The Analysis of Manufacturing Service Ecosystem’s Evolution Stability Based on Evolutionary Game

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Abstract. In the process of successful establishment and development of service ecosystem organization, manufacturing companies not only pay attention to their own resources, business models and competitive advantages, but also pay attention to the positioning in the manufacturing service ecosystem and the symbiosis with other members of the system to achieve complementarity and symbiotic development of resources among members. Based on this, we take the manufacturing service ecosystem in the transformation and upgrading of the manufacturing enterprises in China as the research object, and comprehensively uses the theory of evolutionary game and ecosystem to study the symbiotic evolutionary stability of the manufacturing service ecosystem. Through simulation, we find that integrator is more sensitive to the change of rights than supplier. Our conclusions have certain reference for manufacturing companies to improve the collaborative operation efficiency of manufacturing service ecosystem.

1. Introduction

In the face of changes in the manufacturing environment and corporate profitability, as well as the personalized needs of product users for services, manufacturing companies recognize the limited nature of their resources and need to conduct deep integration of cross-industry external resources, that is, building a manufacturing enterprise as the core Ecosystems to break through the limitations of traditional resource integration[1,2]. Many leading companies at home and abroad have already begun to build their own ecosystems, including the centralized monopoly ecosystem represented by Microsoft, the distributed and shared ecosystem represented by Linux, and the network organizations proposed by Haier during the transition of domestic companies to create a win-win situation, etc. In March 2015, the government work report clearly put forward the strategy of “Made in China 2025”, taking the “transition from production-oriented manufacturing to service-oriented manufacturing” as one of the four major transformations in manufacturing upgrades. It can be seen that the establishment of a fully functional and efficient manufacturing service ecosystem is of great significance to the establishment of Chinese modern industrial system, realization of industrial structure adjustment and upgrading, and transformation of economic growth mode.

For China, service-oriented manufacturing is still a relatively new topic, and it is imperative to build a manufacturing service ecosystem. For big differences among industries and enterprises, the system is in a dynamic and complex environment. There are many relevant stakeholders in the system, and the value network between enterprises is row upon row[3]. What’s more, the participation of customers brings greater opportunities and challenges to the system[4]. Therefore, it is of great significance to accelerate theoretical innovation in the field of service-oriented manufacturing and to develop a manufacturing service ecosystem theory that conforms to the actual development of China’s manufacturing industry.
Based on this, we take the manufacturing service ecosystem as the research object, comprehensively using evolutionary game, ecosystem and other theories to study the evolution and stability of the manufacturing service ecosystem. And focused on the analysis of the influence of power changes between suppliers and integrators in the manufacturing service ecosystem on its evolutionary stability. The research conclusions have certain references for manufacturing companies to improve the collaborative operation efficiency of the manufacturing service ecosystem.

2. Materials and Methods
In the manufacturing service ecosystem, supplier(S), integrator(I), and customer(C) constitute three game players. The supplier is the producer in the system, responsible for the design and production of the product. The integrator, as the core enterprise in the system, is responsible for integrating the supplier’s product service package and providing complete system solutions to customers. Service-oriented manufacturing enterprises (integrators, suppliers) participate in the entire process through customers, and integrators and suppliers transform the supply-demand relationship with customers into a cooperative relationship based on common interests in the system, so as to achieve the double goal of customers’ value creation and enterprises’ value construction. The three parties participating in the game are all “bounded rationality”\(^5\). The supplier’s strategy space is {participate, not participate}, which represents whether to participate in the service cooperation with the integrator. The probability of choosing the corresponding strategy is \(p, (1 − p)\); The integrator’s strategy space is {cooperation, non-cooperation}, which represents whether to cooperate with the supplier, and the probability of selecting the corresponding strategy is \(q, (1 − q)\). The customer’s strategic space is (pay, not pay), which means that customers have the right to choose “pay” or “not pay” for the products or services provided by suppliers and integrators, and the probability of choosing the corresponding strategies is \(z, (1 − z)\). The game relationship among them is shown in Figure 1.

Figure 1. Game relationship of supplier, integrator and customer

When the supplier chooses the strategy of “not participate”, the integrator chooses the strategy of “non-cooperation”, and the customer chooses the strategy of “not payment”, the benefits of the three parties are all 0. When the supplier chooses the “participate” strategy, the integrator chooses the “cooperation” strategy, and the customer chooses the “pay” strategy, the direct benefit obtained by the supplier and integrator is \(E\) \((E > 0)\). Suppliers and integrators cooperate in the system for services. If only one of supplier and integrator provides products or services to customer, the use value obtained by customer is \(U_i\) \((i = S, I)\), \(U_i < U\), and the corresponding cost of the supplier or integrator is \(T_i\). It means that when the supplier and integrator’s service business is internalized, the use value of the product or service that can be provided alone will be lower than the use value of the service cooperation due to the lack of superior technology or service support of the other party. Affected by the dominant position of the core enterprise in the system, the income distribution coefficient is taken as \(\alpha\) \((0 < \alpha < 1)\). The magnitude of \(\alpha\) indirectly reflects the power of the supplier and the integrator, that is, according to the power change, the direct income obtained by supplier is \(\alpha E\), and the direct income obtained by integrator is \((1 − \alpha)E\). Suppliers and integrators cooperate in the system, and the indirect benefit...
generated by the increase in trust and the reduction in transaction costs is \( D_i, D_j > 0 \). At this time, the cost incurred by both parties for value creation is \( C_i, (C_i > T_i) \), and the value generated by the knowledge overflow in the service cooperation process is \( K_i^{[6]} \). As long as the supplier chooses the “not participate” strategy, or the integrator chooses the “non-cooperation” strategy, it will be deemed to have given up market opportunities. Due to the cumulative effect, a potential loss of \( \lambda_i \) will occur.

The customer’s value creation cost in the game is \( C_c \). When the customer chooses to “not pay”, a potential loss of \( \lambda_c \) will occur. If the customer chooses to “pay”, but both the supplier and the integrator are unwilling to provide products or services, the customer will have a loss of \( \pi \). Then have the payoff matrix of supplier, integrator and customer shown in Table 1.

**Table 1. The payoff matrix of tripartite game**

|          | Supplier     | Integrator   | Customer     |
|----------|--------------|--------------|--------------|
| Pay \((z)\) | Participate \((p)\) | Cooperation \((q)\) |              |              |
|          |              | \(K_i + \alpha E + D_S - C_S\) | \(K_S + (1 - \alpha) E + D_I - C_I\) | \(K_S + K_I + U - C_C\) |
|          | Non-cooperation \((1-q)\) | \(E + D_S - T_S\) | \(K_S - \lambda_i\) | \(K_S + U_S - C_C\) |
| Not participate \((1-p)\) | Cooperation \((q)\) | \(K_I - \lambda_S\) | \(E + D_I - T_I\) | \(K_I + U_I - C_C\) |
|          | Non-cooperation \((1-q)\) | \(-\lambda_S\) | \(-\lambda_I\) | \(-\pi\) |
| Not pay \((1-z)\) | Participate \((p)\) | Cooperation \((q)\) | \(K_I + D_S - C_S\) | \(K_S + D_I - C_I\) | \(K_S + K_I - \lambda_C\) |
|          | Non-cooperation \((1-q)\) | \(D_S - T_S\) | \(K_S - \lambda_i\) | \(K_S - \lambda_C\) |
| Not participate \((1-p)\) | Cooperation \((q)\) | \(K_I - \lambda_S\) | \(D_I - T_I\) | \(K_I - \lambda_C\) |
|          | Non-cooperation \((1-q)\) | 0 | 0 | 0 |

According to the payoff matrix, the expected revenue of supplier choosing the strategy of “participate”, \(E_S(p)\), is,

\[
E_S(p) = qz(K_I + \alpha E + D_S - C_S) + (1 - q)z(E + D_S - T_S) + q(1 - z)(K_I + D_S - C_S) + (1 - q)(1 - z)(D_S - T_S)
\]  

(1)

The expected revenue of supplier choosing the strategy of “participate”, \(E_S(1-p)\), is,

\[
E_S(1-p) = qz(K_I - \lambda_S) - (1 - q)z\lambda_S + q(1 - z)(K_I - \lambda_S)
\]  

(2)
The mean revenue of supplier, $E_S$, is,

$$E_S = pE_S(p) + (1 - p)E_S(1 - p)$$ (3)

The expected revenue of integrator choosing the strategy of “cooperation”, $E_i(q)$, is,

$$E_i(q) = pq[K_s + (1 - a)E + D_i - C_i] + (1 - p)z(E + D_i - T_i) + p(1 - z)(K_s + D_i - C_i) + (1 - p)(1 - z)(D_i - T_i)$$ (4)

The expected revenue of customer choosing the strategy of “non-cooperation”, $E_i(1 - q)$, is,

$$E_i(1 - q) = pq(K_s - \lambda_i) - (1 - p)z\lambda_i + p(1 - z)(K_s - \lambda_i)$$ (5)

The mean revenue of integrator, $E_i$, is,

$$E_i = qE_i(q) + (1 - q)E_i(1 - q)$$ (6)

The expected revenue of customer choosing the strategy of “pay”, $E_C(z)$, is,

$$E_C(z) = pq(K_s + K_i + U - C_c) + p(1 - q)(K_s + U_S - C_c) + (1 - p)q(K_i + U_i - C_c) - (1 - p)(1 - q)\pi$$ (7)

The expected revenue of customer choosing the strategy of “not pay”, $E_C(1 - z)$, is,

$$E_C(1 - z) = pq(K_s + K_i - \lambda_c) + p(1 - q)(K_s - \lambda_c) + (1 - p)q(K_i - \lambda_c)$$ (8)

The mean revenue of customer, $E_C$, is,

$$E_C = zE_C(z) + (1 - z)E_C(1 - z)$$ (9)

Then we can get replicator dynamics equations of supplier, integrator and customer as follow,

$$\frac{dp}{dt} = p(1 - p)\{qz[(\alpha - 1)E - \lambda_S] + q(T_s - C_s + \lambda_S) + z(E + \lambda_S) + (D_S - T_S)\}$$ (10)

$$\frac{dz}{dt} = q(1 - q)\{pz[-(\alpha E - \lambda_i) + p(T_i - C_i - \lambda_i)] + z(E + \lambda_i) + (D_i - T_i)\}$$ (11)

$$\frac{d\pi}{dt} = z(1 - z)[pq(U - U_S - U_i + C_c - \lambda_c - \pi) + p(U_S - C_c + \lambda_c + \pi) + q(U_i - C_c + \lambda_c + \pi) - \pi]$$ (12)

From Eq. (10), (11) and (12), we get the dynamic replication differential equation system $\Omega$. In the dynamic game, the probability $p, q$ and $z$ of the strategy chosen by each side are associated to time $t$, so we adopt $p(t), q(t), z(t)$ $\in [0, 1]$ in the game. It is obvious that the solution domain of the dynamic replication differential equation system $\Omega$ is $[0, 1] \times [0, 1] \times [0, 1]$. Since the equilibrium points $(p, q, z)$ make the replicator dynamic equations equal to zero, that is,

$$\begin{align*}
\frac{dp}{dt} &= 0 \\
\frac{dq}{dt} &= 0 \\
\frac{d\pi}{dt} &= 0
\end{align*}$$ (13)

Apparently, there are 8 special equilibrium points: $N_0(0, 0, 0), N_1(1, 0, 0), N_2(0, 1, 0), N_3(0, 0, 1), N_4(1, 0, 1), N_5(0, 1, 1), N_6(1, 1, 0), N_7(1, 1, 1)$. They constitute the boundary of the solution domain of the evolutionary game [7]. At the same time, there is an equilibrium point $N_0(p^*, q^*, z^*)$ that satisfies Eq. (13), where

$$\begin{align*}
p^* &= \frac{Ti-Di-z(E+\lambda_i)}{Ti-Ci+\lambda_i-z(\alpha E+\lambda_i)} \\
q^* &= \frac{z(T_s-D_S-z(E+\lambda_S))}{T_s-C_s+\lambda_S+z(\alpha-1)(E-\lambda_S)} \\
z^* &= \frac{p(T_i-C_i-\lambda_i)-q(T_s-C_s-\lambda_S)-D_s+T_D+T_i}{q((\alpha-1)(E-\lambda_S)+p(\alpha E+\lambda_i)+\lambda_S-\lambda_i)}
\end{align*}$$ (14)

According to Eq. (10), (11) and (12), we can get the Jacobian matrix $^8$ of this evolutionary dynamic system as follows:

$$J = \begin{pmatrix} F_{11} & F_{12} & F_{13} \\ F_{21} & F_{22} & F_{23} \\ F_{31} & F_{32} & F_{33} \end{pmatrix}$$ (15)

Where,

$$\begin{align*}
F_{11} &= (1 - 2p)\{qz[(\alpha - 1)E - \lambda_S] + q(T_s - C_s + \lambda_S) + z(E + \lambda_S) + (D_S - T_S)\} \\
F_{12} &= p(1 - p)\{z[(\alpha - 1)E - \lambda_S] + T_S - C_S + \lambda_S\}
\end{align*}$$
\[ F_{13} = p(1-p)[z(-aE - \lambda_i) + T_i - C_i - \lambda_i], \]
\[ F_{21} = q(1-q)[z(-aE - \lambda_i) + T_i - C_i + \lambda_i], \]
\[ F_{22} = (1 - 2q)[pz(-aE - \lambda_i) + p(T_i - C_i + \lambda_i) + z(E + \lambda_i) + (D_i - T_i)], \]
\[ F_{23} = q(1-q)[p(-aE - \lambda_i) + p + E], \]
\[ F_{23} = q(1-q)[p(-aE + \lambda_i) + z + T_i]. \]

The Jacobian matrix can be used to judge whether the equilibrium point \( N_i (i = 0, 1, ..., 8) \) is an evolutionary stable state (ESS). When \( N_i (p, q, z) \) satisfies the determinant of matrix \( J: \text{Det}(J) > 0 \), and the trace of matrix \( J: \text{Tr}(J) < 0 \), then we can say the system is in the state of evolutionary equilibrium, and \( E(p, q) \) is an ESS\(^9\).

Since the value of \( \text{Det}(J) \) and \( \text{Tr}(J) \) depend on the given parameters, we solve the difficulty in calculation through simulation.

3. Simulation
In this section, we conducted simulation to investigate the impact of parameters on the behavior of supplier, integrator and customer. We use MATLAB R2018a to run the simulation with different initial states to explore the different mutual influence among them. The initial probabilities of supplier, integrator and customers choosing their respective strategies are all 0.5. By setting different values of \( \alpha \), the evolution result obtained is shown in Figure 2, 3, 4. The value of the parameter assignment is shown in Table 2.

| Table 2. The simulation parameters’ value |
|------------------------------------------|
| Parameter | \( E \) | \( \lambda_S \) | \( \lambda_I \) | \( \lambda_C \) | \( T_S \) | \( T_I \) | \( C_S \) | \( C_I \) |
| Value     | 150    | 24     | 22     | 20     | 64     | 55     | 56     | 48     |
| Parameter | \( C_C \) | \( D_S \) | \( D_I \) | \( U \) | \( U_S \) | \( U_I \) | \( \pi \) |
| Value     | 130    | 8      | 9      | 160    | 150    | 140    | 155    |

Figure 2. Evolution trend of the tripartite game (\( \alpha = 0.5 \))
Figure 3. Evolution trend of the tripartite game ($\alpha = 0.7$)

Figure 4. Evolution trend of the tripartite game ($\alpha = 0.3$)

From the simulation results, reasonable parameter settings can make the tripartite game evolve in a direction where supplier, integrator and customer are willing to cooperate in services, which will benefit the development of the manufacturing service ecosystem. And we can find that in the manufacturing service ecosystem, integrator is more sensitive to the change of rights than supplier. When the income distribution coefficient $\alpha$ increase to 0.7, integrator’s strategy changed from cooperation to non-cooperation. But when the income distribution coefficient $\alpha$ decrease to 0.3, the evolution of the three parties is the same as before.

In order to ensure that the benefits of the actions of the three parties are greater than the costs of the corresponding actions, the total and indirect benefits of service cooperation should be increased, and efforts should be made to reduce the costs of value creation by the three parties$^{[9]}$. In addition, suppliers and integrators need to strengthen their innovation skills and strive to create greater use value $U$ for customers. And in the early stage of the development of the manufacturing service ecosystem, the government should appropriately intervene to ensure the rationality of the income distribution coefficient $\alpha$. Attach great importance to theoretical innovation, and continuously improve the value of knowledge spillover generated in the process of service cooperation$^{[10]}$. It’s also means a lot to create a systemic atmosphere for service cooperation to show the potential losses caused by not participating in service cooperation.
4. Conclusion
Through the game analysis of supplier, integrator and customer in the manufacturing service ecosystem, we can draw the following management decision insights: First, increase the total and indirect benefits of service cooperation between supplier, integrator and customer, and strive to reduce three parties’ value creation incurs costs. Secondly, supplier and integrator should strengthen their innovation skills and strive to create greater use value for customer. In addition, all stakeholders should pay attention to theoretical innovation and continuously increase the value of knowledge spillover generated in the process of service cooperation. Finally, a systematic atmosphere for service cooperation should be created to show the potential losses caused by not participating in service cooperation [11].

To develop service-oriented manufacturing and build a manufacturing service ecosystem in the 21st century, leaders of integrator and supplier must strengthen their awareness of service cooperation, customers must actively participate, and the government must focus on the establishment of operating rules and organizational structure [12]. Through the active cooperation of all parties to improve the infrastructure services of the manufacturing service ecosystem, improve coordination and maintenance functions, and support the coexistence of multiple governance structures, it can enhance the cohesion of corporate customers in the system, thereby improving the symbiosis and stability of the entire system, and promoting faster and better development of China’s manufacturing service ecosystem.

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