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Modeling Analysis of Complex Products Resource Integration Behavior Under Distributed Collaborative Technology Innovation Mode

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Abstract According to new features of distributed technology innovation collaboration of complex products of China's aviation, in the multi-agent collaborative R&D process, between main manufacturer and suppliers, this paper summarizes the organizational structure and characteristics of collaborative mode of distributed technology innovation of complex products, basing on the technological innovation and resource integration of complex products, and treating resource contribution rate as a key parameter. It establishes multi-agent resource integration collaborative symbiosis model under distributed collaborative technology innovation mode based on symbiosis theory. And finds that some factors such as the basic attributes of the enterprise, the mutual influence of resources among enterprises and the behavior decision of the main manufacturer have some effects on the resource integration using stability analysis and simulation analysis, which provides a theoretical basis for the main manufacturer to optimize the behavior of suppliers' resource integration.

Keywords distributed technology innovation collaboration; resource integration behavior; main manufacturer-supplier; complex products

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1 Introduction

Complex products refer to the large capital goods or infrastructures, which have large research and development (Hereinafter called as "R&D") investment, high technology content and single or small batch of customers, such as large telecommunication system, mainframe computers, aerospace and energy chemical complex synthesis of large products, systems or infrastructures. The development production of complex products has the characteristics like technical difficulty, high product quality requirements and high knowledge intensity, which embodies a country's highest level of design and manufacturing capability. The success of system innovation of complex product can bring the upgrade of technology to the entire industry, also improve and promote the national competitiveness. Therefore, technical innovation of complex product is essential to national competitiveness, which directly determines the improvements of production efficiency and upgrading of industrial structure in the whole manufacturing industry and has become an important strategy to improve national design and manufacturing capacity. But the technological changing accelerates, the period of product life cycle shortens and the enterprises' living environments change dramatically due to the aggravation of market competition. People come to realize that limited resources for research and development of complex products will become increasingly difficult and we must rely on the internal knowledge.

The collaborative development model of complex products, as an effective mode of inter-firm cooperation, has outstanding performance in dispersing risk and reducing R&D costs. Taking Spanish companies as examples, Bayona, et al. researched and found that the difficulties for the R&D of enterprises lie in the complexity of technology, the uncertainty of R&D technology and the high cost of R&D[1]. The absorptive capacity of enterprise's technology and resources have an important influence on the cooperative effect. Market access, opportunity search and other factors have no significant impact on R&D cooperation. The research also finds that large enterprises are more willing to carry out research and development cooperation. Enterprises hope to innovate through collaboration.

At present, China's aviation manufacturing enterprises pay more attention to cross-industries, and collaboration across borders. And try to promote the level of technology innovation by strengthening the efficient allocation and integration of resources in affiliated enterprises. Due to China's aviation manufacturing industry resources are relatively dispersed, the core technology resources are relatively lacked and numbers of suppliers across regions and borders are very large. Compared to the main manufacturers of complex products, large supplier group shows the characteristics of "distributed". Based on the traditional complex equipment's "main manufacturer-supplier" cooperation mode, people currently pay more attention to the multi-agent distributed collaborative innovation in the process of development and production of aviation complex products, which includes the use of external resources, cooperation seeking, resources sharing and complementary advantages to promote the innovation of enterprises. If traced back, the phenomenon of supplier's distributed collaboration is determined by the relative lack of resources specialization of China's aviation manufacturing enterprises and the core technology. Also by the diverse demands of product R&D resources, and our advancement of strategic high-tech industries, and the realistic demand of accelerating the realization of the "made in China" to "created in China".

Therefore, in order to improve the development of China's complex products more scientifically and effectively, to be the main manufacturer of complex aeronautic products, then exploring the distributed collaborative innovation model between the self and the supplier group under the new situation is the premise of management. In the process of innovation, there are multiple behavioral undertakers and different stakeholders who have different roles, which means that the subject of innovation is not single, with a complex of intrinsic structure, namely, the multi-agent cooperation. Under the multi-agent distributed innovation cooperation, the production resources of complex products are very extensive. The integration of these resources can truly make full use of advantage, maintain the core competitiveness and achieve the sustainable development of enterprises. Accordingly, detailed analysis of multi-agent resource integration behavior under distributed collaborative innovation model is an important basic work for the main manufacturer to adjust and optimize the multi-agent resource integration behavior. This paper is based on the perspective of the main manufacturer management coordination and outlines distributed collaborative innovation model of complex products, using resource integration among distributed subjects as the focal point, and utilizes the symbiosis mechanism to construct a multi-agent resource integration behavior theory model of complex products, under distributed collaborative technology innovation mode then carry out the corresponding simulation analysis.

2 Literature Review

Distributed technology innovation collaboration is a cooperative model with distributed features, which is aimed at technological innovation. O'Sullivan thought that distributed innovation is an innovation built on a special internal interconnection network throughout the supply chain[2]. Bowden considered that distributed innovation is formed by various innovation activities[3]. It is a new technical service development mode which creates high quality products and services through sharing internal and external knowledge and resources. Damanpour thought that distributed innovation management is the process of managing innovation both within and across networks of organizations that have come together to co-design, co-produce and co-service the needs of customers[4]. Liu believed that distributed innovation is based on resource sharing, which is an innovation activity in different geographical areas between enterprises with supply chain partnership[5]. Luo thought distributed innovation is a kind of enterprise choice behavior, which is derived from the knowledge complementarity and the pursuit of resource innovation[6]. It is a process of developing the heterogeneous knowledge based on the complementary synergistic effect.

Investigation found that: distributed innovation mainly concentrates on high tech and information concentrated fields[7]. The proportion of the whole research and development expenditure in these areas is relatively higher than in other industries around the world[8]. Besides, distributed innovation behavior includes many cooperative subjects[9]. Only the effective distribution and balance of the distributed innovation benefits realize, can the stability of the multi subject innovation cooperation achieves[10]. Anderson and Joglekar considered innovation is a complex system, prone to emergent opportunities and risks[11]. Bogers and West showed the strategic implications of the research on distributed innovation by discussing the nature and sources of distributed innovation, how firms can increase the supply of such innovation, and how they can capture the value that is created as such[12]. Kanto, et al. thought that the distributed innovation model which integrates the customer knowledge can effectively help the enterprise to perceive market opportunities which are fast and dynamic[13].

Under the distributed technology innovation coordination, it is necessary to integrate the available resources of multiple subjects and realize the product development ultimately. The integration of technological resources refers to the behavior of integrating resources needed for technological innovation[14]. In supply chains, integration is a means to ensure coherency. Integration can be technological or logistical[15]. Chandra studied the integration and optimization of supply chain and constructed a supply chain model based on collaborative system method[16]. According to a study, Awasthi, et al. found that lack of resource sharing (integration), lack of organizational compatibility, lack of information sharing, lack of responsibility sharing, and lack of planning of supply chain activities are as top five barriers in supply chain integration[17]. Ghobakhloo, et al. found that process integrating of supply chain is an important multidimensional intermediate organizational capability through which the value of IS resources for supply chain management can be materialized[18]. For the manufacturers of complex product, the behavior of technology innovation resources integration is cross-organizational, global and complex. With the development of economic globalization, the communication of capital, technology, information and other resources between aviation manufacturing enterprises has exceeded the national boundaries.

Multiple cooperation of complex products between multi-agent enables the repeated exchanges and integration of resources, also makes the multi-agent's cooperative behavior become a kind of collaborative symbiotic relationship. This symbiosis is a subject resulting from the spontaneous cooperation union behavior, with the aid of external resources to achieve product innovation. In the supply chain, industrial symbiosis is a form of supply chain cooperation in industrial networks in order to achieve collective benefits by leveraging each others' by-products and sharing services and utilities[19]. Shi and Wu applied symbiosis theory and conception into supply chain alliance, established alliance profit allocation mechanism of supply chain from a new perspective, provided a reliable reference method for the efficient and effective operation of alliance to cope with vigorous market competition[20]. Ding, et al. explored the monitoring problem on the symbiotic stability of the supply chain alliance, with a view to prevent the potential risks in supply chain alliance[21]. Zhuo and Wang used evolution games to analyze formation and evolution of supply chain alliance symbiosis[22]. Holgado found that industrial symbiosis can help improve the overall efficiency of the industrial system[23]. The positive impact of implementing symbiotic exchanges between companies would benefit their host region through increased job creation and reduced environmental stress, meanwhile, the entities engaged could benefit from a combination of additional revenue streams and reduced costs.

The current research of distributed innovation mainly focuses on basic theory analysis and operation mechanism analysis of enterprise collaboration. Existing literature and research achievements laid a theoretical foundation for the distributed technology innovation collaboration of complex products. Although there is little literature about distributed innovation and resource integration in the complex products, most scholars think that distributed innovation is used in the high-tech enterprises with high technical content and multi-disciplinary areas collaboration, especially for the detailed analysis of the multinational innovation collaboration. This is very similar with the current R&D model of China's complex products. Therefore, based on the theories of the above literature research, this article systematically analyzes the distributed technology innovation collaborative mode of complex products. And focuses on the operation mechanism of multi-agent resources integration behavior and analyzes main factors of impacting the main manufacturer-supplier resources integration behavior.

3 The Subject Definition Of Distributed Technology Innovation Collaboration and Resource Integration

3.1 Overview of Distributed Technology Innovation Collaboration Model

Distributed technology innovation collaboration of complex products refers that the aviation manufacturing enterprise and its cooperative suppliers take technology innovation as a common goal, by means of resources sharing and information exchanging between different regional enterprises to cooperate together, and to complete the complex products R&D cooperation model. In this cooperation mode, the subjects take the "main manufacturer-supplier" organization mode as the basic cooperation framework. Distributed technology innovation collaboration of complex products starts from technology innovation distribution and redefines the "main manufacturer-supplier" collaborative model. It is a collaborative innovation cooperation behavior, which highlights the cooperation between the main manufacturer and suppliers. This behavior takes the pursuit of technological innovation as an important target, and uses complementary resources as the basic cooperation premise.

The cooperation subjects of distributed technology innovation collaboration are divided into two categories. One is the main manufacturer and the other is a supplier. The main manufacturer is the helmsman and manager of complex products development project, in the absolute heart of cooperation. The supplier is a partner, who belongs to the helper of project research and development, at the subordinate position in collaborative cooperation. Thus, distributed technology innovation collaboration model can be summarized into three main features: 1) Emphasize the cooperation in cross-region and cross-organization; weaken the importance of geographical position. 2) Emphasize the complementary resources in cross-disciplinary and cross-domain; focus on complementary knowledge. 3) Emphasize the consistency and synchronicity of cooperative behaviors; focus on the identity of cooperation.

3.2 Distributed Technology Innovation Collaboration with the Multi-Agent Resource Integration

Resource integration refers to a series of related process of comprehensive utilization of resources[24]. Distributed technology innovation collaboration resources are the generic terms of material resources, technical resources, management resources and other resources which are needed to invest in the development and production process of complex products. This kind of resource is the exclusive resource of the supplier, which represents the core competence of the supplier and is also the key reason for the supplier to win the cooperation opportunity of complex products. As a result, the main manufacturers are more concerned about the dedicated resources of suppliers, with the scientific research of human resources, equipment resources, proprietary technology, resources as the key points. Therefore, the distributed technology innovation collaborative resources in this paper refers to the establishment of human resources, material resources and patent technology, three aspects on the basis of specific resources that supplier can provide.

The behavior subjects of complex products resource integration are the main manufacturer and suppliers. Generally speaking, the main manufacturer is the only, fully responsible for the project control in the product development process, and is the main promoter and executor of the resource integration behavior. Supplier is a large and complex enterprise group in the process of distributed technology innovation collaboration of complex products. According to the importance of the suppliers in the cooperation, all kinds of suppliers can be divided into different levels. Primary subordinate subject refers to core suppliers who establish strategic cooperative partner with the main manufacturer. They are in charge of partial core development work of the complex product and also undertake resource integration management to suppliers of next level (the i-th level affiliated subject). In short, resource integration subject in the process of the complex products distributed collaborative innovation has a multisubject structure of "$1 - n$". Resource integration behavior refers to a process of n different level of suppliers' resources integrated and configured by the main manufacturer, as is shown in Figure 1.

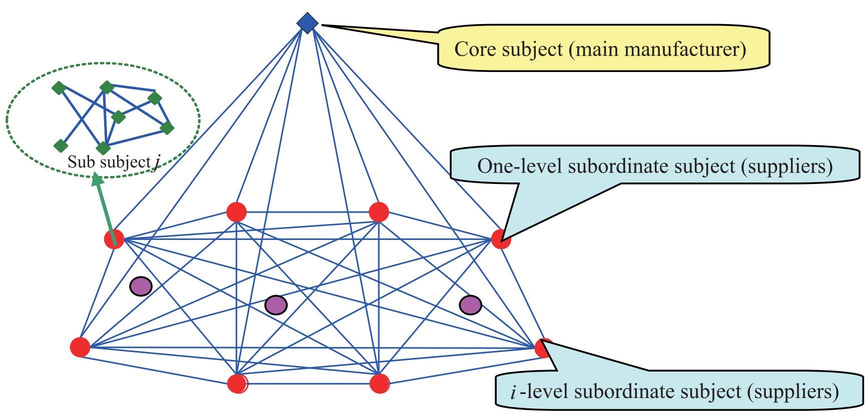


Figure 1 The behavior subject of resource integration

Combined with the above figure, we can find: Firstly, the distributed technology innovation collaboration pattern of complex products distinguishes status difference of the main manufacturer and suppliers in the whole process of the project cooperation. Resource integration behavior between the main manufacturer and suppliers is unequal. Cooperation among multiple agents does not need to manage through the third parties, which is planned and managed by the main manufacturer. Secondly, a vast network of suppliers shows that research and development activities of complex products emphasize more on heterogeneous resource integration and capacity complementation of enterprises in multi-disciplinary area. Resource integration under distributed collaborative innovation of complex products is a comprehensive resource matching problem with heterogeneous complementation. Both sides of supply and demand participating in the resource integration follow the principle of "draw on each others' strength".

4 The Basic Analysis of Multi-Agent Resource Integration Behavior Modeling

4.1 Behavior Analysis of Multi-Agent Cooperative Symbiosis

In the whole production cycle of aviation products, the main manufacturer and suppliers is the cooperation subject of distributed technology innovation collaboration of complex products, and has a long-term cooperation relationship. Suppliers participating in distributed collaborative innovation cooperation constitute a strategic partner group with benefit and risk sharing, and long-term cooperation in the subsequent order reproduction and product improvement process, until the complex product market ends, as is shown in Figure 2. This multiple cooperative behavior between multi-subject promotes enterprise resources to repeatedly communicate and integrate. It urges the multi-agent cooperative behavior into a collaborative symbiotic relationship based on the premise of pursuing the maximization of aviation products value.

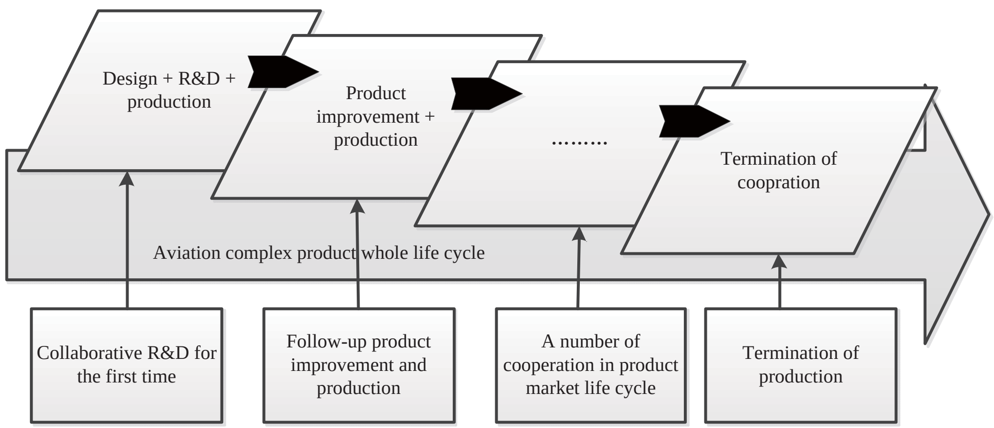


Figure 2 Multi-agent cooperative symbiotic relationship in the whole production cycle of aviation complex products

Multi-agent cooperative symbiosis of complex products is an outward manifestation of the subject's behavior and is a spontaneous cooperation alliance behavior, of which the subject achieves product technology innovation and production with the help of the enterprise external resources. There is an obvious enterprise difference among cooperative alliance members, the difference between core enterprise (such as main manufacturer and the first-tier suppliers) and non-core enterprises (such as the common supplier). It forms an asymmetric and mutually beneficial symbiotic model through the complementary advantages of the resources and maintains the alliance symbiotic relationship through positive effects of multiple subjects. With the development of the different stages of the whole production cycle, the cooperative symbiotic relationship among multi-agents is also in the process of dynamic evolution[25]. Through the existing research results, it can be found that the symbiotic relationship between the subjects of cooperation is conducive to the discovery of the interaction between multi-agent cooperative behavior and the mechanism of behavior evolution. In the whole life cycle of complex products, based on the premise of resource complementation and long-term cooperation, the main manufacturer and suppliers constitute an interdependent symbiotic relationship. Compared with cooperative symbiotic relationship of common products, there are five different aspects in the symbiotic relationship of complex aeronautic products (as is shown in Table 1).

Table 1 Comparison of the symbiotic relationship between complex products and common products

Serial number	Different items	Cooperative symbiosis of aviation complex products	Cooperative symbiosis of common products
1	Symbiotic subject	Main manufacturers and suppliers	Core enterprises and satellite companies
2	Symbiotic status	Active and follow-up	Core and non-core
3	Independence of the main body of symbiosis	Are able to survive independently	The core enterprise has the ability of independent development, the development of satellite enterprises under the independent case decay until death
4	Symbiotic goal	Focus on the technological value creation of the unit resource	Focus on production output under the unit resource input
5	Symbiotic essence	Complementation and integration of heterogeneous resource	Industrial linkage between the up-stream and down-stream supply chain

Based on this, this paper will use the symbiosis theory to build a symbiosis model under the integration of multi-agent distributed resources, based on the heterogeneous resources complementation and make correlation analysis.

4.2 Basic Assumptions of the Model

To illustrate the multi-agent cooperative symbiosis behavior model of complex products, the following model assumptions are set up:

Assumption 1 A certain segment of relevant R&D work of a certain complex product can be divided into a master subsystem P^0 (namely the main manufacturer is responsible for the R & D) and m subsystems $P^i\,(i = 1, 2, \cdots, n)$ (namely, suppliers participate in collaborative work).

Assumption 2 R&D of a certain Complex product is completed by a main manufacturer M and n suppliers $S_i\,(i = 1, 2, \cdots, n)$. In order to facilitate the division of responsibilities and simplify the study, it is assumed that there is a one-to-one correspondence between the number of suppliers and the number of subsystems.

Assumption 3 In order to reflect the essence of resource integration in the process of collaborative R&D of complex products, it is assumed that there is a resource complementation between the supplier groups and supplier's cooperative behavior will affect other subjects.

4.3 Basic Analysis of Model

Due to the influence of resources complementary, the symbiotic relationship between the main manufacturer and suppliers has evolved into a symbiotic relationship based on promoting economic growth by product technology innovation, which is under the essence of resource integration. In this symbiotic relationship, coordination symbiotic value-added effect and resource integration value-added effects determine the development of the symbiotic relationship between the main manufacturer and suppliers.

① Synergistic symbiotic value-added effect and connotation

If the interest of the main manufacturers M is $x_0 > 0$, the interest of the supplier S_i is $x_i > 0\,(i = 1, 2, \cdots, n)$. When the main manufacturer and suppliers independently use their own resources for R & D production, only consider the impact of resource input on interests, the interests are

$$x_i = a_i R_i', \quad i = 0, 1, \cdots, n. \tag{1}$$

R_i' means actual resource value of which the subject puts into production, under normal circumstances, enterprise resources in the short term will not produce significant changes. Therefore, this paper assumes that resources of the subject R_i' has the maximum value $\bar{R}_i$; a_i means resource contribution rate under the condition of independent subject which is generally determined by the basic properties of the enterprise and the characteristics of the industry.

When the main manufacturer and suppliers collaborate, collaborative overall interests are

$$\begin{cases} R_c = \sum\limits_{i=0}^{n} R_i', \\ X_c = \sum\limits_{i=0}^{n} x_i + X_s. \end{cases} \tag{2}$$

X_c expresses the symbiotic interests, X_s expresses symbiotic added value under the integration of resources. When $X_s \geq 0$, the benefit of the cooperative behavior of each subject is not simply linear superposition, it produces a very important "symbiotic added value" effect in the process of resource overlay. Symbiotic value-added effect originates from the increase of the contribution rate of each participant's resources. Resource contribution rate is the ratio of the income and the resource investment value. Complex product is a large system with high technical content and high performance. Compared to the general product, its product value has more obvious advantages. Therefore, for each subject participating in collaboration, symbiotic value-added effect is based on the following condition: benefit of using resources to collaboratively produce complex products, is larger than that of using the same resources to independently produce ordinary products to obtain, as is shown in Formula (2).

② Resource integration effect and connotation

Studies have shown that the diversity established under the heterogeneous resources complementary cooperation is very favorable for forming the core competitive ability. Enterprises achieve complementary advantages through the acquisition and resources exchange. Resource complementation has a positive effect on the innovation performance of enterprises. Therefore, for complex products, there is a significant correlation between the size of symbiotic value-added effect and the matching degree of the resources involved in the subject.

When the resource of the subject is more matched with the resources needed by the corresponding subsystem, resource complementation between the subjects is better. Then collaborative symbiotic value-added effect will be more obvious. It is assumed that the resources matching degree is ψ_i. $\psi_i = 0$ means that the resources provided by the subject are completely mismatched with the resources needed by the subsystem. $\psi_i = 1$ means the resources provided by the subject are completely matched with the required resources. When the main manufacturer M and n suppliers S_i make innovative collaboration of complex products, the interests of the subject will be affected by the following factors: 1) Input resources value R_i'; 2) Resources contribution rate a_i; 3) Resources matching degree ψ_i; 4) The relative influence coefficient of the subject j on the subject i under the complementary effect of resources.

Therefore, as is shown in Formula (2), the overall interest of the main manufacturer-supplier under innovation collaboration is expressed as follows:

$$X_c = \sum_{i=0}^{n} a_i R_i' + X_s, \quad X_s = \sum_{i=0}^{n}\sum_{j=0}^{n} b_{ij}\psi_j a_i R_i'. \tag{3}$$

Make $B = (b_{ij})_{(n+1)\times(n+1)}$ and

$$B= \begin{bmatrix} b_{00} & b_{01} & b_{02} & \cdots & b_{0n} \\ b_{10} & b_{11} & b_{12} & \cdots & b\cdots \\ b_{20} & b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ b_{n0} & b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}. \tag{4}$$

When $i = j$, make $b_{ij} = 0$. When $i \neq j$, b_{ij} expresses the influence coefficient of subject j on subject i. Only when mutual influence coefficient among enterprises is non-negative ($b_{ij} \geq 0$), enterprises can be collaborative. If $b_{ij} < 0$, it is indicated that the benefit of enterprise collaboration will be damaged, the synergy will not happen. Therefore, the range of values b_{ij} is $b_{ij} \geq 0$

Make (3) unite like items and get:

$$X_c = \sum_{i=0}^{n} \left(1 + \sum_{j=0}^{n} b_{ij}\psi_j\right) a_i R_i'. \tag{5}$$

At this point, the interests of main body i in the cooperation of technology innovation of complex products:

$$X_i = \left(1 + \sum_{j=0}^{n} b_{ij}\psi_j\right) a_i R_i'. \tag{6}$$

Apparently, $\sum_{j=0}^{n} b_{ij}\psi_j$ means the sum of complementary resources degree of subject j to subject i in the process of collaborative innovation. That is, when the resource matching degree of other participants (including suppliers and main manufacturer) is higher and the influence coefficient is bigger, the resource complementary effect among participants will be more obvious.

Through Formula (5), we can find that the "complementary effect of resources" is the basic reason of the "symbiotic added-value effect". The complementary resources of each subject make the contribution rate of the main resource to be further increased through the integration of resources and produce the "symbiotic value-added effect".

5 Multi-Agent Cooperative Symbiotic Resource Integrated Behavior Modeling

Due to the subjects have long-term cooperation in the process of complex aeronautic product innovation collaboration, we can assume that the interests of all participants continuously change, then interest relative growth rate of subject is $\frac{1}{X_i}\cdot\frac{\mathrm{d}X_i}{\mathrm{d}t}$. The formula (1) shows that the interest of the subject is related to the resource input and resources contribution rate. In order to make a difference between the value of resource investment in the R&D of complex products and that of same resources put into normal products, this paper assumes that when the main manufacturer and suppliers are in the complex products collaborative innovation, total resources input is a relatively fixed value, resource contribution rate is developed with the development of science and technology innovation. Thus, the interest relative growth rate of the subject can be simplified as the growth rate of the resources contribution rate, which is $\frac{1}{X_i}\cdot\frac{\mathrm{d}X_i}{\mathrm{d}t}=\frac{1}{a_i}\cdot\frac{\mathrm{d}a_i}{\mathrm{d}t}$. Here is the construction of multi-agent cooperative symbiosis model under the collaborative mode of distributed technology innovation of complex products.

5.1 Construction and Stability Analysis of Multi-Agent Cooperative Symbiosis Model

Considering the subject's scientific and technological innovation ability, the resource contribution rate of the subject's individual production meets the Logistic model:

$$\frac{\mathrm{d}a_i}{\mathrm{d}t}=k_ia_i\left(1-\frac{a_i}{\overline{a_i}}\right). \tag{7}$$

k_i expresses the growth rate of resource contribution rate of the subject i under the independent production, $\overline{a_i}$ expresses the maximum value of resource contribution rate of the subject i under the limited situation of science and technology innovation ability.

There is a mutual influence of the subject in the cooperation process. Considering the impact of the other n participants on the subject i, the main resource contribution rate of the subject i meets the following formula:

$$\frac{\mathrm{d}a_i}{\mathrm{d}t}=k_ia_i\left(1-\frac{a_i}{\overline{a_i}}+\sum_{j=0}^{n}b_{ij}\psi_j\frac{a_j}{\overline{a_j}}\right). \tag{8}$$

In order to simplify the operation, we take the "one main manufacturer and two suppliers" as an example to analyze the synergy.

If $n=2$, Formula (8) can be converted to:

$$\begin{cases} f(a_0,a_1,a_2)\equiv\dfrac{\mathrm{d}a_0}{\mathrm{d}t}=k_0a_0\left(1-\dfrac{a_0}{\overline{a_0}}+b_{01}\psi_1\dfrac{a_1}{\overline{a_1}}+b_{02}\psi_2\dfrac{a_2}{\overline{a_2}}\right)=0,\\ g(a_0,a_1,a_2)\equiv\dfrac{\mathrm{d}a_1}{\mathrm{d}t}=k_1a_1\left(1-\dfrac{a_1}{\overline{a_1}}+b_{10}\psi_0\dfrac{a_0}{\overline{a_0}}+b_{12}\psi_2\dfrac{a_2}{\overline{a_2}}\right)=0,\\ k(a_0,a_1,a_2)\equiv\dfrac{\mathrm{d}a_2}{\mathrm{d}t}=k_2a_2\left(1-\dfrac{a_2}{\overline{a_2}}+b_{20}\psi_0\dfrac{a_0}{\overline{a_0}}+b_{21}\psi_1\dfrac{a_1}{\overline{a_1}}\right)=0. \end{cases} \tag{9}$$

The solution of differential equations (9) can obtain 8 equilibrium points:

$P_1(0,0,0)$, $P_2(0,0,\overline{a_2})$, $P_3(0,\overline{a_1},0)$, $P_4(\overline{a_0},0,0)$, $P_5(\overline{a_0}\frac{1+b_{01}\psi_1}{1-b_{01}\psi_1 b_{10}\psi_0},\overline{a_1}\frac{1+b_{10}\psi_0}{1-b_{01}\psi_1 b_{10}\psi_0},0)$, $P_6(\overline{a_0}\frac{1+b_{02}\psi_2}{1-b_{02}\psi_2 b_{20}\psi_0},0,\overline{a_2}\frac{1+b_{20}\psi_0}{1-b_{02}\psi_2 b_{20}\psi_0})$, $P_7(0,\overline{a_1}\frac{1+b_{12}\psi_2}{1-b_{12}\psi_2 b_{21}\psi_1},\overline{a_2}\frac{1+b_{21}\psi_1}{1-b_{12}\psi_2 b_{21}\psi_1})$.

To simplify the expression, make

$$\begin{cases} \omega = b_{01}\psi_1 b_{10}\psi_0 + b_{02}\psi_2 b_{20}\psi_0 + b_{12}\psi_2 b_{21}\psi_1 + b_{01}\psi_1 b_{12}\psi_2 b_{20}\psi_0 + b_{02}\psi_2 b_{10}\psi_0 b_{21}\psi_1, \\ \xi_0 = b_{01}\psi_1 + b_{02}\psi_2 + b_{01}\psi_1 b_{12}\psi_2 + b_{02}\psi_2 b_{21}\psi_1 - b_{12}\psi_2 b_{21}\psi_1, \\ \xi_1 = b_{10}\psi_0 + b_{12}\psi_2 + b_{02}\psi_2 b_{10}\psi_0 + b_{12}\psi_2 b_{20}\psi_0 - b_{02}\psi_2 b_{20}\psi_0, \\ \xi_2 = b_{20}\psi_0 + b_{21}\psi_1 + b_{01}\psi_1 b_{20}\psi_0 + b_{10}\psi_0 b_{21}\psi_1 - b_{01}\psi_1 b_{10}\psi_0. \end{cases} \tag{10}$$

The balance point P_8 can be expressed as $P_8(\overline{a_0}\frac{1+\xi_0}{1-\omega},\overline{a_1}\frac{1+\xi_1}{1-\omega},\overline{a_2}\frac{1+\xi_2}{1-\omega})$.

Combined with the resources integration problems under the distributed technology innovation collaboration of complex products, polynomial represented by the above four parameters ω,ξ_0,ξ_1,ξ_2 describes detailedly the mutual influence relationship between the main manufacturer and two suppliers.

① Realistic meaning of ω

Based on complex products innovation collaboration, ω expounds the comprehensive influence degree of resources integration behavior in cooperation. There are two kinds of influence degree, one is the cross impact among the subjects, the other is the circulation effect. The "effect" is expressed by the degree of complementation between the subjects. In the whole coordination process, resource complementation between the subjects determines the resource contribution rate of each other, as is shown in Figure 3. According to the expression of ω, it can be known that only when the main manufacturer and suppliers group have a positive effect, the group can play a synergistic effect. So when $\omega > 0$, it has the economic meaning.

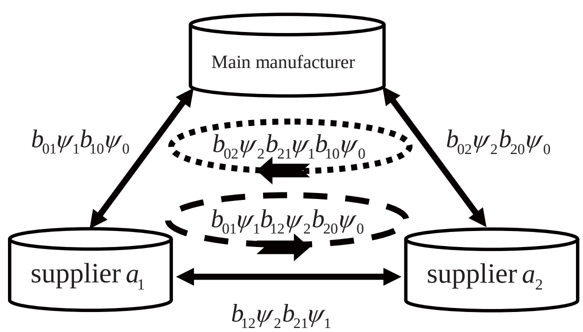


Figure 3 Schematic diagram of the comprehensive influence degree of resource integration on the whole body

② Realistic meaning of ξ_i $(i = 0,1,2)$

Based on product innovation collaboration, ξ_i expounds the influence degree of the other participants in the contribution rate of the main resources i by the complementary effect of resources. Take the main manufacturer as an example, supplier S_1 and supplier S_2 have an impact on the main manufacturer. Besides, the mutual impact between the two suppliers will also have secondary impacts on the main manufacturers, as is shown in Figure 4. Obviously, based on innovation collaboration, the main manufacturer and suppliers form a symbiotic group.

So only when $\xi_i > 0$, it has the economic meaning. There is a positive effect between the subjects.

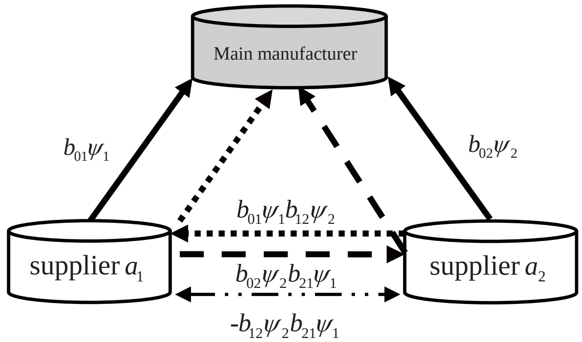


Figure 4 Schematic diagram of the influence degree of resource integration behavior on collaborative individuals

Balance point P_8 expresses that the resource contribution rate of the main manufacturer M, supplier S_1 and supplier S_2 are $\overline{a_0}\frac{1+\xi_0}{1-\omega}$, $\overline{a_1}\frac{1+\xi_1}{1-\omega}$, $\overline{a_2}\frac{1+\xi_2}{1-\omega}$. If the above three equations are not zero, then the subject can meet the cooperative symbiosis under the resource integration behavior. Therefore, when the condition meets the following inequality, the equilibrium point P_8 has the economic meaning:

$$\begin{cases} \overline{a_0}\dfrac{1+\xi_0}{1-\omega} > 0, \\ \overline{a_1}\dfrac{1+\xi_1}{1-\omega} > 0, \\ \overline{a_2}\dfrac{1+\xi_2}{1-\omega} > 0. \end{cases}$$

Solve the above inequalities and get: $\omega > 1, \xi_0 < -1, \xi_1 < -1, \xi_2 < -1$ or $\omega < 1, \xi_0 > -1, \xi_1 > -1, \xi_2 > -1$. From the above, we can know that $\xi_i > 0$, the symbiotic conditions of the main manufacturer M, supplier S_1 and supplier S_2 are $0 < \omega < 1$.

Obviously, only when balance point P_8 achieves stability, then three participants in the process of innovation collaboration of complex products can achieve the symbiotic development. Therefore, the seven equilibrium points from P_1 to P_7 are not discussed in detail in this paper and only make stability analysis to P_8. According to the stability theory of differential equation[26], when and only when $0 < \omega < 1$, the equilibrium point P_8 is the stable point. $0 < \omega < 1$ refers that the impact of resource integration on the interests of enterprises among subjects has certain limitation. Its practical significance is that in the complex products collaborative innovation process, although there is positive interaction between enterprises, the enterprise's own property is still the primary factor which has an influence on enterprise resource contribution rate. This is decided by the enterprise's core competitive ability and can't be replaced by any enterprise. It also shows that level differences of various types of enterprises must be in a reasonable range. Only when the level of technology is similar to enterprise strength, will inter enterprise resources integration behavior realize a mutually beneficial and benign development. For the whole life cycle of complex products in the current technological development environment, resource integration behavior of the main manufacturer and suppliers makes the mutual influence between enterprises continue to grow. The resource contribution rate of each subject is continuously improving. However, growth space of resource contribution rate will be affected by the enterprise scientific research ability and the current level of social science and technology. When $\omega \geq 1$, the equilibrium point of differential equations (9) is unstable. $\omega \geq 1$ refers that the degree of mutual influence among different subjects can become wider. Mapping to reality, it can be understood like this: For the complex products, in the process of the main manufacturer and suppliers' collaboration, it may create a new production technology. And once the new technology can be successfully developed and put into production, it will lead to a milestone when collaborative enterprise realizes science and technology development. At this time, for any collaborative subject, the symbiotic stability under the existing technical productivity will be broken, the resource contribution rate will continue to grow and seek new stability in the new technological development environment.

5.2 Construction and Stability Analysis of Multi-Agent Cooperative Symbiosis Model Under Active and Dynamic Behavior

In Model (9), the main manufacturer and suppliers have a peer-to-peer relationship. But in the actual process, they have a kind of non-reciprocal relationship of "active and follow-up". Two types of subject are in a upstream and downstream relationship of the supply chain. The main manufacturer with right status advantage can have the right of active intervention and management to the supplier. In the collaborative process, the main manufacturer's behavior is active and supplier's behavior is a reaction to the main manufacturer's, which has an apparent followability. Therefore, to pursue the efficiency of resource integration, the main manufacturer needs to take the initiative to intervene in the resource integration activities of complex products.

Taking into account that all participants are interest seekers, according to the viewpoint of western economics, resource optimization allocation, in fact, is a process that derives from production relations analysis and ultimately rests in the distribution of value and interests. As a result, the way that the main manufacturer intervene in resource integration can ultimately be achieved through the adjustment of benefit allocation of collaborative subject. For the main manufacturer, the ultimate embodiment of resources integration is the distribution of the overall interests. Therefore, from the perspective of interest allocation, multi-agent cooperative symbiosis model under the active and dynamic behavior is constructed from the angle of the main manufacturer. Generally speaking, the most reasonable cooperative profit distribution principle is: Each participant achieves their own created achievements, namely, the value X_i is created by the resources provided by itself in the integration of value-added profits, as is shown in Formula (6). But considering the unequal status of collaborative subject, the main manufacturer as a rational economic man can redistribute the value X_i of theoretical interest distribution using their own decision-making power and stimulate subject cooperative behavior change through the interest adjustment. As is shown in Figure 5, either the main manufacturer or suppliers, when their respective resource input value remains constant, the resource contribution value (interest) has three special numerical numbers: The original interest in the independent state, theoretical benefit distribution in the collaborative state and the actual benefit distribution in the collaborative state. From the independent state to collaborative state, intersubjective collaboration creates the "resource integration value-added profit"; in the collaborative state, the unequal status of subject makes profit distribution appear in non equivalence of theory and practice.

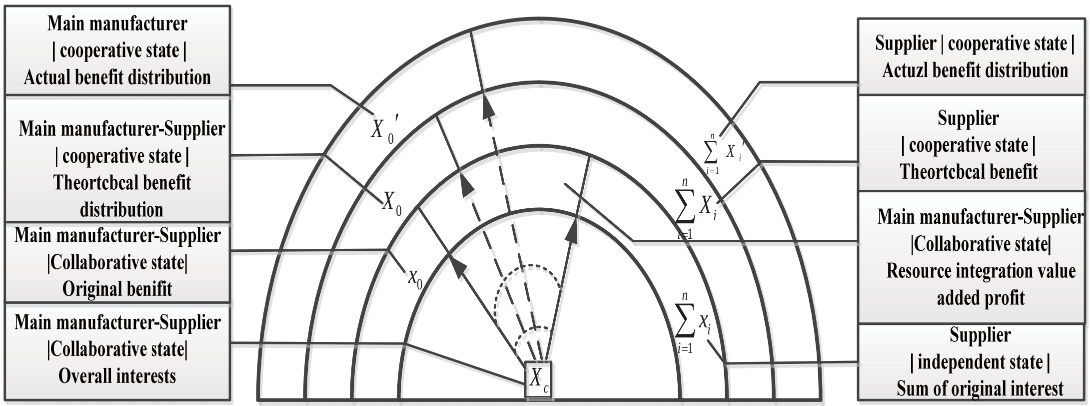


Figure 5 Collaborative profit distribution graph of the main manufacturer and suppliers

Assume that the actual benefit distribution of the main manufacturer is

$$X_0' = \left(1 + \sum_{j=0}^{n} b_{0j}\psi_j\right) a_0 R_0' + \Delta X_s. \tag{11}$$

ΔX_s expresses the profit value created by the main manufacturer's non-self resources, obtained from value-added profit of resource integration.

The actual benefit sum of all suppliers is

$$\sum_{i=1}^{n} X_i' = \sum_{i=1}^{n} X_i - \Delta X_s. \tag{12}$$

According to the definition of resource contribution rate:

$$a_i = \frac{X_i}{R_i'}. \tag{13}$$

When the actual resource input value a_2 of the enterprise is relatively stable, the resource contribution rate is positively related to the benefit. Therefore, according to Formula (11) we can know that when benefit changes, actual resource contribution rate also changes. If the resource input value is fixed, the resource contribution rate of the main manufacturer and suppliers in the cooperative state can meet the following formula:

$$\begin{cases} \dfrac{\mathrm{d}a_0}{\mathrm{d}t} = k_0 a_0 \left(1 - \dfrac{a_0}{\overline{a_0}} + \displaystyle\sum_{j=1}^{n} b_{0j}\psi_j \dfrac{a_j}{\overline{a_j}} + \vartheta_0\right), \\ \dfrac{\mathrm{d}a_i}{\mathrm{d}t} = k_i a_i \left(1 - \dfrac{a_i}{\overline{a_i}} + \displaystyle\sum_{j=0}^{n} b_{ij}\psi_j \dfrac{a_j}{\overline{a_j}} + \vartheta_i\right). \end{cases} \tag{14}$$

ϑ_i indicates the impact coefficient produced on the resources contribution rate of the subject when the main manufacturer intervenes in cooperative group resource integration. Combined with the collaborative model of main manufacturer and suppliers, the relationship between influence coefficient ϑ_i can be divided into the following three categories: The first category: When $\vartheta_i = 0$ $(i = 0, 1, \cdots, n)$, the main manufacturer fails to take measures, and resource contribution rate of cooperative groups is not affected. The second category: When $\vartheta_0 > 0$, main manufacturer makes its own resources contribution ratio increase using their decision-making power to obtain the excess interest, based on enhancing the overall resource integration efficiency of aviation products. For resource integration value-added benefits generated by cooperative behavior of complex products is a relatively fixed value, then the excess profit of the main manufacturer directly leads to the total profit of all suppliers becoming less. Therefore, for the set $\{\vartheta_1, \vartheta_2, \cdots, \vartheta_n\}$, there is at least one supplier's actual benefit allocation value being lost. The third category: When $\vartheta_0 < 0$, the main manufacturer follows altruistic principle to take positive incentive strategy for suppliers to promote resource integration and chooses to assign their deserving benefits to suppliers in the final distribution of benefits. At this time, resource contribution rate of the main manufacturer will decrease. Therefore, for set $\{\vartheta_1, \vartheta_2, \cdots, \vartheta_n\}$, there is at least one supplier's actual benefit allocation being increased. For convenience, we assume that the main manufacturer is fair to any supplier, there is no difference between suppliers, so active intervention of the main manufacturer is for all suppliers.

The innovation collaboration of complex product involves $(n + 1)$ subjects, the constructed symbiotic model is an equation group with $(n + 1)$ dimensional. In order to simplify the research operation, this paper takes $n = 2$ and studies the symbiotic situation between one main manufacturer and two suppliers.

The formula (14) is written as the following equations:

$$\begin{cases} f(a_0, a_1, a_2) \equiv \dfrac{\mathrm{d}a_0}{\mathrm{d}t} = k_0 a_0 \left(1 - \dfrac{a_0}{\overline{a_0}} + b_{01}\psi_1 \dfrac{a_1}{\overline{a_1}} + b_{02}\psi_2 \dfrac{a_2}{\overline{a_2}} + \vartheta_0\right) = 0, \\ g(a_0, a_1, a_2) \equiv \dfrac{\mathrm{d}a_1}{\mathrm{d}t} = k_1 a_1 \left(1 - \dfrac{a_1}{\overline{a_1}} + b_{10}\psi_0 \dfrac{a_0}{\overline{a_0}} + b_{12}\psi_2 \dfrac{a_2}{\overline{a_2}} + \vartheta_1\right) = 0, \\ k(a_0, a_1, a_2) \equiv \dfrac{\mathrm{d}a_2}{\mathrm{d}t} = k_2 a_2 \left(1 - \dfrac{a_2}{\overline{a_2}} + b_{20}\psi_0 \dfrac{a_0}{\overline{a_0}} + b_{21}\psi_1 \dfrac{a_1}{\overline{a_1}} + \vartheta_2\right) = 0. \end{cases} \tag{15}$$

Solve the above equations; the following eight equilibrium points can be solved:

$$\begin{aligned} &P_1(0,0,0), P_2(0,0,(1+\vartheta_2)\overline{a_2}), P_3(0,(1+\vartheta_1)\overline{a_1},0), P_4((1+\vartheta_0)\overline{a_0},0,0), \\ &P_5\left(\overline{a_0}\cdot\frac{1+\vartheta_0+(1+\vartheta_1)b_{01}\psi_1}{1-b_{01}\psi_1\cdot b_{10}\psi_0}, \overline{a_1}\cdot\frac{1+\vartheta_1+(1+\vartheta_0)b_{10}\psi_0}{1-b_{01}\psi_1\cdot b_{10}\psi_0}, 0\right), \\ &P_6\left(\overline{a_0}\cdot\frac{1+\vartheta_0+(1+\vartheta_2)b_{02}\psi_2}{1-b_{02}\psi_2\cdot b_{20}\psi_0}, 0, \overline{a_2}\cdot\frac{1+\vartheta_2+(1+\vartheta_2)b_{20}\psi_0}{1-b_{02}\psi_2\cdot b_{20}\psi_0}\right), \\ &P_7\left(0, \overline{a_1}\cdot\frac{1+\vartheta_1+(1+\vartheta_2)b_{12}\psi_2}{1-b_{12}\psi_2\cdot b_{21}\psi_1}, \overline{a_2}\cdot\frac{1+\vartheta_2+(1+\vartheta_1)b_{21}\psi_1}{1-b_{12}\psi_2\cdot b_{21}\psi_1}\right), \end{aligned}$$

make

$$\begin{cases} \zeta_0 = \vartheta_1 b_{01}\psi_1 + \vartheta_2 b_{02}\psi_2 + \vartheta_2 b_{01}\psi_1 b_{12}\psi_2 + \vartheta_1 b_{02}\psi_2 b_{21}\psi_1 - \vartheta_0 b_{12}\psi_2 b_{21}\psi_1, \\ \zeta_1 = \vartheta_0 b_{10}\psi_0 + \vartheta_2 b_{12}\psi_2 + \vartheta_2 b_{10}\psi_0 b_{02}\psi_2 + \vartheta_0 b_{12}\psi_2 b_{20}\psi_0 - \vartheta_1 b_{20}\psi_0 b_{02}\psi_2, \\ \zeta_2 = \vartheta_1 b_{21}\psi_1 + \vartheta_0 b_{20}\psi_0 + \vartheta_0 b_{21}\psi_1 b_{10}\psi_0 + \vartheta_1 b_{20}\psi_0 b_{01}\psi_1 - \vartheta_2 b_{01}\psi_1 b_{10}\psi_0. \end{cases} \tag{16}$$

Then the equilibrium point P_8 can be expressed as

$$P_8\left(\overline{a_0}\frac{1+\vartheta_0+\zeta_0+\xi_0}{1-\omega}, \overline{a_1}\frac{1+\vartheta_1+\zeta_1+\xi_1}{1-\omega}, \overline{a_2}\frac{1+\vartheta_2+\zeta_2+\xi_2}{1-\omega}\right).$$

According to the characteristics of innovation collaboration of complex product, symbols $\zeta_0, \zeta_1, \zeta_2$ in the equilibrium point P_8 respectively indicate the resource interaction relationship between subjects with consideration of the fixed influence factors. Compare the formula (16) with the formula (10), we can find that the difference between ζ_i $(i = 0, 1, 2)$ and $\zeta_0, \zeta_1, \zeta_2$ lies in the existence of the factors affecting the behavior of the main manufacturer. Take ζ_0 as an example to make a detailed explanation.

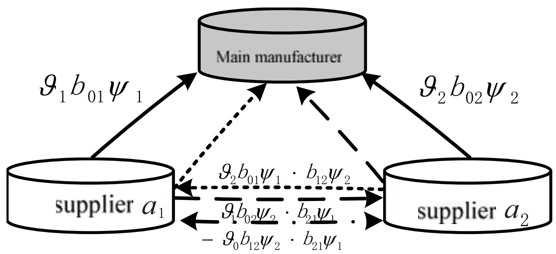


Figure 6 The influence sketch chart of active intervention of the main manufacturer in the intergration of resources

According to Figure 6, ζ_0 illustrates the impact of resource contribution rate of suppliers on the main manufacturer under considering the active intervention of the main manufacturer in resources integration. Suppliers directly affect the main manufacturer and indirectly affect the main manufacturer through the transmission of the relationship.

According to the expression of the equilibrium point P_8, we can know that achieving symbiotic conditions between the main manufacturer and suppliers needs to meet the following inequalities:

$$\begin{cases} \overline{a_0}\dfrac{1+\vartheta_0+\zeta_0+\xi_0}{1-\omega} > 0, \\ \overline{a_1}\dfrac{1+\vartheta_1+\zeta_1+\xi_1}{1-\omega} > 0, \\ \overline{a_2}\dfrac{1+\vartheta_2+\zeta_2+\xi_2}{1-\omega} > 0. \end{cases}$$

According to the definition of $\vartheta_i (i = 0, 1, 2)$, we can know that when $\vartheta_0 < 0$, and $\vartheta_1 > 0, \vartheta_2 > 0$, ϑ_0 needs to meet $-(1 + \zeta_0 + \xi_0) < \vartheta_0 < 0$, $\omega < 1$; when $\vartheta_0 > 0$ and $\vartheta_1 < 0, \vartheta_2 < 0, \vartheta_1, \vartheta_2$ needs to meet $-(1 + \zeta_1 + \xi_1) < \vartheta_1 < 0$, $-(1 + \zeta_2 + \xi_2) < \vartheta_2 < 0$, $\omega < 1$.

Obviously, only when the equilibrium point P_8 is stable, all subjects can realize the symbiotic development in the process of technological innovation of complex products. Similarly, this paper only focuses on the stability analysis to P_8.

According to the stability theory of differential equation, when meet the conditions

$$\begin{cases} \vartheta_0 > 0, \\ -(1+\zeta_1+\xi_1) < \vartheta_1 < 0, \\ -(1+\zeta_2+\xi_2) < \vartheta_2 < 0, \\ \omega < 1, \end{cases} \tag{17}$$

or

$$\begin{cases} -(1+\zeta_0+\xi_0) < \vartheta_0 < 0, \\ \vartheta_1 > 0, \\ \vartheta_2 > 0, \\ \omega < 1. \end{cases} \tag{18}$$

The equilibrium point P_8 is the stable point of the equation group.

The conditions that equilibrium point P_8 achieves stability can be divided into two categories, the first category, the condition (17) indicates that when the main manufacturer has self-preference ($\vartheta_0 > 0$), the suppliers' profit will decrease, the correction coefficient is negative, but the decline is limited, no larger than its collaborative value-added degree obtained from collaborative symbiosis ($\vartheta_i > -(1+\zeta_i+\xi_i)$); The second category, the condition (18) indicates that when the main manufacturer has altruistic preferences ($\vartheta_0 < 0$), the suppliers' profit will increase, the correction coefficient is positive, but the profit increase is limited, and the premise of the main manufacturer to take altruistic behavior is no harm to the fundamental interests in their own collaboration ($\vartheta_0 > -(1+\zeta_0+\xi_0)$).

The practical significance of the above stable conditions is as follows:

Firstly, "active and dynamic" status difference between the main manufacturer and suppliers in the collaborative symbiosis makes the strategic sequence of the main manufacturer and suppliers different. The main manufacturer has decision-making power and can actively use resource integration management strategy which has "selfish" and "altruistic" preference. Suppliers can decide their own strategy only after the main manufacturer determines their strategy.

Secondly, no matter what preference strategy the main manufacturer takes, the intensity of strategy needs to be within the acceptable range of collaborative subjects. When the main manufacturer wants to obtain additional profits from the resource integration behavior of suppliers, they can only modify from collaborative value-added benefits of the supplier and can not violate the benefit achieved by the supplier from their own resources creation. When the main manufacturer voluntarily shares their own profits with suppliers, it is necessary to ensure that the interest created on their own doesn't suffer the loss.

Thirdly, no matter what kind of intervention of resources integration behavior will be taken, as long as final profit of suppliers is within an acceptable range, any supplier will exist for a long time in this symbiotic relation, until symbiotic development is restricted by the objective factors, and the enterprise resource contribution rate will no longer grow and tend to be stable. Once the impact of the active behavior of the main manufacturer is beyond acceptable range of collaborative subject, the symbiotic relation will not be stable until the collapse.

6 Simulation Analysis of the Influencing Factors of Multi-Agent Collaborative Behavior

Based on the above analysis, this section will divide the key influencing factors of multiagent resources integration behavior change into three categories: Firstly, the basic attributes of the enterprise are mainly expressed through the initial value of the four variables k_i, $\bar{a}_i$, ψ_i and a_i. Secondly, mutual influence between enterprises is mainly expressed through b_{ij}; Thirdly, the influence of the main manufacturer's subjective behavior decision is mainly expressed through ϑ_i.

In order to make a comparative analysis of the three key factors more intuitively, this paper adopts the control variable method to carry on the related numerical assumptions and uses Matlab to carry on the graph simulation. The related simulation graphs and conclusions are as follows.

① Comparison of independent state and collaborative symbiosis

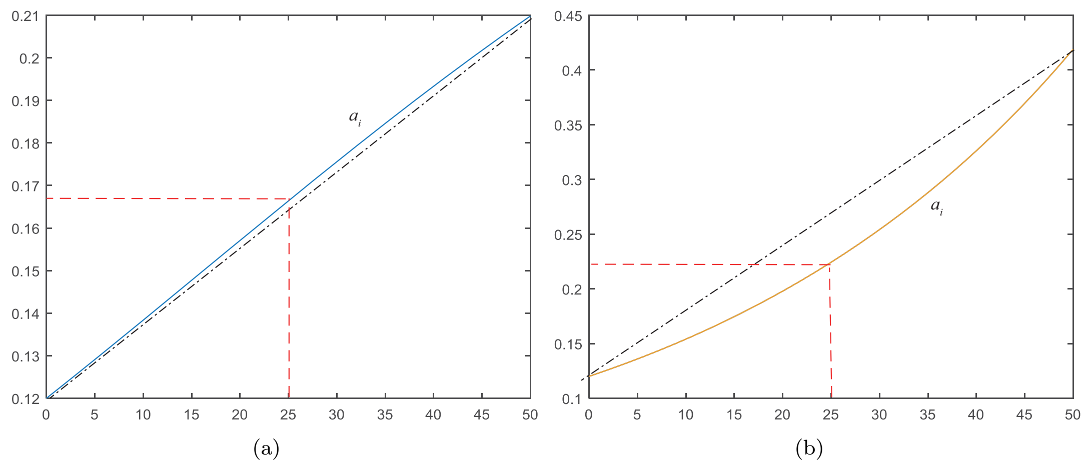


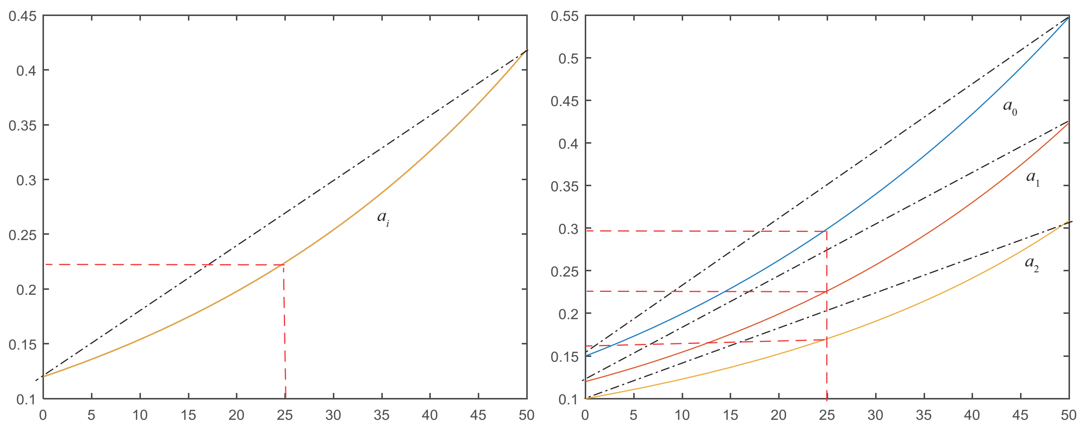
Figure 7 Comparison of the independent state and cooperative symbiosis state

When each participating subject is independent, resource contribution rate can be obtained by the formula (7) with time goes by. The simulation result is in Figure 7 (a), which horizontal axis represents time and vertical axis represents the resource contribution rate (the same below). Without taking the basic attribute differences and unequal status between participating subjects into account, the respective resource contribution rate of the three subjects (i.e., a main manufacturer and two suppliers), in collaborative symbiotic state, as time goes by, can be simulated according to Formula (9), and the result is shown in Figure 7 (b). The simulation result is in Figure 7 (b). It can be found that the increase of the resource contribution rate under the multi-agent collaborative symbiosis state is obviously more than that under the independent state, which shows that, for each subject, collaborative symbiotic behavior makes the resource utilization rate become larger and benefit of resource input from the main units also becomes bigger.

② The impact of enterprise's own basic attributes

If don't take influence differences between enterprises into account. Assuming that b_{ij} $(i \neq j)$

remains the same, that the comprehensive ability of main manufacturer M is superior to that of supplier S_1 and supplier S_2 is weakest. Comparison with Figure 8 (a) and Figure 8 (b), it can be found that initial resource contribution rates of the main manufacturers M, supplier S_1 and supplier S_2 are 0.2, 0.15, 0.1 and the levels of technological innovation are in turn decreased. This shows that when the enterprise's own resources contribution rate is higher and technological innovation ability is the most powerful, growth rate of resource contribution rate is the fastest in the collaborative symbiotic behavior.



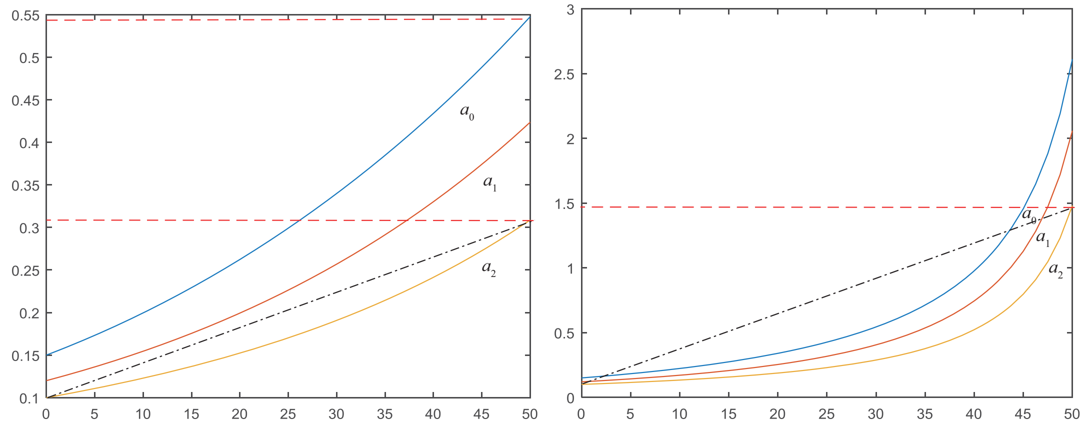
(a) (b)

Figure 8 Comparison of differences among enterprises basic attributes

③ Interaction effect among the various enterprises

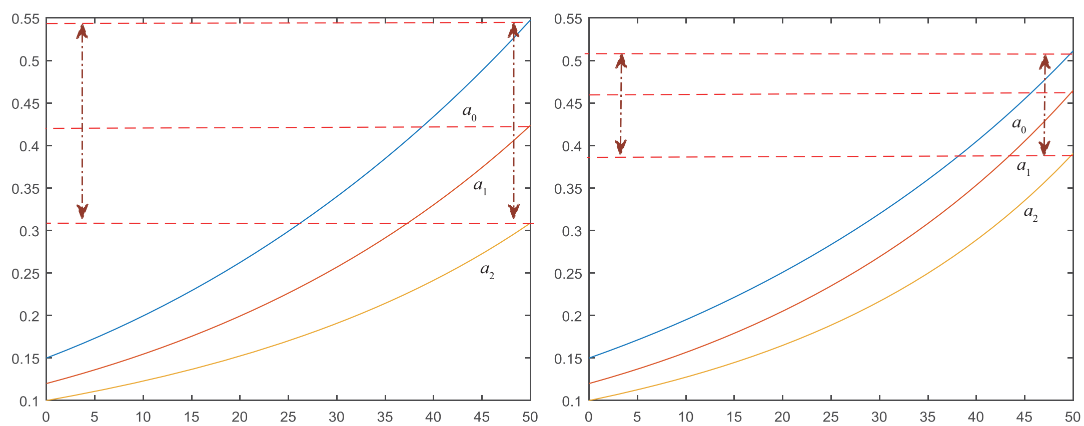
Assuming that the mutual influence between enterprises is equal, and the simulation results under numerical variation are shown in Figure 9 (a) and Figure 9 (b). Assume $b_{ij} = 0.5\ (i \neq j)$ in Figure 9 (a) and $b_{ij} = 0.9\ (i \neq j)$ in Figure 9 (b). It is found that, when the value of b_{ij} is greater, resource contribution growth rate of each subject grows faster. This shows that when the interaction effect between enterprises is bigger, the spillover effect of each enterprise in the collaborative symbiosis is more obvious. At the same time, we can find that although the degree of influence between enterprises will has an impact on the changes of resource contribution rate, the sortings of resource contribution rate of each subject are decided by its own basic attributes.

In the actual operation, the interaction among the participants does not remain the same. By analysis of enterprise cluster symbiosis model it is found that: When there is a mutually beneficial behavior among enterprises, enterprises with large scale of production will have a more significant effect than that of small scale enterprises[27]. On the basis of the above, this paper assumes that "the main manufacturer M is superior to supplier S_1 and supplier S_2 is the weakest", and that the mutual influence between enterprises is $b_{ij} = \begin{bmatrix} 0 & 0.5 & 0.3 \\ 0.7 & 0 & 0.4 \\ 0.8 & 0.6 & 0 \end{bmatrix}$. The simulation of the data obtained is in Figure 10 (b). By comparing, considering the effect of asymmetric relation between enterprises, when the time is $t = 50$, the difference between the maximum and minimum resource contribution rate of collaborative subjects narrows. This suggests that when enterprises with different attributes cooperate, the impact of strong and weak enterprises will change with their own attributes. In the collaborative symbiotic process, the gap of resource contribution rate between enterprises will gradually decrease to help each other between strong and weak enterprises to optimize supplier groups.



(a) (b)

Figure 9 Comparison of the absolute degree of influence among enterprises

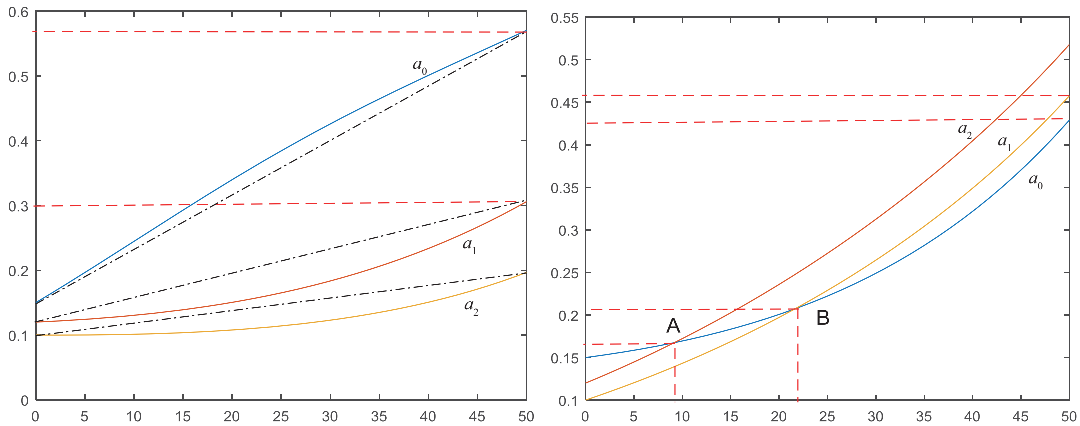


(a) (b)

Figure 10 Comparison of the relative influence degree of enterprises

④ Impact of the initiative of the main manufacturer

For the main manufacturer, there are two main types of behaviors that the main manufacturer actively intervenes in resources integration: Self intervention and altruistic behavior intervention. For the convenience of study, it is assumed that the main manufacturer makes no-difference correction to suppliers and adds a correction factor based on Figure 10 (b). When the main manufacturer chooses hoggish behavior, we get simulation graph Figure 11 (a). It can be found when the main manufacturer chooses hoggish behavior, the more benefit in the process of collaborative symbiosis can be obtained, the greater resources contribution rate is. At this point, in the premise of ensuring that the suppliers' cooperative profits are greater than that of the independent profits, suppliers' resource contribution growth rates decrease significantly. When the main manufacturer chooses altruistic behavior, we get simulation graph Figure 11 (b). It can be found that altruistic behavior of the main manufacturer makes the interests of the suppliers improve significantly, as A points and B points are shown. Resource contribution rates of supplier S_1 and supplier S_2 are higher than that of main manufacturer respectively and grow rapidly, while the main manufacturer's is relatively slow. This suggests that the main manufacturers of active interventions will have obvious effect to the whole innovation collaborative group, synergies of suppliers will change as the dominance of the main manufacturers.



(a) (b)

Figure 11 Comparison chart of active behavior of main manufacturer

7 Conclusion

This paper selects long-term cooperation among the subjects in the whole production cycle of complex products as the research background. On the premise of the technological innovation resources promoting value creation, and selects the resource contribution rate as the core variables measuring multi-agent coordination symbiosis and establishes cooperative symbiosis behavior model under the background of multi-subject resource integration. Aiming at the unequal relation of multi-subject's status, this paper mainly analyzes "active motion — follow motion", the multi-agent collaborative symbiosis model between the main manufacturer and suppliers, and carries out the model simulation and analysis of the key factors. The results show that in the development activities of complex products, resource integration behavior between the main manufacturer and suppliers group will greatly enhance the technical innovation level of collaborative subject, and will effectively promote the efficient development of complex products. At the same time, the results also show that the basic attributes of enterprises, the degree of interaction between enterprises, the main manufacturers of active performance, etc, will have an obvious effect on complex products R&D activities.

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