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Collaborative Super-Network Equilibrium Model and Algorithm Solution for Complex Equipment Development

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Abstract

In order to effectively maintain the relationship between the main manufacturer and the first-tier supplier, each party should promote the collaborative development of complex equipment, and utilize the ideas and methods of the super-network. This paper at first discusses the social network, coordination network, and cooperation network that influence and interact with each other. Then, this study consider taking the social relationship level, coordination degree, and cooperation level of the super-network jointly developed by the main manufacturer and supplier.Three decision variables establish multi-objective optimal decision model which is based on the different preference such as maximum relationship value, the lowest coordination cost, the minimum coordination risk, the largest cooperation benefit, and the minimum cooperation risk. Next, this study constructs a super-network equilibrium model of complex equipment to collaborative research, useing inequality variation to solve the complex equipment development on super-network equilibrium. Finally, the model is verified to check on the validity and rationality of the model by case study.

Keywords: collaborative development; coordination mechanism; super-network; cooperation level; variational inequality

1．Introduction

In this 21st century globalization era, , manufacturing industry is facing tremendous pressure from homogenious competition and customized demand. Research and development, manufacturing, marketing, services, and capital operations have all been pushed forward to cater the whole world. With the emergence of complex equipment such as large aircraft, ships, rockets, and

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automobiles, in order to deploy manufacturing resources on a global scale, a manufacturing industry can take advantages on the chain, and seize of the world market. The complex equipment development model has also gradually evolved into a "main manufacturer-supplier". model. Under the "main manufacturer-supplier" model, the relationship between the main manufacturer and Tier 1 supplier has changed from the traditional trading relationship. The main manufacturer is at the core, and has certain control rights to the supplier, and can adjust each supplier's activities. When there is leader control system in the supply chain, the original supply chain incentive model is no longer applicable. In the cooperation between the main manufacturer and the Tier 1 supplier, once the profit distribution mechanism is set up improperly, or the cooperation contract breaks down, there will be a huge gap in the cooperation between the main manufacturer and the supplier, and the cooperation is even more difficult to sustain. As the main manufacturer is dominated by the supply chain, the main problems are going to be about how to coordinate the conflicts of interest with suppliers, establish an effective benefit distribution mechanism and incentive mechanism, mobilize the enthusiasm of suppliers, and explore the way of long-term cooperation is managed with Tier 1 suppliers. Suppliers subordinate to the supply chain maintain competitive cooperation with other suppliers of the same status, and maintain good cooperation with the main manufacturers, which promotes the improvement of interests. How to establish a coordination mechanism between the main manufacturer and the supplier suitable for this model is particularly important.

At present, the research on the main manufacturer-supplier coordination is mainly based on three aspects: profit distribution, incentive mechanism, and coordination and control means. **L**et's discuss them one by one.

a. Interest distribution mechanism.

In the production system of the "main manufacturer-supplier" model, due

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to the individual rationality of the main manufacturers and suppliers, the parties in the supply chain may damage the interests of other members while pursuing the optimal personal interests, thereby making the supply overall benefits of the chain difficult to maximize. In order to effectively solve the conflicts of interest and stability of all parties in the supply chain, some experts and scholars have constructed a utilization allocation mechanism from the perspective of interest distribution. At present, the research on the distribution of benefits in the supply chain mainly focuses on the aspects of optimization of mutual interests and methods of benefit distribution. For the study of the optimization of mutual interests, Duea, David D, and John V (1998) and other scholars have found that the fierce competition in the market can promote the optimization of contracts between enterprises, and also increase the benefits of cooperation. The distribution will have different effects on the cooperation profit distribution. Zhao Xiaoli and Yan Jianxun (2007) used the game model to construct the profit distribution factors with benefit distribution method, and designed the principle of benefit distribution based on cooperative contribution and risk compensation. For the method of benefit distribution, the current academic community mainly uses factor distribution methods based on output, price, supply chain contract, Shapley value method, linear programming method, core method, and other methods. Among them, Srinagesh Gavimen (2001) designed the production and profit distribution mechanism of individual producers and n retailers according to the cooperation interests and the supplier's supply capacity, the number of retailers, and the needs of consumers. In response to changes in contract parameters affecting the rational distribution of the benefits of supply chain members, Ilaria G, Pierpaolo P (2004) constructed a supply chain contract for changes in contract parameters. Gerard PC and Martin AL (2005) designed the distribution model of economic income based on the supply chain parties. Yang Jijun, Xu Weisheng, et al. (2009) adopted the improved core method, based on the characteristics of supply chain, using the theory and method of game theory to study the applicability

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and stability of supply chain benefit distribution. In view of the conflict of interest involved in the collaborative development process between the main manufacturer and the supplier, Chen Hongzhuan et al. (2012) used Nash Equilibrium, Conflict Analysis, and Shapley to involve the super-conflict equilibrium model and give the conflicting strategies solution between manufacturers and suppliers

b. Incentives

The main manufacturer-supplier incentive mechanism for the collaborative development of complex equipment is mainly based on the supply chain incentive mechanism and the incentives are based on the Stackelberg equilibrium model in the main manufacturer-supplier model. The discussion of the supply chain incentive mechanism mainly focuses on analyzing incentive barriers, establishing incentive mechanisms, setting incentive ratios, and giving incentive strategies. For example, Zhu and You (2011) used the “trust-agent” theory and method to construct the incentive mechanism of the main manufacturers and suppliers for the information rent. Naini (2011), Ghosh, Shah (2012), and other scholars analyzed the problem of profit distribution incentive under symmetric information, and used the game model to solve the Pareto optimality of optimal effort and income, Cao Wu, Zhou, Ge (2013) studied the incentive contract design process of manufacturers under asymmetric information, and discussed the validity of the sub-optimal contract based on one-time transfer payment and linear split payment and the realistic conditions for implementing these two types of contracts, and further proposed a nonlinear coordination contract based on the Nash negotiation solution]. He, Chen, and Yao (2014) used game theory to analyze the impact of information sharing on information asymmetry, and established a game model of information sharing incentives dominated by product service integrators, and gave some incentive strategy for information sharing in product services supply chain. In the main manufacturer-supplier mode, the main manufacturer is in a dominant position, the supplier is subordinate, and the main

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manufacturer can exercise some control or guidance on the supplier, so that the decision process of the main manufacturer towards supplier gradually have some of the characteristics of the Stackelberg's general decision-making process. Some scholars use the Stackelberg equilibrium model to study the main manufacturers and suppliers incentives. Among them, Tian and Guo (2004) introduced the incentive-inducing mechanism into the Stackelberg model, and analyzed the equilibrium between the dominant and follower non-cooperation and cooperation. Fu and Zeng (2007) for the three cases of Nash game, Stackelberg game, and cooperative game used the differential game method to solve the optimal advertising strategy for a single manufacturer and a single retailer. Li and Yang (2012) used Stackelberg game and Nash equilibrium theory to construct and implement upstream to the benefit distribution mechanism in the three scenarios after the level VMI implements incentives for suppliers. Throughout the existing incentive model based on Stackelberg game theory, it can be seen that Stackelberg master-slave incentive research is basically limited to one main and one aspect, and the research is aimed at suppliers' motivation in the state of cooperation, and neglects suppliers. In the state of participating in coordination under the competitive state, it is difficult to effectively solve the incentive problem of one master and multiple slaves.

c. Research on coordination and control methods

At present, domestic and foreign scholars' research on supply chain coordination and control methods mainly focuses on analyzing the causes of conflicts in supply chain, proposing strategies and methods for conflict resolution, and giving different situations. For the reasons of supply chain conflicts, domestic and foreign scholars have studied it from different perspectives. Among them, Nagarajan and Greys (2008), after studying the contract of supply chain members, found that manufacturers and suppliers caused conflicts due to inconsistency and information asymmetry of interest. In view of the coordination and control issues jointly developed by the main

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manufacturers and suppliers, some scholars used qualitative methods to analyze the relationship between the main manufacturers and suppliers, and believed that the construction of efficient organizational systems, management models, etc. was an effective way to resolve conflicts. Some other scholars have used the game theory, principal-agent model, and optimization model ideas and methods to construct a master manufacturer and supplier coordination model. Among them, Kim B (1999) used principal-agent theory and game model to analyze the profitability of the cooperation between the main manufacturer and the supplier and the non-cooperation situation, and believed that the main manufacturer and the supplier establishing a risk partnership has the long-term development of collaborative development. Gerard and Cachon (2002) used the newsboy model and contract theory to construct a supply chain contract coordination model for the coordination and control of manufacturers and suppliers. Hou and Qiu (2010) used supermodel game theory to solve the competitive equilibrium conditions between manufacturers and suppliers, and pointed out that by setting a reasonable balance, manufacturers and suppliers could be collaboratively developed. In order to solve the coordination between business and supplier relations, Chen, Liu, et al. (2012) designed a dual effort supply chain coordination mechanism based on the individual effort level and cooperation degree of suppliers. all of which was under the Nash equilibrium and coordinated control was under the non-coordinated control of the main manufacturer research on the balance of cooperation and other issues, and established the benefit distribution plan for the coordinated control of the main manufacturers.

From the existing research, the research on benefit distribution mechanism, incentive mechanism, conflict coordination and control has achieved great results and has many references. However, the supply chain coordination system for collaborative research of complex equipment is still incomplete, especially in the new model of “main manufacturer-supplier”.

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There are many theoretical and practical problems of the coordination system urgently needed to be solved. The main performance is that the conflict coordination between the main manufacturer and the supplier is mostly limited to a linear way, and the research on the nonlinear network coordination mechanism is limited. The current research conflict coordination method is single, and it is difficult to meet the coordination of complex equipment collaborative development. Especially in the main manufacturing-supplier mode, there is a close transaction relationship and coordination between the main manufacturer and the supplier, which constitutes a layered and complex equipment development network. The implementation of coordination on the supplier based on the linear method is obviously not in line with the actual situation. While in fact, the current research based on the nonlinear network-type coordination mechanism is still in its infancy.

2 . Collaborative Development of Super-network Model for Complex Equipment

In the production system of the "main manufacturer-supplier" model, the main manufacturer is the core enterprise of the complex equipment in the supply chain, in order to establish a long-term and stable cooperative relationship with suppliers, and effectively mobilize the enthusiasm of suppliers to participate in cooperation. In order to make it collaboratively developed, an effective conflict coordination mechanism must be established in the supply process. Due to the new supply chain management model of "main manufacturer-supplier", the main manufacturer has the advantages of information and status, not only in the case of the information asymmetry between the main manufacturer and the supplier, but also the information asymmetry between the suppliers. It is difficult to be symmetrical, and there are many suppliers involved in coordination and incentives. There are more complex relationships between the main manufacturers and

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suppliers. Therefore, the traditional coordination and incentive theory under the new model of coordination and incentive mechanism design will be limited; it cannot play a good coordination role. Thus, this paper uses the super network to explore the competitive cooperation relationship between the main manufacturers and suppliers under the "master manufacturer-supplier" model, and build a super network equilibrium model for the collaborative development of complex equipment, in order to provide the support of theory and method to managers and decision makers.

2.1 The Related Concepts of Collaborative Development of Super-Network Related to Complex Equipment

In the process of collaborative development of complex equipment, there is a multi-layered relationship between the main manufacturer and the supplier, and there is a flow of capital and technology between the main manufacturer and the supplier. In summary, the main manufacturer and the supplier have social relations, cooperative relations, and coordination relationships, and mutual influence and mutual restraint. As a powerful tool for studying the relationship between networks, super-network theory can describe this relationship well. Based on the super-network, the main manufacturer and supplier collaboratively develop the social relations and cooperation relations of each subject. The coordination relationship can form a social relationship network, a coordination network, and a cooperation network, respectively. Although relational networks, coordination networks, and cooperative networks have the same nodes, the connections between nodes are different, so the two are independent and related to each other, and have multiple dimensions and multiple attributes. A super network can be developd in coordination with complex equipment that coordinates global

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optimization and individual optimization conflicts. Through the above analysis, the master manufacturer-supplier relationship collaboratively develops the super network composed of a social relation network, a collaboration network, and a coordinated network. And each network is a sub-network of the super network.

Here is Definition 1 for the main manufacturer-supplier production system. If the network consists of social relations network, a cooperative network, and a coordination network between the main manufacturer and the supplier, which interact with each other and restrict each other, it is said that the network is the main manufacturer-supplier collaborative development of the super-network, recorded as N_s. For convenience, social network, cooperative network, and coordination network are recorded as respectively r, c, d .

Here is Definition 2 in the main manufacturer and supplier collaborative development super-network N , if triad $G_s = (V, E_s, L_s)$ can satisfy the set of points formed by the main manufacturer and supplier in the network $V = \{0, 1, 2, ..., n\}$,among which, o represents main manufacturer, $i = 1, 2, ..., n$ represents supplier, $E_s = (e_{ab}^s)$ is the set of edges formed by any two nodes $a, b \in V$ 且 $a \neq b$ in a super-network N_s , $L_s = (l_{ab}^s)$ is the weight of the edge e_{ab}^s of the super-network N_s (that is, the network flow), and $N_s \left(s = r, d, h \right)$ is regarded as a sub-network of the main manufacturer-supplier collaborative development super-network N .

For the social network of collaborative development of complex equipment, the network flow l_{ab}^r represents the relationship flow of the main manufacturer and supplier collaborative development super-network, also known as the

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relationship level, and it is recorded as r_{ab}, which indicates the relationship strength between any two nodes $a,b \in V$ 且 $a \neq b$, among which, $r_{ab} \in [0,1]$ and $r_{ab} = 0$ have no relationship, and when $r_{ab} = 1$, it means that the relationship between the two subjects is the strongest. Therefore, according to the actual need, the level of relation can be divided into two types: weak relation and strong relation. Weak relation is generally used when each subject in the collaborative development of complex equipment selects subject innovation, which shows that the two sides of collaborative development can obtain the complementary information of heterogeneous resources. The weaker the relationship is, the less information the two sides of collaborative development of complex equipment can get. The establishment of strong relation is mainly based on the deep exchange between the two sides of the collaborative development of complex equipment, in which both have more opportunities to share and acquire tacit knowledge. The stronger the relationship is, the more tacit knowledge can be transferred[25]. According to the actual situation of collaborative development of complex equipment, the relationship evolution trend of social network of collaborative development of complex equipment is from weak to strong, and the level of relationship will be maintained in strong relationship after reaching strong relationship instead of reverting to a weak relationship. in reality, no one is willing to destroy strong relationships that have been built up with a lot of time and effort) so that the "strong relationships" will continue to strengthen or remain unchanged until the whole network tends to balance and the "relationship level" change ends. Next, collaborative development parties will work to maintain this "relationship level".

For the coordination network, the network stream l_{ab}^{d} represents the

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coordination flow of the cooperation flow between the main manufacturer and the supplier in the collaborative development of the super-network, set as d_{ab}, which indicates the degree of coordination between the main manufacturer and the supplier, or between any two suppliers. The range of values is d_{ab}, $d_{ab} \in [0,1]$. In general, the coordination network should implement strong coordination at the beginning of the collaborative development between the main manufacturer and the supplier. With the deepening of the collaborative development, the various subjects enter into a strong relationship and deeper cooperation, at this time, the coordination network can take stable (or weak) coordination. However, in real life, due to the limitation of funds, ability, willingness, and so on, it may adopts weak coordination for each subject. In the process of collaborative development of complex equipment, coordination level and cooperation level show a certain relationship. With the increase of coordination level, cooperation level obviously increases. When the cooperation level increases to a certain extent, the increasing speed of cooperation level is slow. It may no longer increase or remain in a relatively stable state.

For cooperative networks, the network stream l_{ab}^{h} represents the cooperation flow between the main manufacturer and the supplier in the collaborative development of the super-network, set as h_{ab}, which represents the degree of cooperation between any two nodes $a, b \in V$ 且 $a \neq b$. If the level of relationship is enhanced, the cooperation between node a and node b will be promoted and the cooperation degree will become closer. However, when the level of cooperation increases to a certain extent, no matter how closely coordinated and promoted the cooperative subject relationship is, the innovation subjects will not want to further deepen cooperation, but to maintain a balanced level of cooperation.

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In the process of collaborative development super-network by the main manufacturer-supplier, social relations level, cooperation level and coordination level are mutually interacted and restricted. With the increase of social relations level, the cooperation level between nodes will increase. With the increase of the coordination level, the cooperation level will increase obviously. When the coordination level increases to a certain extent, the cooperation level will increase slowly, and there is a tendency not to increase in the same level with that of the coordination level, and it remains in a relatively stable state. With the increase of coordination intensity, the cooperation level between the nodes increases correspondingly, and the social relations level is also improved.

Definition 3 is for network flow $L_s\left(s=r,d,h\right)$. If it meets the constraint condition of the optimal objective of all subjects, that is $L_s = s^*$, network flow is called in circulation, otherwise, the collaborative innovation network flow gets fracture.

Definition 4 sets the main manufacturer-supplier collaborative development super-network N, for any sub-network $N_s\left(s=r,d,h\right)$. If all network flows are in circulation, the super-network is called a balanced super-network.

Through Definition 3 and 4, it can be seen that if the interest of all subjects in the main manufacturer-supplier collaborative development super-network is satisfied (that is, all network flows are in circulation), this super-network has equilibrium, which means that the main manufacturer-supplier cooperative development super-network can not only maximize the benefits of each innovation subject, but also create the most suitable cooperative environment for the manufacturer-supplier cooperative development super-network.

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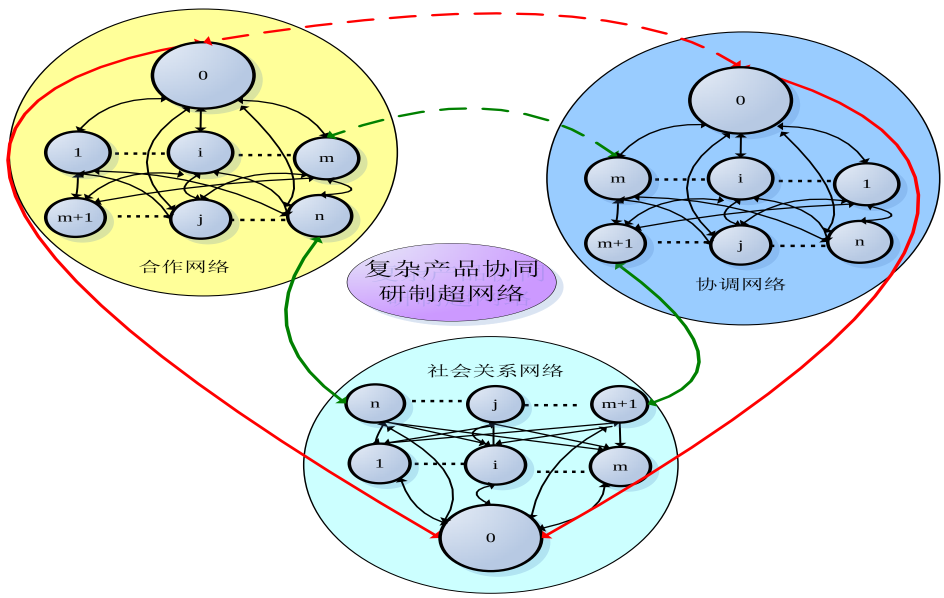
3.2 The Construction of Super-Network Equilibrium for Complex Equipment Collaborative Development

Aiming at the coordination problem of complex equipment collaborative development system, this paper will look at a complex equipment collaborative development super-network. The network is N , composed of social network, collaboration network and coordinate network, as shown in figure 1.



Fi

g 1. Complex Equipment Collaborative Development Super-network

In the collaborative development of the super-network N between the main manufacturer and the supplier, the node set $V = \{0,1,2,...,n\}$ is composed of the main manufacturer and the supplier in the network, in which 0 represents the main manufacturer and $i = 1,2,...,n$ represents the suppliers.

(1) Related Attribute Variables of Social Network

① The relation level (relationship flow) is set as r_{ab}, which indicates the relationship level between the node a and node b , in which

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$a,b=0,1,2,...n$ and $a \neq b$, $r_{ab} \in [0,1]$, $r_{ab} \in R_+^{2(n+1)}$.

② The relation value is set as V_{ab}, which indicates the value produced between the node a and node b under the existing relation level r_{ab}, and assumes that V_{ab} is the continuous differentiable convex function $V_{ab} = V_{ab}(r_{ab})$ on the relation level r_{ab}. For any relation level r_{ab}, node a and node b will produce some value. Generally speaking, the relationship level is proportional to the relationship value.

③The relation cost is set as Cr_{ab}, which indicates the capital and value (cost) to be paid for the establishment of the relationship level r_{ab}, and Cr_{ab} can be set up as a continuous differentiable convex function about the relation level r_{ab}.

④Social relation risk is set as CCr_{ab}, which indicates a certain amount of capital needs to be paid when establishing a relationship level r_{ab}. Because of the influence of various external things, it does not necessarily reach a predefined level of relationship. In this case, the node needs to face a certain risk, the higher the degree of cooperation and coordination between the nodes, the less risk the node faces. Therefore, the risk of social relations can be expressed as $CC_{rab} = CC_{rab}(r_{ab}), \forall a,b$, and CC_{rab} can be set as a continuous differentiable convex function in the defined domain.

(2) Related Attribute Variable of Coordination Network

The coordination network is coordinated by the main manufacturer to the suppliers, so it will produce the corresponding coordination cost, the coordination benefit, the coordination risk, and so on. In fact, coordination benefits and coordination risks are reflected in the final product. After the main manufacturer

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coordinates with the suppliers, the production cost of the suppliers will be reduced, the product quality will be improved, and the profit of the suppliers will be raised virtually. In addition, with the improvement of product quality, the profit of main manufacturer will also increase.

① Coordination degree (coordination flow) is set as d_{ab}, which indicates the coordination degree between node a and node b, and $d_{ab} \in [0,1]\ \forall a,b$;

② Coordination benefit is set as DR_{ab}, which indicates the benefits node a and b obtaining from the existing coordination flow d_{ab}, so $DR_{ab} = DR_{ab}(d_{ab}), \forall a,b$, DR_{ab} can be set as a continuous differentiable convex function of the coordination flow.

③ Coordination cost is set as Cd_{ab}, which indicates the cost that each subject has to pay for the implementation of the coordination flow d_{ab}.In the case of a certain coordination flow d_{ab}, the cost paid by each participant is also affected by the relation level r_{ab}. For example, among the interest subjects with a high level of relationship, for the sake of the next cooperation, the cost will be relatively small. Therefore $Cd_{ab} = Cd_{ab}(r_{ab}, d_{ab}), \forall a,b$ as mentioned above, Cd_{ab} is the subtraction function about the r_{ab} and d_{ab}, Cd_{ab} can be set as the continuous differentiable convex function in the defined domain.

④ Coordination risk is set as CCd_{ab}, which indicates the risk of establishing a degree of coordination (coordination flow) d_{ab} among subjects. In the process of coordination, the risk of coordination is also affected by the level of relationship. For the subjects with high level of relationship, the risk is relatively small because

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of the deep friendship between them and the greater degree of trust in each other. However, among the subjects with low level of relationship, for their own benefit, they are unwilling to make too much contribution to coordination, so the coordination risk is relatively large. Therefore, $CCd_{ab} = CCd_{ab}\left(r_{ab}, d_{ab}\right), \forall a, b$. To sum up, CCd_{ab} is the subtraction function of r_{ab} and d_{ab}, which is set as a continuous differentiable convex function in a defined domain.

（3）Related Attribute Variables of Cooperative NNetworks

① Cooperation level (cooperative flow) can be set as h_{ab}, which indicates the cooperation degree between node a and node b, and $h_{ab} \in [0,1]$.

② Cooperative benefits is set as CR_{ab}, which means the benefits are derived from the existing level of cooperation h_{ab} so that CR_{ab} can be set as a continuous differentiable convex function in the defined domain $CR_{ab} = CR_{ab}\left(h_{ab}\right), \forall a, b$.

③ The cooperation cost is set as CC_{ab},which means the cost that must be paid to establish cooperation level h_{ab}. The cost of cooperation is affected by the relationship flow r_{ab} and coordination flow d_{ab} because, at a certain level of cooperation, the closer the relationship between the various subjects and the greater the degree of coordination, the less the cost will be paid. Therefore, $CC_{ab} = CC_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right), \forall a, b$, CC_{ab} can be set as a continuous differentiable convex function of the level of cooperation.

④ Cooperative risk is set as CH_{ab}, which means the risk caused by establishing the level of cooperation h_{ab}. Because the cooperative risk is also affected by the relationship flow and coordination flow, so that

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$CH_{ab} = CH_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right), \forall a, b$. CH_{ab} can be set up as a continuous differentiable convex function of the level of cooperation h_{ab}.

Each node in a main manufacturer-supplier collaborative development super-network will consider the following four principles when establishing cooperative relationship, social relations, coordination relationships, and their intensity:

(1) The principle of maximum value of the relationship:

$$\max \sum_{b} V_{ab} = \max \sum_{b=0}^{n} V_{ab}\left(r_{ab}\right)$$

（1）

(2)The principle of maximum return:

$$\max \sum_{b}\left(CR_{ab} + DR_{ab}\right) = \max \sum_{b=0}^{n}\left(CR_{ab}\left(h_{ab}\right) + DR_{ab}\left(d_{ab}\right)\right)$$

（2）

(3) The principle of lowest cost:

$$\min \sum_{b=0}^{n}\left(CC_{ab} + Cr_{ab} + Cd_{ab}\right) = \min \sum_{b=0}^{n}\left(CC_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right) + Cr_{ab}\left(r_{ab}\right) + Cd_{ab}\left(r_{ab}, d_{ab}\right)\right)$$

（3）

(4)The principle of minimum risk:

$$\min \sum_{b=1}^{p}\left(CCr_{ab} + CH_{ab} + CCd_{ab}\right) = \min \sum_{b=1}^{p}\left(CCr_{ab}\left(r_{ab}\right) + CH_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right) + CCd_{ab}\left(r_{ab}, d_{ab}\right)\right)$$

（4）

Different types of super-networks have different preferences for the above principles. In order to better understand and deepen the characteristics of collaborative development of super-networks between main manufacturers and suppliers, we have different weights for different principles here, which are set as:

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$\alpha_1, \alpha_2, \alpha_3, \alpha_4$, and $\sum_{k=1}^{4} \alpha_k = 1, \alpha_k > 0 \left(k = 1, 2, 3, 4\right)$. Based on the above analysis, it can be obtained that the collaborative development of super-network equilibrium model of complex equipment is as follows:

$$
\begin{aligned}
&\max \alpha_1 \sum_{b=0}^{n} V_{ab}\left(r_{ab}\right) + \alpha_2 \left(\sum_{b=0}^{n} \left(CR_{ab}\left(h_{ab}\right) + DR_{ab}\left(d_{ab}\right) \right) \right) \\
&-\alpha_3 \left(\sum_{b=0}^{n} \left(CC_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right) + Cr_{ab}\left(r_{ab}\right) + Cd_{ab}\left(r_{ab}, d_{ab}\right) \right) \right) \\
&-\alpha_4 \left(\sum_{b=1}^{p} \left(CCr_{ab}\left(r_{ab}\right) + CH_{ab}\left(r_{ab}, d_{ab}, h_{ab}\right) + CCd_{ab}\left(r_{ab}, d_{ab}\right) \right) \right)
\end{aligned}
\qquad (5)
$$

Among which, $0 \le r_{ab} \le 1, 0 \le h_{ab} \le 1, 0 \le d_{ab} \le 1$, $\forall a, b, a \ne b$, $\sum_{k=1}^{4} \alpha_k = 1, \alpha_k > 0 \left(k = 1, 2, 3, 4\right)$。

3.3 Solution and Algorithm Realization of Super-Network Equilibrium Model for Complex Equipment Collaborative Development

Since the functions in formula (5) are continuous differentiable convex functions, the objective functions in (5) are also continuous differentiable convex functions. According to the relevant theoretical knowledge of variational inequalities[26], formula (5) can be transformed into the form of variational inequalities for the optimization conditions of all cooperative subjects:

$$
\begin{aligned}
&\sum_{a=0}^{n}\sum_{b=0}^{n} \left(-\alpha_1 \frac{\partial V_{ab}}{\partial r_{ab}} + \alpha_3 \left(\frac{\partial CC_{ab}}{\partial r_{ab}} + \frac{\partial Cr_{ab}}{\partial r_{ab}} + \frac{\partial Cd_{ab}}{\partial r_{ab}} \right) + \alpha_4 \left(\frac{\partial CCr_{ab}}{\partial r_{ab}} + \frac{\partial CH_{ab}}{\partial r_{ab}} + \frac{\partial CCd_{ab}}{\partial r_{ab}} \right) \right) \left(r_{ab} - r_{ab}^{*} \right) \\
&+\sum_{a=0}^{n}\sum_{b=0}^{n} \left(-\alpha_2 \frac{\partial DR_{ab}}{\partial d_{ab}} + \alpha_3 \left(\frac{\partial CC_{ab}}{\partial d_{ab}} + \frac{\partial Cd_{ab}}{\partial d_{ab}} \right) + \alpha_4 \left(\frac{\partial CH_{ab}}{\partial d_{ab}} + \frac{\partial CCd_{ab}}{\partial d_{ab}} \right) \right) \left(d_{ab} - d_{ab}^{*} \right) \\
&+\sum_{a=0}^{n}\sum_{b=0}^{n} \left(-\alpha_2 \frac{\partial CR_{ab}}{\partial h_{ab}} + \alpha_3 \frac{\partial CC_{ab}}{\partial h_{ab}} + \alpha_4 \frac{\partial CH_{ab}}{\partial h_{ab}} \right) \left(h_{ab} - h_{ab}^{*} \right) \ge 0 \quad \left(\forall \left(r_{ab}, d_{ab}, h_{ab} \right) \in K \right) \\
&K = \left\{ \left(r_{ab}, d_{ab,} h_{ab} \right) \middle| 0 \le r_{ab} \le 1, 0 \le d_{ab} \le 1, 0 \le h_{ab} \le 1, \forall a, b \text{且} a \ne b \right\}
\end{aligned}
$$

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（6）

In order to make it easy to analyse, this paper makes:

$$F_{1ab}=-\alpha_1\frac{\partial V_{ab}}{\partial r_{ab}}+\alpha_3\left(\frac{\partial CC_{ab}}{\partial r_{ab}}+\frac{\partial Cr_{ab}}{\partial r_{ab}}+\frac{\partial Cd_{ab}}{\partial r_{ab}}\right)+\alpha_4\left(\frac{\partial CCr_{ab}}{\partial r_{ab}}+\frac{\partial CH_{ab}}{\partial r_{ab}}+\frac{\partial CCd_{ab}}{\partial r_{ab}}\right) \quad (7)$$

$$F_{2ab}=-\alpha_2\frac{\partial DR_{ab}}{\partial d_{ab}}+\alpha_3\left(\frac{\partial CC_{ab}}{\partial d_{ab}}+\frac{\partial Cd_{ab}}{\partial d_{ab}}\right)+\alpha_4\left(\frac{\partial CH_{ab}}{\partial d_{ab}}+\frac{\partial CCd_{ab}}{\partial d_{ab}}\right)$$

（8）

$$F_{3ab}=-\alpha_2\frac{\partial CR_{ab}}{\partial h_{ab}}+\alpha_3\frac{\partial CC_{ab}}{\partial h_{ab}}+\alpha_4\frac{\partial CH_{ab}}{\partial h_{ab}}$$

（9）

Then, the above inequalities can be expressed as $\left(F\left(X^*\right), X-X^*\right)\geq 0$, $F\left(X^*\right)=\left(F_{1ab},F_{2ab},F_{3ab}\right)$.

Among them, $X^*=\left(r_{ab}^*,d_{ab}^*,h_{ab}^*\right)$, $a,b=0,1,2...,n且a\neq b$, representing the transvection on R^N.

According to the variational inequality theory, the formula (5) has a unique solution $X^*=\left(r_{ab}^*,d_{ab}^*,h_{ab}^*\right)$. According to the condition of super-network equilibrium, when the social relationship level, the coordination level, and the cooperative relationship between main manufacturer and supplier obtain right flow $r_{ab}^*,d_{ab}^*,h_{ab}^*$, the collaborative development of complex equipment is in equilibrium, that is, the main manufacturer and supplier realize the collaborative development of complex equipment.

In order to find the equilibrium solution of super-network in the collaborative development of complex equipment, we need to design the corresponding algorithm to solve the problem. However, in the previous literature, the main methods for solving variational inequalities are Euler algorithm, general projection

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algorithm, modified projection algorithm, and projection dynamic system algorithm, which are either demanding or slow to converge. In this paper, projection contraction algorithm is used to solve finite dimensional variational inequality problems $VI(\Omega,F)$, that is, solving a vector $X^* \in K,$ and satisfying $\left\langle F\left(X^*\right), X-X^*\right\rangle \geq 0, \forall X^* \in K \subseteq R^N$, among which, $F: K \to R^N$ is continuous function, K is closed convex set, $\langle \bullet,\bullet \rangle$ indicates the transvection on R^N. Accordingly, the steps of the projection contraction algorithm are as follows:

Step 1: Making $\beta_0 = 1, \gamma \in (1,2), v \in (0,1), u^0 \in K 且 k = 0$;

Step 2: Setting $\tilde{u}^k = P_K\left[u^k - \beta_k F\left(u^k\right)\right], r^k = \dfrac{\beta_k \left\|F\left(u^k\right) - F\left(\tilde{u}^k\right)\right\|}{\left\|u^k - \tilde{u}^k\right\|}$

When $r^k > v$, implementing $\beta_k = \dfrac{2}{3}\beta_k * \min\left\{1, \dfrac{1}{r^k}\right\},\ \tilde{u}^k = P_K\left[u^k - \beta_k F\left(u^k\right)\right],\ r^k = \dfrac{\beta_k \left\|F\left(u^k\right) - F\left(\tilde{u}^k\right)\right\|}{\left\|u^k - \tilde{u}^k\right\|}$, and making $d\left(u^k,\tilde{u}^k\right) = \left(u^k - \tilde{u}^k\right) - \beta_k\left[F\left(u^k\right) - F\left(\tilde{u}^k\right)\right], \alpha_k = \dfrac{\left(u^k - \tilde{u}^k\right)^T d\left(u^k,\tilde{u}^k\right)}{\left\|d\left(u^k,\tilde{u}^k\right)\right\|^2}$, $u^{k+1} = u^k - \gamma \alpha_k d\left(u^k,\tilde{u}^k\right)$.

When $r_k \leq \mu$, implementing $\beta_k = \beta_k * 1.5$, this program ends.

Step 3: Making $\beta_{k+1} = \beta_k$ and $k = k+1$, return to step 2.

Note: $P_K(x)$ is the projection of x onto K.

4. The Numerical Case

In order to verify the validity and reasonableness of the model, an aero engine company and its supplier are taken as an example, and the aero-engine company

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has two suppliers to provide related parts. In order to make more profits, reduce the risk of development, and improve the competitiveness of the product, the aero-engine company, as the main manufacturer, needs to coordinate its suppliers to maintain the product quality and the development progress of corresponding pace. In order to reduce the cooperation cost and increase the profit, suppliers need to strengthen cooperation with manufacturers and other suppliers. In order to develop a certain type of engine, the aero-engine company actively cooperates with its two suppliers. Based on the experience of previous cooperation, the relevant parameters can be estimated. From the model constructed in this paper, we know that $a,b=0,1,2$. By substituting the parameters based on empirical estimation into the corresponding formula, we can obtain:

$$V_{01}\left(r_{01}\right)=16r_{01}+5,V_{02}\left(r_{02}\right)=14r_{02}+4,V_{12}\left(r_{12}\right)=12r_{12}+2$$

$$Cr_{01}\left(r_{01}\right)=5{r_{01}}^{2}+3,Cr_{02}\left(r_{02}\right)=3{r_{02}}^{2}+2,Cr_{12}\left(r_{12}\right)=4{r_{12}}^{2}+2$$

$$CC_{r01}\left(r_{01}\right)=4{r_{01}}^{2}+1.5,CC_{r02}\left(r_{02}\right)=2{r_{02}}^{2}+2,CC_{r12}\left(r_{12}\right)=2{r_{12}}^{2}+2$$

$$DR_{01}\left(d_{01}\right)=4d_{01}+4,DR_{02}\left(d_{02}\right)=2.7d_{02}+3,DR_{12}\left(d_{12}\right)=3d_{12}+3$$

$$Cd_{01}\left(r_{01},d_{01}\right)=6{d_{01}}^{2}+2r_{01}d_{01}+2,Cd_{02}\left(r_{02},d_{02}\right)=3{d_{02}}^{2}+r_{02}d_{02}+1,$$
$$Cd_{12}\left(r_{12},d_{12}\right)=5{d_{12}}^{2}+2r_{12}d_{12}+2$$

$$CCd_{01}\left(r_{01},d_{01}\right)=3d_{01}r_{01}+1,CCd_{02}\left(r_{02},d_{02}\right)=4d_{02}r_{02}+1,CCd_{12}\left(r_{12},d_{12}\right)=2d_{12}r_{12}+1$$

$$CR_{01}\left(h_{01}\right)=4.2h_{01}+7,CR_{02}\left(h_{02}\right)=4h_{02}+5,CR_{12}\left(h_{12}\right)=4h_{12}+6$$

$$CC_{01}\left(r_{01},d_{01},h_{01}\right)=7r_{01}h_{01}+4d_{01}h_{01}+2,CC_{02}\left(r_{02},d_{02},h_{02}\right)=5r_{02}h_{02}+3d_{02}h_{02}+2,$$
$$CC_{01}\left(r_{12},d_{12},h_{12}\right)=5r_{12}h_{12}+4d_{12}h_{12}+1$$

$$CH_{01}\left(r_{01},d_{01},h_{01}\right)=8{h_{01}}^{2}+5r_{01}d_{01}+1,CH_{02}\left(r_{02},d_{02},h_{02}\right)=6{h_{02}}^{2}+3r_{02}d_{02}+1,$$
$$CH_{12}\left(r_{12},d_{12},h_{12}\right)=9{h_{12}}^{2}+2r_{12}d_{12}+2$$

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To find the optimal solution, by using matlab2012b, based on the modified projection algorithm, setting initial values 0 and convergence precision $\varepsilon = 10^{-3}$, and iterating 59 steps, we can get that $r_{01} = 0.1243, r_{02} = 0.3183, r_{03} = 0.2617$, $d_{01} = 0.3673, d_{02} = 0.2025, d_{03} = 0.2619, h_{01} = 0.4956$, $h_{02} = 0.6331, h_{03} = 0.4092$, $\alpha_1 = 0.1263, \alpha_2 = 0.4562, \alpha_3 = 0.2496, \alpha_4 = 0.1679$. Accordingly, we can also get that the objective function of super-network equilibrium of complex equipment is 10.5279, that is, when the objective function is 10.5279, the aero-engine manufacturer and supplier can achieve collaborative development.

Through case stimulation, it shows that the super-network equilibrium model can quantitatively describe the multi-dimensional and multi-attribute complex relationship between the main manufacturer and supplier of complex equipment, and calculate the equilibrium conditions for the collaborative development of complex equipment.

5. Conclusion

In this paper, the coordination mechanism of collaborative development of complex equipment production system is discussed, and the super-network equilibrium model of complex equipment collaborative development is constructed, which is used to describe and depict the social relationship, cooperation relationship and coordination relationship between the main manufacturers and suppliers of complex equipment, and obtain the conditions of collaborative development of complex equipment by solving the hyper-conflict equilibrium. Based on the model and case analysis, the model constructed in this paper can well describe the multi-dimensional and multi-attribute complex relationship between the main manufacturers and suppliers of complex equipment.

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The results show that the model constructed in this paper has broken through the traditional linear cooperation mode, and has changed to the network-based main manufacturer-supplier collaboration mode. Collaborative development has become the best way for the subjects of complex equipment collaborative development to cooperate deeply and optimize the development. The collaborative development of the main manufacturer and supplier can be realized, which can provide decision-making basis and theoretical support for managers and decision-making to deal with complex equipment coordination problems.

In the future research, aiming at the conflict of interest between the main manufacturers and suppliers in the collaborative development of complex equipment, the appropriate conflict coordination mechanism and incentive mechanism should be constructed. The next research can study what kind of incentive strategy is used to motivate suppliers, what kind of interest coordination mechanism is constructed, and what corresponding countermeasures and suggestions are given for different actual situations. Therefore, the research results and feasibility in practical application can be further discussed.

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