ISBN: 978-981-18-5852-9
WCSE 2022 Spring Event: 2022 9th International Conference on Industrial Engineering and Applications
doi: 10.18178/wcse.2022.04.089

Stability Analysis of Symbiotic Evolution of Manufacturing Service Ecosystems Based on Lotka-volterra Model

Yaqi Zhang [1], Jing Wang [2] ,Hao Wang[3] and Yachao Zhang [4]

[1] The School of Economics and Management, Xi'an University of Technology

[2] The School Management, The Open University of Shaanxi

[3] The School of Economics and Management, Xi'an University of Technology

[4] XI AN Chaoma Technology Co., Ltd.

Abstract. Manufacturing Service Ecosystem (MSE) is a symbiotic evolutionary value co-creation network with service integrator (SI) as the core, through the joint collaboration among service providers(SPs). How to coordinate the behavior between SI and SPs, encourage organizations to participate in the operation of MSE, and promote the MSE to reach a stable state has become an important direction of MSE theoretical research. Considering various symbiotic relationships between agents and the influence of technical factors in the system environment, based on the Lotka-Volterra model from an ecological perspective, this paper introduces the contribution coefficient between two agents and the externality coefficient of technology, constructs a MSE evolution model, and explores the symbiotic evolution mechanism of MSE agents. The main research work includes the growth law of the qualitative parameters of SI and SP, the equilibrium point of the symbiotic evolution model and its stability conditions, in addition, the simulation analysis of the symbiotic evolution process of suppliers and service integrators and the stability influencing factors. The results show that reciprocal symbiosis is the best symbiosis model for SI and SP; initial service resources, contribution coefficient, externality coefficient, natural growth rate and upper limit value of service resources have influence on the evolution path of manufacturing service ecosystem and the stability value of service resources.

Keywords: manufacturing service ecosystem, symbiotic stability, Lotka-volterra model.

1. Introduction

Facing the changes in manufacturing and survival environment and the transformation of enterprise profitability, enterprises need to optimize and integrate the scattered manufacturing and potential service resources embedded in the traditional supply network to survive, and gradually form a new ecological network organization with optimal resource allocation as the link. In the face of this new network organization, some scholars have proposed service ecosystem [1], manufacturing service system (MSS) [2], service-oriented manufacturing network (SMN) [3] (Feng, 2019), and supply ecosystem [4], manufacturing service ecosystem (MSE) [5]. And it is agreed that how to coordinate the behavior among various suppliers and service integrators, motivate organizations to participate in the operation of manufacturing service ecosystem, and promote the manufacturing service ecosystem to reach a balanced and stable state has become an important direction of manufacturing service ecosystem theory research. Among them, using the idea of modularization, Wei Zhang put forward the ecological evolution model of manufacturing service system driven by service providers. However, the study of subjects is limited to the relationship between suppliers and manufacturers, without considering the blocking effect of the ecosystem environment on subjects and the blocking and weakening effect of multiple symbiotic relationships among subjects, and the symbiotic evolutionary utility of the manufacturing service ecosystem cannot be well answered.

The study of the symbiotic relationship of the participants has always been an important issue in the theoretical study of ecosystem. Symbiotic relationship is the relationship of interaction, mutual dependence and common development between subjects based on the vision of value co-creation. The subject of symbiosis is the community of interests. Some scholars believed that symbiosis among enterprises is self-adjusting, and when the external environment changes or some aspects of the enterprises in the symbiotic system change, the symbiotic model and symbiotic system will change to better adapt to the development of the whole symbiotic system [6]. Some other scholars suggested that unifies the participants in a mutually beneficial symbiotic system, striving to maximize the total benefits while satisfying the objectives of the participants, and finally achieving a stable and balanced dynamic system [7].

In addition, Lotka-Volterra model is widely used to study system stability, which is not only applied to the fields of physics, chemistry, and biology, but also extended to the fields of population and economy. Some scholars have used the Lotka-Volterra model to analyze the ecological relationship between the purchase of domestic technology and the introduction of foreign technology [8], and to analyze the interaction mechanism between the service manufacturing and advanced manufacturing in China [9].

Therefore, we construct a manufacturing service ecosystem evolution model based on the Lotka-Volterra model and considers the effects of symbiotic relationship and technology externality coefficients on MSE equilibrium stability to explore the symbiotic evolution mechanism of manufacturing service ecosystem.

2. Symbiotic Evolution Model Of Manufacturing Service Ecosystem

2.1. Model Assumptions

In a MSE environment, the focal firm interacts with other firms, such as service providers, end users, competitors and complementary firm[4]. We only discusses the symbiotic evolutionary mechanisms of the MSE generated between the service integrator (SI) and the service provider (SP), without considering the relations between the other subjects due to their different evolutionary mechanisms, aiming to help the two subjects make optimal symbiotic decisions to achieve a stable and balanced dynamic system. In the MSE, the SI acts as a predator to integrate production modules and service modules, while the SP acts as a bait to provide intermediary services to the SI, so as to indirectly provide services to end users. At this time, the process can be regarded as a cooperative relationship. However, there is not only a cooperative relationship between SI and SP. End users can bypass service integrators and directly seek services from providers. At this time, the two subjects become a competitive relationship. In fig.1, we show the structure diagram of the MSE.

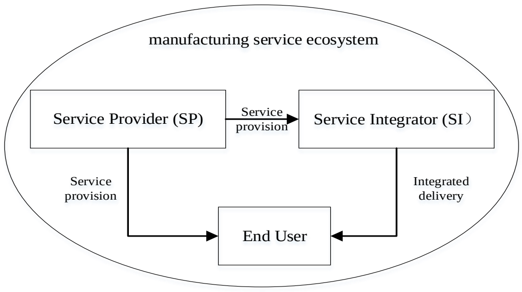


Fig. 1: The depiction of the MSE.

Taking Wei Zhang as a reference [2], we assume that the service relationship between the service provider and the manufacturer can be explained by the relationship between predator and prey in nature, and that Lotka–Volterra model, can be used to describe and simulate the evolution mechanism of this relationship. In addition, we use the subject's possession of service resources to reflect the size of the subject's service capacity. The more service resources, the higher the service capacity and service quality, and the greater the interest space. Based on this, we made model description and parameter assumption in the following aspects.

Assumption 1: There is only one SI and one SP in each symbiotic relationship. And the growth process of service capability of service integrator (provider) is represented by the change of occupied service resources.

Assumption 2: The growth process of service resources of SI and SP follows the logistic growth law. And when the marginal output of service resources of the service integrator (provider) is equal to the marginal input, the service integrator (provider) stops growing and reaches the maximum service resources.

Assumption 3: The development of digital intelligence technology and the symbiotic relationship between the subjects jointly act on the growth process of service resources of subjects, and the result of the joint action cannot exceed the growth of their own service resources in the ideal state.

2.2. Model Formulation

The basic evolution model based on Lotka-Volterra is established as follows:

$$\begin{cases} \dfrac{dy_1}{dt} = r_1 y_1 \left(1 - \dfrac{y_1}{N_1}\right), y_1(0) = y_{10} \\ \dfrac{dy_2}{dt} = r_2 y_2 \left(1 - \dfrac{y_2}{N_2}\right), y_2(0) = y_{20} \end{cases} \tag{1}$$

In (1), $y_1(t)$, $y_2(t)$ represents service resources that change over time of SI and SP respectively, r_1, r_2 represents growth rate of service resources under the ideal state, and $r_i>0$, N_1, N_2 represents the maximum value of service resources of SI and SP under the constraint of total service resources in MSS, y_{10}, y_{20} represents the initial service resources of SI and SP. In addition, r_1y_1, r_2y_2 represents growth trend of service resources of SI and SP, y_1/N_1, y_2/N_2 indicates the blocking effect on the growth of its own service resources caused by the consumption of limited resources in MSE.

In addition, With the advent of digital technology, the boundary of service has become blurred, resulting in the symbiotic relationship between two subjects becoming more complex. Therefore, the evolution mechanism under the joint action of digital technology and symbiosis is considered. The symbiotic evolution model is established based on the (1) as follows:

$$\begin{cases} \dfrac{dy_1}{dt} = r_1 y_1 \left(1 - (1-\mu_1)\dfrac{y_1}{N_1} + \alpha \dfrac{y_2}{N_2}\right), y_1(0) = y_{10} \\ \dfrac{dy_2}{dt} = r_2 y_2 \left(1 - (1-\mu_2)\dfrac{y_2}{N_2} + \beta \dfrac{y_1}{N_1}\right), y_2(0) = y_{20} \end{cases} \tag{2}$$

In (2), μ as an externality coefficient of digital intelligence technology, which Indicates digital technology improves the efficiency of service providers and integrators in obtaining and utilizing service resources. $1-\mu$ represents the extent to which the blocking effect of service resource growth is reduced. α represents the SP's contribution coefficient to the SI, which reflects the resource growth of SI caused by the resource growth blocking of SP under the action of symbiotic relationship, β represents the contribution coefficient of the SI to the SP, which reflects the resource growth of SP caused by the resource growth blocking of SI under the action of symbiotic relationship. Taking Margulis as a reference [10], we assume that under different symbiotic relationships, α , β have different value combinations. As is shown in tab 1. $\mu+\alpha(\beta)$ refers to jointly act on the growth process of service resources of subjects. Therefore, the result of the joint action cannot exceed the growth of their own service resources in the ideal state, which should be assumed $\mu+\alpha(\beta)<1$.

Table 1: Contribution Coefficient And Symbiotic Relationship

Value combination	**Symbiotic relationship**
α=0, β=0	Independent coexistence
α<0, β<0 and α=β	Equal competition
α<0, β<0 and α<-1 or β<-1	Malicious competition
αβ<0	Parasitic
α>0, β=0 or α=0, β>0	Partial benefit symbiosis
α>0, β>0 and α≠β	Asymmetric reciprocal symbiosis
α>0, β>0 and α=β	Symmetrical reciprocal symbiosis

2.3. Stability Analysis of Symbiotic Evolution Model

Under different symbiotic relationships, the stable state of the evolution equilibrium point of MSE is also different. The equilibrium point means that the service resources of SI and SP are no longer expanded, and the service capacity remains stable. When t→∞, let $dy_1/dt=0$, $dy2/dt=0$ to obtain the equilibrium point of symbiotic evolution of MSE as follows:

$$\begin{cases} f(y_1,y_2)=r_1y_1(1-(1-\mu_1)\dfrac{y_1}{N_1}+\alpha\dfrac{y_2}{N_2})=0 \\ g(y_1,y_2)=r_2y_2(1-(1-\mu_2)\dfrac{y_2}{N_2}+\beta\dfrac{y_1}{N_1})=0 \end{cases} \quad (3)$$

Four equilibrium points of symbiotic evolution of SI and SP are obtained, as follows:

$$E_1(0,0), E_2(N_1,0), E_3(0,N_2),$$

$$E_4(\frac{N_1(1+\alpha-\mu_2)}{(1-\mu_1)(1-\mu_2)-\alpha\beta},\frac{N_2(1+\beta-\mu_1)}{(1-\mu_1)(1-\mu_2)-\alpha\beta})$$

The stability of equilibrium point E is judged by approximate linear method, that is, $f(y_1,y_2)$ and $g(y_1,y_2)$are expanded as first-order Taylor at point E, and the stable equilibrium point and stability conditions of the system are obtained by solving Jacob matrix in Table 2.

Table 2: Equilibrium Point And Stability Condition

Equilibrium point	**Stability condition**
$E_1(0,0)$	instable
$E_2(N_1,0)$	instable
$E_3(0,N_2)$	instable
$E_4\left(\frac{N_1(1+\alpha-\mu_2)}{(1-\mu_1)(1-\mu_2)-\alpha\beta},\frac{N_2(1+\beta-\mu_1)}{(1-\mu_1)(1-\mu_2)-\alpha\beta}\right)$	$\alpha\beta<(1-\mu_1)(1-\mu_2)$

As shown in the table 2, among the four equilibrium points of symbiosis mode, $E_1(0,0)$, $E_2(N_1,0)$, $E_3(0,N_2)$, these three results are unstable, and when the enterprise's contribution coefficient and externality coefficient meet $\alpha\beta<(1-\mu_1)(1-\mu_2)$, SI and SP reach stable equilibrium

2.4. Numerical Analysis

We analyze Simulation analysis of symbiotic evolution under different symbiotic relationships in this section. we assume that the natural growth rate, service resource ceiling and initial service of the subject under different contribution coefficients remain unchanged. In addition, we assume $r_1=0.2$, $r_2=0.1$, $\mu_1=\mu_2=0.1$, $N_1=1000$, $N_2=1000$, $y_{10}=100$, $y_{20}=100$. We use Mathematica to simulate the research results, classify the simulation results in Table 3 and draw the trend chart of symbiotic evolution steady state of SI and SP in Fig 2 and 8.

Table 3: Simulation Results Under Different Symbiosis Modes

Fig. 1. **Symbiotic model**	Fig. 2. **Initial Value**			Fig. 3. **Stable Point**	
	α	***β***	***μ***	***(X1, Y1)***	***(X2, Y2)***
Independent coexistence	0	0	0	（61，1000）	（123，1000）
	0	0	0.1	（50，1111）	（99，1111）
Equal competition	-0.2	-0.2	0.1	（139，909.1）	（156，909.1）
Malicious competition	-0.2	-1.2	0.1	（93，1100）	（254，0.01）
parasitic	-0.05	0.05	0.1	（81，1046）	（93，1169）
reciprocal symbiosis	0.4	0.2	0.1	（95，1781）	（98，1507）
	0.4	0.4	0.1	（88，2000）	（91，2000）

A.Independent Coexistence

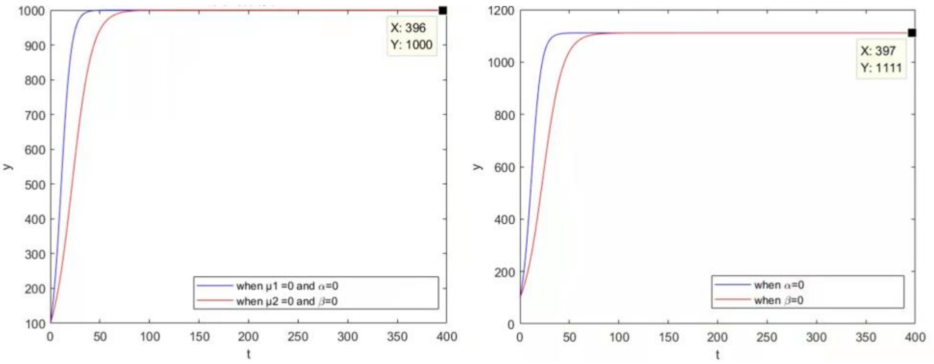


Fig. 2:Under the condition of $\mu_i=0$ and $\mu_i\neq0$.

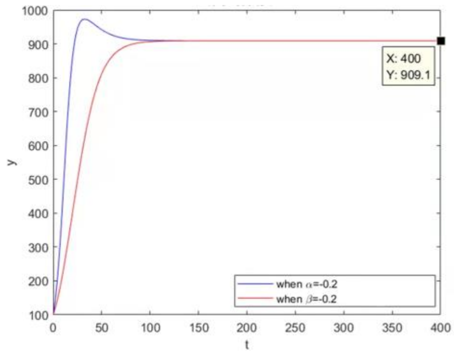
The subject's occupation of service resources and service provision do not affect each other, therefore, $\alpha=0, \beta=0$. The symbiotic evolution in the case of $\mu_i=0$ and $\mu_i\neq0$ is analyzed respectively. as is shown in Fig 2. When $\mu_1=\mu_2=0$, the SI and the SP reach a stable state, the numerical values are equal, both of which are the upper limit of their service resources. When $\mu_i\neq0$ and $\mu_1=\mu_2=0.1$. The values of the SI and the SP are equal when they reach the stable state, but the value in the stable state exceeds the upper limit of service resources under their independent survival.

B. Equal Competition

At this time, $\alpha=\beta$ and $\alpha<0, \beta<0$. We assume $\alpha=-0.2, \beta=-0.2$, as is shown in Fig 3. The interests of SI and SP are damaged under the relationship of equal competition. when SI and SP reach a stable state, the numerical value is less than the upper limit of occupied service resources under their independent survival.

C. Malicious Competition

In the malicious competition environment, the interests of SI and SP are damaged. Assuming that the interests of suppliers are more damaged, Therefore, $\beta<\alpha<0$, We assume $\alpha=-0.2, \beta=-1.2$， as is shown in Fig 4, at this time, the contribution of SP to SI is negative, and when they reach a stable state, the numerical value of SI is less than the upper limit of service resources under their independent survival. The provider will be the first to decline or exit the MSE, because the SI does not provide or only provides a very small amount of service business.



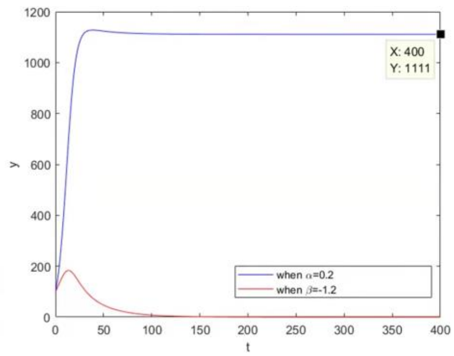
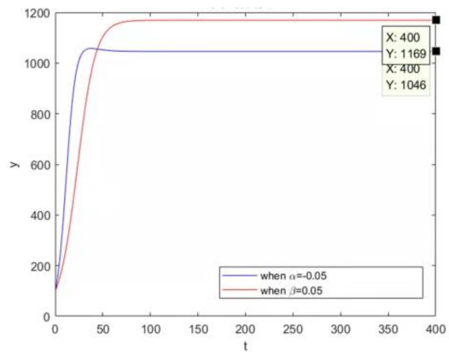


Fig. 3: Equal competition.   Fig. 4: Malicious competition.

D. Parasitic

As the core of MSE, the SP is parasitic on SI. Therefore, $\alpha<0, \beta>0$, We assume $\alpha=-0.05, \beta=0.05$, as is shown in Fig 5, SI belongs to the party with damaged interests in the parasitic relationship, and the SP belongs to the party with increased interests in the parasitic relationship. SP play a negative role in weakening the growth of suppliers' service resources, and the stable value of service integrators is less than the upper limit of their independent growth service resources. SI play a positive role in promoting the growth of suppliers. When the provider reach a stable state, the value is greater than the upper limit of service resources for its independent growth.



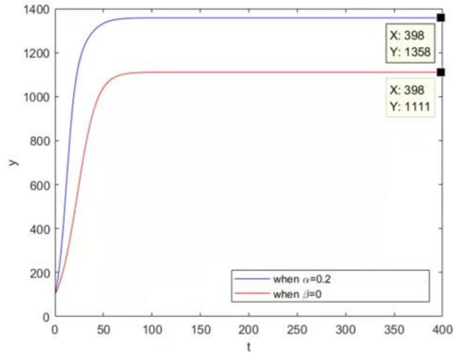


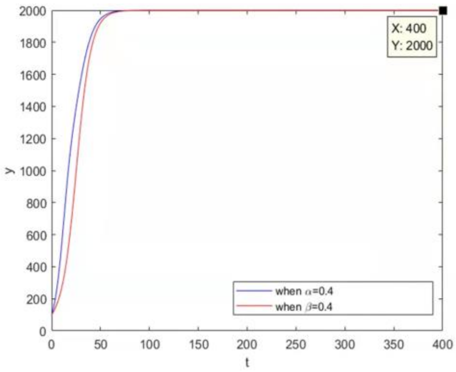
Fig. 5: Parasitic.   Fig. 6: Partial benefit symbiosis.

E. Partial Benefit Symbiosis

As is shown in Fig 5, When α is positive, the SI belongs to the party with increased interests in the symbiotic relationship of partial interests. and the value of the stable state of the SI exceeds the upper limit of its independent growth service resources. $\beta=0,$ the growth of service resources of the provider is not affected by the service integrator. When the provider reaches a stable state, the value is equal to the upper limit of its independent growth of service resources.

F. Reciprocal Symbiosis

Consider the symmetry and asymmetry of reciprocity respectively. Under asymmetric reciprocity, as the core of the MSE, the benefits of SI are greater than those of SP. Therefore, $\alpha>\beta>0$, We assume $\alpha=0.4,\beta=0.2$. Under reciprocity, the growth of service resources of SI and SP benefits from another subject and is affected to the same extent. Therefore, $\alpha=\beta$, We assume $\alpha=\beta=0.4$. as is shown in Fig 7, The service resources of SI and SP are positively promoted by each other. When the two entities reach a stable state, the value exceeds the upper limit of their independent growth of service resources. And $\alpha>\beta$, SP have a greater impact on SI. The upper limit of service resources in the stable state of SI is greater than that in the stable state of SP. as is shown in Fig 8, $\alpha=\beta$， There is no difference in the possession and benefit of service resources between SI and SP. The service resource upper limit values of SI and SP in stable state are equal, and both are greater than the service resource upper limit values of their independent growth.



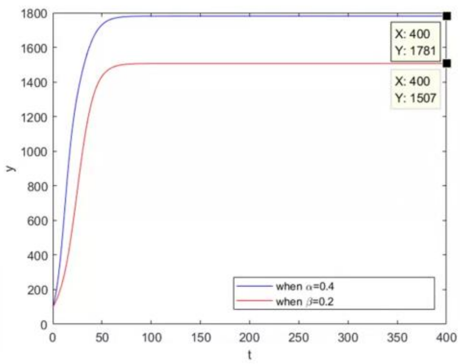


Fig. 7: Symbiotic evolution α=β.   Fig. 8: Symbiotic evolution α≠β.

3. Conclusion

In this paper, we established a Lotka-Volterra model for the ecological evolution mechanism of MSE. And we get following conclusions and management significance. Firstly, the symbiotic evolution process of manufacturing service ecosystem is affected by the contribution coefficient between the two types of subjects. Secondly, the value of service resources of the two types of subjects in the stable state of Symbiosis Evolution is related to their contribution coefficient, the upper limit value of service resources and the externality coefficient of digital technology. The above research conclusions help to reveal the symbiotic evolution process of MSE, and help the SP and SP make correct symbiotic decisions. By making correct symbiotic decisions, understanding the influencing factors of symbiotic relationship construction, mastering the symbiotic evolution path of MSE subjects, and clarifying the structural characteristics of the MSE evolution process, the subjects of MSE build more stable, lasting and mutually promoting symbiotic relationships, thus ensuring the sustainability of MSE.

The limitation of this study is that only SI and SP in the MSE are selected for the study to explore the symbiotic relationship and the evolutionary process, while ignoring the different influencing factors that end users and complementary companies may bring. Therefore, the future research can be extended to the symbiotic evolutionary process between multiple subjects to further explore the evolutionary path of the MSE and the factors influencing its stability.

This work was supported by the Humanities and social sciences of the Ministry of Education Foundation of China (Program No. 16YJC630170).

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