the players.

2 Model Construction and Assumptions

2.1 Basic Assumptions

According to their importance to inter-enterprise information sharing, the enterprises that share information are divided into two groups, core enterprises and ordinary enterprises, in the study of enterprise cooperation in industry clusters. This paper assumes that the gains and losses arising from information sharing among enterprises in industry clusters can be quantified and that all parameters are greater than zero.

H1: There are only two game subjects: core enterprises and ordinary enterprises, both of which are finite rational and have incomplete information symmetry, and both of which aim to maximize their own profit.

H2: There are two alternative strategies for both core and ordinary enterprises, namely "synergy" and "non-synergy". The "synergy" strategy of the core enterprises refers to the core enterprises' initiative to share their own information on supply and demand, management and technology with other ordinary enterprises in the industry cluster to promote cooperation, and to take the main task of building a synergy platform. The "non-cooperation" strategy of the core enterprises refers to the negative attitude towards cooperation in order to maintain their advantages in terms of market share, technology and information access. The "synergy cooperation" strategy of ordinary enterprises refers to participating in the synergy cooperation of core enterprises and providing the manufacturing industry cluster with the required information to promote network synergy; and the "non-synergy cooperation" strategy of ordinary enterprises refers to not abiding information sharing rules, stealing or leaking core information from other companies, and adopting a negative response to synergy.

H3: Assumptions related to ordinary enterprises. The basic benefit of information sharing for ordinary enterprises is R_1, where the cost of positive information sharing for ordinary enterprises is C_1. The cost of negative information sharing for ordinary enterprises is C_2, which is relatively low, and there is a quantitative relationship $0 > C_1 > C_2 > 0$. In "synergy" strategy of the core enterprises, the additional benefit of positive information sharing by ordinary enterprises is W_1, and the loss of negative information sharing by ordinary enterprises is F_1. The loss to the core enterprise as a result of an ordinary enterprise breaking the rules and sharing negative information is P.

H4: Core enterprise related assumptions. The basic benefit that core enterprises can obtain from information sharing is R_2. The cost that core enterprises invest in information sharing is C_3 (including human and material resources and capital investment for building information sharing platforms). If the core enterprise chooses the "no-cooperation" strategy, the corresponding benefit loss is T.

H5: At the initial moment, assume that the probability of an ordinary enterprise adopting a "synergy" strategy is x and the probability of adopting a "non-synergy" strategy is $1 - x$; the probability of a core enterprise adopting a "synergy" strategy is y and the probability of adopting a "non-synergy" strategy is $1 - y$. $x, y \in [0, 1]$, and x, y are functions of time t.

Based on the above assumptions, the relevant parameters in the game model between ordinary enterprises and core enterprises are summarized to obtain Table 1.

2.2 Evolutionary Game Model Construction

Based on the assumptions from H1 to H5 and the parameter settings in Table 1, the payoff matrix for the game between ordinary and core enterprises is established and the payoff matrix is shown in Table 2:

Table 1. Captions should be placed above the tables

Parameters	Meaning
R_1	Underlying benefits for ordinary enterprises in information sharing
C_1	Costs for the ordinary enterprises adopting a "synergy" strategy
C_2	Costs for the ordinary enterprises with a "no synergy" strategy
W_1	Additional benefits for ordinary enterprises when both ordinary enterprises and core enterprises engage in active information sharing
F_1	Losses due to penalties for ordinary enterprises that adopt a "no synergy" strategy
R_2	Underlying benefits available to core enterprises in information sharing
C_3	Costs to the core enterprises of adopting a "synergy" strategy
L	Additional benefits to the core enterprises when both ordinary and core enterprises are actively sharing information
T	Core enterprises choose a "no synergy" strategy, resulting in a corresponding loss of benefits
P	Losses to core enterprises from negative information sharing by ordinary enterprises in breach of rules
x	Probability of the ordinary enterprises adopting a "synergy" strategy
y	Probability of core enterprises adopting a "synergy" strategy

Table 2. Ordinary and core enterprise game payoff matrix

		Core Enterprises	
		synergy y	No synergy $1 - y$
Ordinary Enterprises	Synergy x	$R_1 - C_1 + W_1$	$R_1 - C_1$
		$R_2 - C_3 + L$	$R_2 - T$
	No synergy $1 - x$	$R_1 - C_2 - F_1$	$R_1 - C_2$
		$R_2 - C_3 - P$	$R_2 - P - T$

3 Model Analysis

3.1 Equilibrium Point Solving

Let the average enterprise's payoff when it adopts a "synergy" strategy be M1, the payoff when it adopts a "non-synergy" strategy be M2, and the average expected payoff be $\overline{M}$. From the game income matrix of core enterprise and ordinary enterprise, it can be obtained:

The benefits to the average enterprise of adopting a 'synergy' strategy are M1 and can be expressed as:

$$M_1 = y(R_1 - C_1 + W_1) + (1\text{-}y)(R_1 - C_1) \quad (1)$$

The benefit to the average enterprise of adopting a 'no-cooperation' strategy is M2 and can be expressed as:

$$M_2 = y(R_1 - C_2 - F_1) + (1\text{-}y)(R_1 - C_2) \quad (2)$$

The average expected benefits of information sharing for an average business $\overline{M}$ can be expressed as:

$$\overline{M} = xM_1 + (1\text{-}x)M_2 \quad (3)$$

Therefore, the replication dynamics equation for the average enterprise choosing a "synergy" strategy is:

$$F(x)=dx/dt=x(M_1\text{-}M) = x(1\text{-}x)(M_1 - M_2) = x(1\text{-}x)[y(W_1+F_1)+C_2 - C_1] \quad (4)$$

Let the payoff of the core enterprise when it adopts the "synergy" strategy be N1, the payoff of the "non-synergy" strategy be N2, and the average expected payoff be $\overline{N}$, and the payoff matrix of the game between the core enterprise and the average enterprise will be:

$$N_1 = x(R_2 - C_3 + L) + (1\text{-}x)(R_2 - C_3\text{-}P) \quad (5)$$

The benefits of a 'no-cooperation' strategy for core enterprises are N2 and can be expressed as:

$$N_2 = x(R_2\text{-}T) + (1\text{-}x)(R_2\text{-}P\text{-}T) \quad (6)$$

The average expected benefits of information sharing among core enterprises $\overline{N}$ can be expressed as:

$$\overline{N} = yN_1 + (1\text{-}y)N_2 \quad (7)$$

Therefore, the replication dynamics equation for a core enterprise choosing a "synergy" strategy is:

$$F(y)=dy/dt=y(N_1\text{-}N) = y(1\text{-}y)(N_1 - N_2) = y(1\text{-}y)(xL - C_3 + T) \quad (8)$$

Combining Eqs. (4) and (8) yields

$$\begin{cases} F(x) = x(1-x)[y(W_1 + F_1) + C_2 - C_1] \\ F(y) = y(1-y)(xL - C_3 + T) \end{cases} \quad (9)$$

Let $\begin{cases} F(x) = \frac{dx}{dt} = 0 \\ F(y) = \frac{dy}{dt} = 0 \end{cases}$, yield $\begin{cases} x_1 = 0 \\ y_1 = 0 \end{cases}$, $\begin{cases} x_2 = 1 \\ y_2 = 0 \end{cases}$, $\begin{cases} x_3 = 0 \\ y_3 = 1 \end{cases}$, $\begin{cases} x_4 = 1 \\ y_4 = 1 \end{cases}$, $\begin{cases} x_5 = \frac{C_3 - T}{L} \\ y_5 = \frac{C_1 - C_2}{W_1 + F_1} \end{cases}$

Table 3. Evolutionary equilibrium points corresponding to the strategies of the game subjects

Balancing point	Balanced point strategy
S1 (0, 0)	Ordinary enterprises adopt a non-synergy strategy and core enterprises adopt a non-synergy strategy
S2 (1, 0)	Ordinary enterprises adopt a synergy strategy, core enterprises adopt a non-synergy strategy
S3 (0, 1)	Ordinary enterprises adopt a non- synergy strategy, core enterprises adopt a synergy strategy
S4 (1, 1)	Ordinary enterprises adopt a synergy strategy, core enterprises adopt a synergy strategy
S5 (x5, y5)	The strategies adopted by both ordinary and core enterprises fall between synergistic and non-synergistic cooperation

Therefore, there are five evolutionary equilibrium points in the game system between ordinary enterprises and core enterprises, which are set as S 1(0, 0), S 2(1, 0), S 3(0, 1), S 4(1, 1) and $S_5(\frac{C_3-T}{L}, \frac{C_1-C_2}{W_1+F_1})$ respectively. The evolutionary equilibrium points correspond to the strategies of the game subjects as shown in Table 3.

3.2 Equilibrium Point Stability Analysis

To analyze the stability of the game equilibrium point, Friedman builds a Jacobi matrix from the replicated dynamic equations of the game subject, and solves the determinant of the matrix by Jacobi to obtain the value of the determinant (det J) and the trace of the matrix (tr J), which is used as the basis for determining whether the game strategy at the equilibrium point is a stable point, when det J > 0 and tr J < 0, the strategy corresponding to the game equilibrium point is an evolutionary stable point strategy (ESS).

S1 to S5 for the 5 equalizations point det J and tr J respectively:

$$S_1(0,0):\begin{cases}\det(J)=(C2-C1)(T-C3)\\ tr(J)=(C2-C1)+(T-C3)\end{cases}\tag{10}$$

$$S_2(1,0):\begin{cases}\det(J)=(C1-C2)(L+T-C3)\\ tr(J)=(C1-C2)+(L+T-C3)\end{cases}\tag{11}$$

$$S_3(0,1):\begin{cases}\det(J)=(W1+F1+C2-C1)(C3-T)\\ tr(J)=(W1+F1+C2-C1)+(C3-T)\end{cases}\tag{12}$$

$$S_4(1,1):\begin{cases}\det(J)=(-W1-F1-C2+C1)(-L+C3-T)\\ tr(J)=(-W1-F1-C2+C1)+(-L+C3-T)\end{cases}\tag{13}$$

$$S_5(\frac{C3-T}{L},\frac{C1-C2}{W1+F1}):\begin{cases}\det(J)=\frac{(C3-T)(L+T-C3)(C1-C2)(C1-C2-W1-F1)}{L(W1+F1)}\\ tr(J)=0\end{cases}\tag{14}$$

The stability analysis of the equilibrium point of the game is shown in Table 4.

Table 4. Stability analysis of the equilibrium point of the game

	Conditions	Balancing point	Det J	Tr J	Results
Scenario1	$T - C_3 > 0$ $L + T - C_3 > 0$ $W_1 + F_1 + C_2 - C_1 > 0$	S_1	−	Q	Saddle Point
		S_2	+	+	Unstable
		S_3	−	Q	Saddle Point
		S_4	+	−	Stable
Scenario2	$T - C_3 > 0$ $L + T - C_3 > 0$ $W_1 + F_1 + C_2 - C_1 < 0$	S_1	−	Q	Saddle Point
		S_2	+	+	Unstable
		S_3	−	Q	Saddle Point
		S_4	−	Q	Saddle Point
Scenario3	$T - C_3 < 0$ $L + T - C_3 > 0$ $W_1 + F_1 + C_2 - C_1 > 0$	S_1	+	−	Stability (ESS)
		S_2	+	+	Unstable
		S_3	+	+	Unstable
		S_4	+	−	Stability (ESS)
Scenario4	$T - C_3 < 0$ $L + T - C_3 < 0$ $W_1 + F_1 + C_2 - C_1 > 0$	S_1	+	−	Stability (ESS)
		S_2	−	Q	Saddle Point
		S_3	+	+	Unstable
		S_4	−	Q	Saddle Point
Scenario5	$T - C_3 < 0$ $L + T - C_3 > 0$ $W_1 + F_1 + C_2 - C_1 < 0$	S_1	+	−	Stability (ESS)
		S_2	+	+	Unstable
		S_3	−	Q	Saddle Point
		S_4	+	−	Stability (ESS)
Scenario6	$T - C_3 < 0$ $L + T - C_3 < 0$ $W_1 + F_1 + C_2 - C_1 < 0$	S_1	+	−	Stability (ESS)
		S_2	−	Q	Saddle Point
		S_3	−	Q	Saddle Point
		S_4	+	+	Unstable

Note: " +" means that the corresponding value is positive, "−" means that the corresponding value is negative, "Q" means that the corresponding value can be positive or negative

4 Numerical Simulation

4.1 Numerical Simulation and Analysis

In this paper, MATLAB is used to simulate the evolutionary stable strategy (ESS) of the inter-enterprise information sharing game model under different scenarios. In the evolutionary game model of corporate information sharing among manufacturing enterprises, W1, F1, T, L and C3 represent the additional benefits of positive information sharing for ordinary enterprises, the losses caused by the penalties for negative information sharing for ordinary enterprises, the core enterprises' negative information. The values of these

Table 5. Initial willingness parameters

Parameters	R_1	R_2	C_1	C_2	C_3	P	L	W_1	F_1	T
Numerical values	1	1	0.6	0.3	0.8	0.5	0.2	0.2	0.2	0.3

parameters vary according to the difference in decision making between core enterprises and ordinary enterprises, and the changes in parameters such as costs and benefits will further influence the behavior of the game players. The initial parameters are shown in Table 5.

At the same time, the stability of scenarios 1, 3, 5 and 6 in Table 4 were verified according to the parameters in Table 6 to obtain the evolutionary paths of the strategies of ordinary and core enterprises under different scenarios (Fig. 1), and the evolutionary paths are shown in Figs. 2, 3, 4 and 5 (In these four figures, the Y-axis represents Core enterprises Synergy probability and the X-axis represents Ordinary enterprises Synergy probability):

Change the initial values of the parameters and in Table 7, respectively.

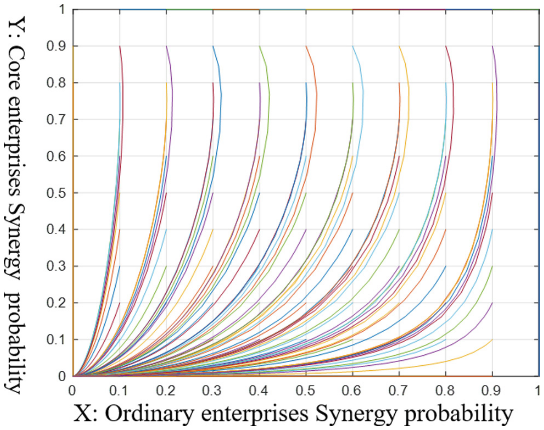


Fig. 1. Evolutionary path for ordinary and core businesses

Table 6. Parameter settings for different scenarios

Parameters	R_1	R_2	C_1	C_2	C_3	P	L	W_1	F_1	T
Scenario 1	1	1	0.6	0.3	0.8	0.2	0.2	0.2	0.2	0.9
Scenario 3	1	1	0.6	0.3	0.8	0.2	0.8	0.2	0.2	0.3
Scenario 5	1	1	0.4	0.3	0.8	0.2	0.8	0.2	0.2	0.3
Scenario 6	1	1	0.4	0.3	0.8	0.2	0.2	0.2	0.2	0.3

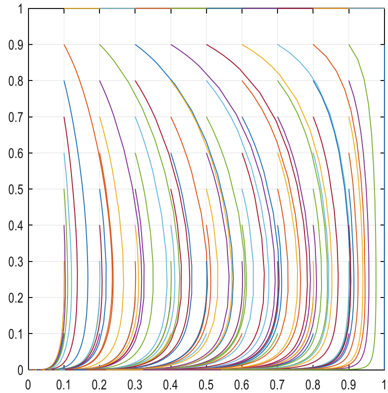


Fig. 2. Scenario 1

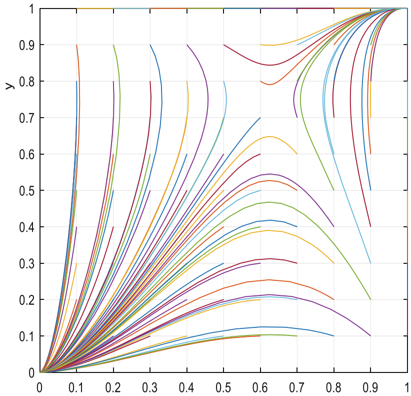


Fig. 3. Scenario 2

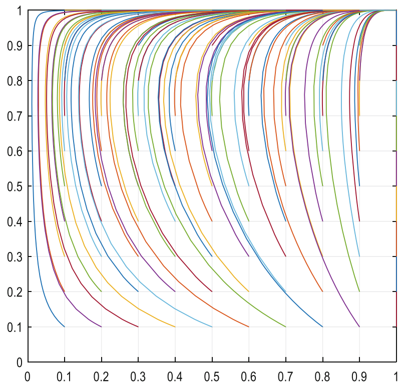


Fig. 4. Scenario 3

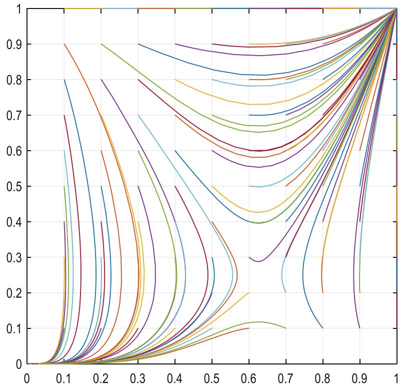


Fig. 5. Scenario 4

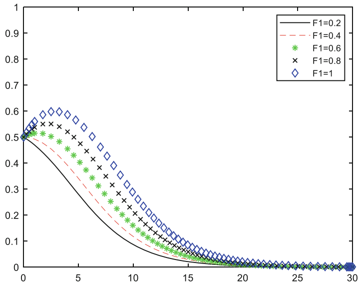
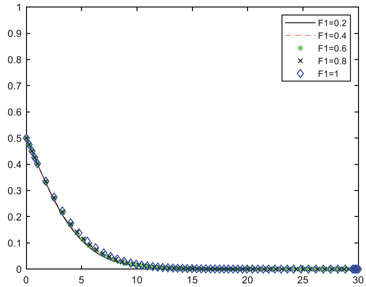
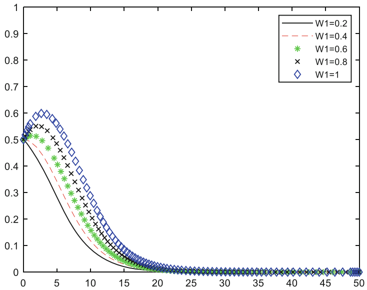
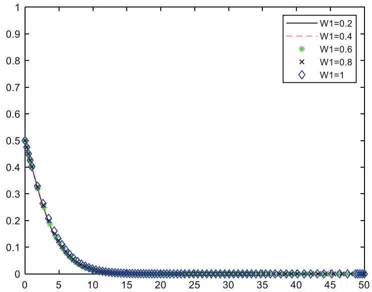
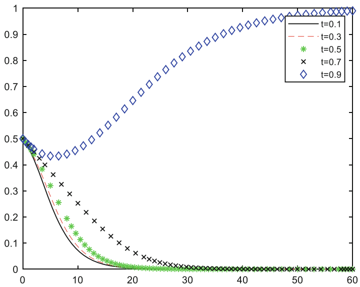
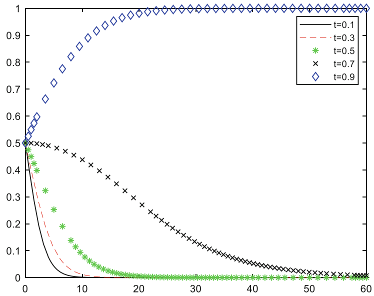
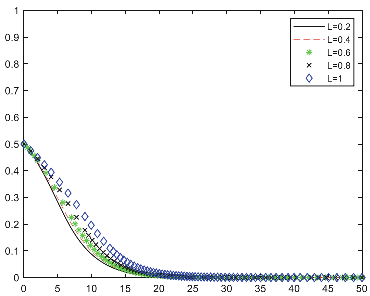
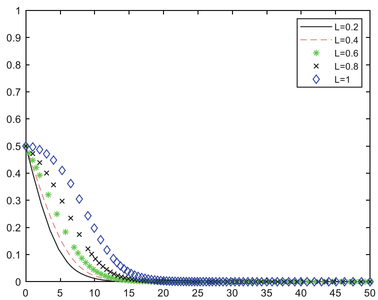
4.2 Analysis of Results

Based on the basic theory of evolutionary games, MATLAB software was used to simulate the evolutionary paths of the strategy choices of ordinary and core enterprises. And simulate the stable evolutionary states of ordinary and core enterprises for different parameter changes, with the following conclusions:

Impacts of parameter changes on core enterprises: Either of the parameters of benefit loss (T) and cost (C_3) is a key decision parameter for core enterprises when making decisions. If the benefit loss (T) from negative information sharing is high for core enterprises or the cost of positive information sharing (C_3) is low for core enterprises, core enterprises will choose the "synergy cooperation" strategy. A change in the additional benefit (L) of positive information sharing is not the only basis for a core enterprise's decision, but an increase in the benefit can slow down the core enterprise's tendency to evolve towards 0. Changing the penalty for negative information sharing (W_1) and the benefit when sharing positive information (F_1) does not change the core enterprise's strategy choice.

Impacts of parameter changes on the ordinary enterprises: The choice of behavioral strategy of the ordinary enterprises is influenced not only by the additional benefits of positive information sharing (W_1) and the losses of the enterprises from penalties for negative information sharing (F_1), but also by the core enterprise's strategy for information sharing (the core enterprise is influenced by factors such as loss of benefits T, costs C_3 and additional benefits L). In the absence of necessary warnings and penalties, ordinary enterprises may choose a 'no-cooperation' strategy because negative information sharing behaviors, such as information leakage, are not penalized. And if the benefits of positive information sharing are too low, this may also affect their motivation and initiative to share. When the core enterprises choose a "synergy" strategy due to changes in parameters such as loss of benefits (T) and costs (C_3), over time, the strategies of ordinary enterprises are influenced by the strategy choices of the core enterprise and tend to be "synergy".

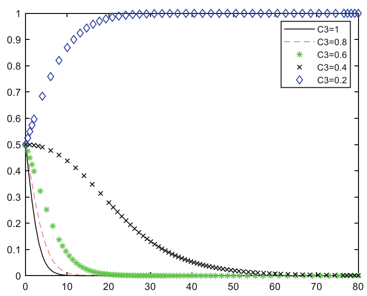
Table 7. Changing trends

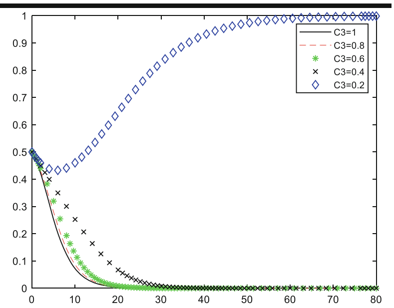
Parameters	Ordinary Business	Core Businesses
F_1		
W_1		
T		
L		

(*continued*)

Table 7. (*continued*)

C3





5 Conclusions and Recommendations

This paper constructs an evolutionary game model of "common enterprise - core enterprise" to study the competitive relationship of information sharing in industrial clusters, in view of the problem of information separation and lack of cooperation and synergy among manufacturing enterprises. After considering the risk of information sharing, MATLAB is used to simulate and verify the evolutionary paths of game subjects in the game model. The impact of changes in various parameters on the strategy choice of game subjects is analyzed, and finally suggestions are made to promote stable cooperation in manufacturing industry clusters. Through the joint efforts of both parties to promote information sharing between enterprises, the high-quality collaborative development of the manufacturing industry is achieved.

5.1 Conditions Influencing Cooperation in Information Sharing

Firstly, the costs and benefits of information sharing between ordinary enterprises and core enterprises are analyzed, and a game model benefit matrix is constructed to form the replication dynamic equation and further obtain the Jacobi matrix. Then, the Jacobi matrix is analyzed to obtain the conditions for cooperation between ordinary enterprises and core enterprises. Finally, through simulation analysis, the influencing factors of cooperation in information sharing between firms are derived. The loss of benefits and the cost of active information sharing are the deciding factors for the core enterprises in their information sharing strategy decisions, and the evolutionary strategies of ordinary enterprises are influenced by the core enterprises. When the core enterprise's strategy evolves to "synergy", the ordinary enterprise's strategy will also evolve to "synergy".

5.2 Proposals to Promote Stable Cooperation

Firstly, a communication mechanism should be established by enterprises to mitigate the risk of information sharing. This involves enhancing connections between enterprises, creating information dissemination channels, and establishing a platform for information sharing. The aim is to facilitate the free flow of information related to synergy activities among enterprises in manufacturing industry clusters. By involving core enterprises and encouraging more cluster enterprises to participate in manufacturing cooperation, the scope of information sharing can be expanded, thereby reducing the associated risks.

Secondly, an incentive and constraint mechanism should be implemented to minimize the cost of information sharing. One approach is to establish a performance management platform tailored to the characteristics of manufacturing industry clusters. This platform would align the interests of all parties involved and boost their enthusiasm. It would foster a symbiotic system with strong interdependencies within the cluster, thereby enhancing the cohesion of the manufacturing industry cluster. Operational rules should be clarified, outlining the responsibilities, obligations, rewards, and penalties associated with information sharing among enterprises. Such measures would promote positive information sharing and ultimately reduce the cost of information sharing, fostering value co-creation.

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