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Quality Assurance Method for the Supply Chain of the Complex Product Under Reference Point Effects

Xiaojing Li*
College of Economics and Management
Zhejiang Normal University
Jinhua Zhejiang, China
lixiaojing2017@hotmail.com

Yuan Liu
College of Economics and Management
Zhejiang Normal University
Jinhua Zhejiang, China
liuy@zjnu.cn

***Abstract*—In the process of the supply chain's quality cooperation, a main manufacturer's psychological utility is not only affected by the delivery's quality level but also the quality reference point, which is the industry average level. The participants' economic value has been calculated by adjusting the risk avoidance coefficient, the production cost function and the quality improvement profit in the contract. Meanwhile, the objective programming model is constructed to calculate the maximum quality equilibrium solution of both parties. In this way, supplier's behavior is effectively controlled to realize the reciprocal transaction of supply chain quality cooperation.**

Keywords—quality assurance; psychological utility; reference points

I. INTRODUCTION

Complex products are large-scale products or systems with complex structure, high additional value, high engineering technology content and high integration of components, such as aircraft, large ships, satellites, launch vehicles and etc. Due to the characteristics of multiple objects and high complexity, it is difficult for the main manufacturer to control the behavior of suppliers only with verbal agreement. Therefore, the main manufacturer must strictly monitor the quality management activities of its subordinate suppliers and the quality level of the products they provide in order to gain the quality advantage in the fierce market competition and occupy the leading position in the market.

In the quality cooperation, the main manufacturer's perceived quality of the product delivered by the supplier depends not only on the quality level of single batch delivery, but also on the horizontal comparison with the average quality level of the industry. If the quality level of the delivery is higher than the average quality level of the industry, the main manufacturer will gain additional psychological perception benefits. Otherwise, the psychological perception benefits of the main manufacturer will be lower than before.

Recently, many scholars contribute to the research on the supply chain quality management nowadays. Three aspects are given as below.

(1) The influence of the reference point on cooperation. In the process of supply-chain transaction, participants' psychological utilities always affected by comparisons, which can be calculated by designing reference points as evaluation criteria. Liu et. al used the prospect theory and the strategic customer framework to discuss the reference effect on newsvendor's decision behavior in a market with strategic customers. The result indicated that the ordering quantity and the pricing strategy are influenced in terms of newsvendor's reference effect, loss aversion, product cost, and salvage price [1]. Mandal et.al studied the firms order and price decision about the operations management problems with reference points effect. The result showed that the loss aversion has impact on firm's ordering and pricing decisions[2]. Jiang and Ren proposed dynamic reference points on the basis of different flight delay scenarios and passengers' attributes. The prospect values of passenger behavior under different delay time were dynamically changed related to passenger attributes and delay scenarios[3]. Wang and Wang investigated the inventory management problem, the impact of the loss degree and the quantity-oriented reference point is investigated jointly on the optimal ordering quantity and the profit maximization of the retailer has been studied by a numerical approach. It has found that there exists a unique optimal order quantity while maximizing the expected utility[4].

(2) The quality assurance and incentive methods of supply chain. Quality assurance and incentive in supply chain cooperation were applied to ensure the component's quality, which is a key factor that affects cooperation. Branislav et.al studied the link between the organizational culture dimensions with the use of quality improvement methodologies and supply chain company performance. By using the sample investigation in a sample of 200 organizations in a Canadian multinational company' supply chain, it has come to the conclusion that organizations can improve business performance levels by selecting appropriate quality improvement programs depending on existing organizational culture dimensions[5]. Quigley et. al proposed a Poisson–Gamma model within the Bayesian framework to help supply-chain managers decide the optimal investment level for improving the supply quality performance under epistemic uncertainty on unconformance[6]. Chakraborty et al. proposed a cost-sharing mechanism between retailers and manufacturers to motivate the improvement of product quality [7]. Yoo and Cheong investigated the collaborative product quality improvement in a buyer-driven supply chain. Two reward schemes for supplier quality improvement are proposed. The managerial guidelines for implementing quality management in the supply chain are presented, derived from analytical comparison and numerical experiments[8].

(3) The psychological utility of supply chain based on the reference points. When the reference points exist, the psychological utility is not only affected by the economic value. Meanwhile, there are a lot of differences between the psychological utility of various references points in the supply chain transaction. Eckerd et.al conducted research with a laboratory experiment, which is focused on the role of psychological contracts in a supply chain setting. They have found that while the breach factors significantly impact task behavior, these relationships are not explained by psychological contract violation. On the contrary, violation is useful in explaining, in part, the results pertaining to fairness perceptions [9]. Eckerd et.al evaluated changes in decision-making behaviors and assessments of attitudinal outcomes regarding trust and repurchase intentions. The results show that cultural factors affect supply chain decision-making behaviors, like the post-breach behavioral differences based on national culture [10]. Mir et.al designed an experiment by the leverages attribution theory to evaluate the influence of psychological contracts on supplier switching behavior. They found the complex and highly nuanced role of psychological contracts in buyer-supplier exchange[11].

Most previous studies focused on quality assurance, reference points, and the psychological contract. However, the research about quality assurance of complex products based on psychological perception is premature. Consequently, how to design a proper quality assurance function should be considered as one of the critical problems in supply chain cooperation. The existing literature has been extended to investigate the quality management of the supply chain. The quality reference point has been set on the process of the quality calculation. The expected function is used to guarantee components with higher quality level so that the participants' cooperation can reach an equilibrium at a certain point.

This paper contributes to explore the quality assurance methods in the supply chain of complex products from the psychological perspective. Specifically, in Chapter 2, the component's quality measure standardization is presented. In Chapter 3, the reference point is proposed and the calculation formulas are introduced to determine the quality level of components from the psychological perspective. Besides, a goal programming model is established for optimizing the main manufacturer's psychological utility considering the reference point. In Chapter 4, a case study about the engine transaction between two company is conducted. In Chapter 5, some conclusions and future works are given.

II. The Generalized Quality of Outsourcing Components in Supply Chain Cooperation

A. The Generalized Quality of the Large-the-best Type

The large-the-best type (L type) refers to the quality indicator with directly proportional between the performance value and the quality level, such as maximum thrust, stability, and maximum load. Let the performance value of L type quality characteristic Y be y , and the tolerance interval be $[y_l, y_u]$ where y_u is the optimal target value (the maximum ideal value) ,and y_l is its minimum acceptable value. The quality level of Y is:

$$r = \begin{cases} \dfrac{y - y_l}{y_u - y_l}, y \in (y_l, y_u] \\ \varepsilon, y = y_l \\ 0, y < y_l \end{cases} \quad (1)$$

ε is a minimal positive real number.

B. The Generalized Quality of The Small-the-best Type

The small-the-best type (S type) refers to the cost index with inversely proportional between the performance value and the quality level, such as failure rate, failure efficiency and defective rate. Let the performance value of S type quality characteristic Y be y , and the tolerance interval be $[y_l, y_u]$, where y_l is the optimal target value (minimum ideal value) of Y , and y_u is its maximum acceptable value. The quality level of Y is:

$$r = \begin{cases} \dfrac{y_u - y}{y_u - y_l}, y \in (y_l, y_u] \\ \varepsilon, y = y_u \\ 0, y > y_u \end{cases} \quad (2)$$

ε is a minimal positive real number.

C. The Generalized Quality of The Nominal-the-best Type

The nominal-the-best type (N type) refers to the quality indicator with target value is in the middle of the tolerance range, such as length, width, angle and so on. The quality level of the product is declined if the positive and negative deviations exist among the quality performance value and the optimal target value. Let the performance value of N type quality characteristic Y be y , and the tolerance interval be $[y_l, y_u]$, where y_l and y_u are the minimum and maximum tolerance lines, and the optimal quality target value be μ . The quality level of Y is:

$$r = \begin{cases} \dfrac{y - y_l}{\mu - y_l}, y \in [y_l, \mu] \\ \dfrac{y_l - y}{y_u - \mu}, y \in [\mu, y_u] \\ \varepsilon, y = y_l or y_u \\ 0, y \notin [y_l, y_u] \end{cases} \quad (3)$$

ε is a minimal positive real number.

Formulas (1) ~ (3) conducted dimensionless processing on the original quality data, eliminate the possible influence caused by different quality units and enhance the normalization

and comparability of the data. The variation range of quality level is $[0,1]$. When the quality performance value reaches the optimal target value, the quality level is the maximum value; On the contrary, the quality level is the minimum value $r = 0$.

III. Research on the Complex Product Supply Chain Quality Assurance Method Concerning Psychological Utility

A. The Economic Profit Function of Both Parties in the Supply Chain Quality Cooperation

In the process of complex product's quality cooperation, the main manufacturer will get the quality improvement profit $\Phi(r)$ while pay the fixed cost B to supplies. And suppliers need to invest cost $C(r)$ to the production. In conclusion, the participants' economic profit function can be defined as following.

$$\begin{aligned} \pi_M(r) &= \Phi(r) - B \\ \pi_S(r) &= B - C(r) \end{aligned} \tag{4}$$

In order to reach the quality equilibrium point at the participant's maximum economic utility, the objective programming model is constructed as following.

$$\begin{cases} \max imize \pi_M(r) \\ \max imize \pi_S(r) \\ s.t. \begin{cases} \pi_S(r) > \pi_{s^*}, C_1 \\ \pi_M(r) > \pi_{M^*}, C_2 \\ 0 < r \le 1, C_3 \end{cases} \end{cases} \tag{5}$$

In the cooperation, suppliers will reduce the production cost greatly without quality assurance. In that case, the equilibrium point can only be reached at the opportunity benefit with the lowest quality level.

Assume that $C(r)$ is monotone increasing bivariate function, has a direct ratio with the quality level. On the contrary, $\Phi(r)$ is a monotone increasing bivariate function with an inverse ratio with quality level. Adjust the derivatives of all the functions to intersect at the industry average level r_1, $\frac{\partial \pi_M(r_1)}{\partial r} = 0$, $\frac{\partial \pi_S(r_1)}{\partial r} = 0$, which is shown in Fig. 1.

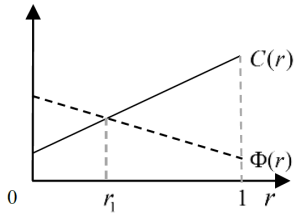

Fig. 1. The participants' quality improvement profit funtion and the production cost function.

B. The Participants' Psychological utility in the Supply Chain Quality Cooperation

(1) The definition of the participants' psychological utility in the quality cooperation

Definition 1: The quality reference point defines as average industry quality level, which is transferred according to Equation (1) at the same delivery.

In the process of the quality cooperation in the supply chain, the relationship between the main manufacturer's psychological utility $v_M(r)$ and the quality level r is shown in Fig. 2.

Here, the abscissa means the quality level r and the ordinate represents the main manufacturer's psychological utility function $v_M(r)$. When the quality level r is lower than the industry quality level r_1, the loss aversion coefficient β makes the psychological utility $v_M(r)$ decreased a lot at the reference point r_1.

(2) The psychological utility of the participants' in the supply chain

Denoted the industry average quality level as the loss aversion reference point r_1, which has an effect on the participants' psychological utility can be shown as below.

As shown in Fig. 3, $r \in (0,1)$. In the supply chain cooperation, when $r < r_1$, the main manufacturer will have a psychological utility decline $\beta[\pi_M(r) - \pi_M(r_1)]$. On the contrary, when $r > r_1$, the participants' psychological utility won't be affected by the loss aversion coefficient.

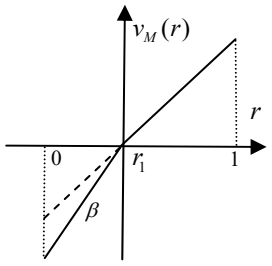

Fig. 2. The relationship between the main manufacturer's psychological utility and the quality level.

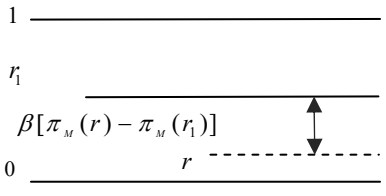

Fig. 3. The reference effect on the participants' psychological utility.

C. The Quality Cooperation Method of the Complex Product Supply Chain Under the Psychological Perspective

It can be seen from Fig. 2 and Fig. 3, if the loss aversion coefficient exists, there will be a gap between the psychological utility $v_M(r)$ and $\pi_M(r)$ when the quality of the components delivered by the suppliers is lower than the industry average level r_1. The reference point is considered in this paper. When $r \in (0, r_1)$, the main manufacturer will connect the psychological utility decline with economic profit to motivate the suppliers to improve the components' quality in the delivery. Meanwhile, the objective programing model is adopted to calculated the equilibrium quality point of the maximum psychological utility of both parties. In particular, the effects only happen to the main manufacturer, the suppliers' economic profit won't be influenced by the reference point.

From the information has been mentioned above, $v_M(r)$ and $v_S(r)$ can be represented as below.

$$\begin{aligned} v_M(r) &= \begin{cases} \beta[\pi_M(r) - \pi_M(r_1)] + \pi_M(r), (0, r_1) \\ \alpha[\pi_M(r) - \pi_M(r_1)] + \pi_M(r), (r_1, 1) \end{cases} \\ v_S(r) &= \begin{cases} \beta[\pi_M(r) - \pi_M(r_1)] + \pi_S(r), (0, r_1) \\ \alpha[\pi_M(r) - \pi_M(r_1)] + \pi_S(r), (r_1, 1) \end{cases} \end{aligned} \tag{6}$$

The expected function of the participants $E(v_M(r))$, $E(v_S(r))$ can be respectively defined as following.

$$\begin{aligned} E(v_M(r)) &= \begin{cases} \int_0^r (\beta[\pi_M(r) - \pi_M(r_1)] + \pi_M(r)) f(r) dr, (0, r_1) \\ \int_{r_1}^r (\alpha[\pi_M(r) - \pi_M(r_1)] + \pi_M(r)) f(r) dr, (r_1, 1) \end{cases} \\ E(v_S(r)) &= \begin{cases} \int_0^r (\beta[\pi_M(r) - \pi_M(r_1)] + \pi_S(r)) f(r) dr, (0, r_1) \\ \int_{r_1}^r (\alpha[\pi_M(r) - \pi_M(r_1)] + \pi_S(r)) f(r) dr, (r_1, 1) \end{cases} \end{aligned} \tag{7}$$

Here, $f(r)$ is the participants' probability density function.

The objective programming model is constructed as following.

$$\begin{cases} \max imize\ E(v_M(r)) \\ \max imize\ E(v_S(r)) \\ s.t. \begin{cases} v_S(r) > \pi_S^*, C_1 \\ v_M(r) > \pi_M^*, C_2 \\ 0 < r \le 1, C_3 \end{cases} \end{cases} \tag{8}$$

Here, π_M^* and π_S^* represent the participants' opportunity earnings, which is defined as the economic profits at the average industry quality level r_1.

The main manufacturer needs to adjust every single part in the expected utility function to ensure the benefit maximization of both parties in the cooperation. The derivates of the participants' expected utility function are represented as following.

$$\begin{aligned} \frac{\partial E(v_M(r))}{\partial r} &= \begin{cases} (\beta[\pi_M(r) - \pi_M(r_1)] + \pi_M(r)) f(r), (0, r_1) \\ (\alpha[\pi_M(r) - \pi_M(r_1)] + \pi_M(r)) f(r), (r_1, 1) \end{cases} \\ \frac{\partial E(v_S(r))}{\partial r} &= \begin{cases} (\beta[\pi_M(r) - \pi_M(r_1)] + \pi_S(r)) f(r), (0, r_1) \\ (\alpha[\pi_M(r) - \pi_M(r_1)] + \pi_S(r)) f(r), (r_1, 1) \end{cases} \end{aligned} \tag{9}$$

Here, β represents the loss aversion coefficient, α represents the gain perspective coefficient, $0 < \alpha < \beta < 1$. Moreover, $\alpha < \beta$ means the main manufacturer is more sensitive about the loss. Define $\frac{\partial E(v_M(r))}{\partial r}, \frac{\partial E(v_S(r))}{\partial r}$ as a non-negative number constantly in $(0, r_1)$, which can be shown as following.

$$\begin{aligned} [\beta(\Phi(r) - \Phi(r_1)) + (\Phi(r) - B)] f(r) > 0 \\ [\beta(\Phi(r) - \Phi(r_1)) + (B - C(r))] f(r) > 0 \end{aligned} \tag{10}$$

Define $\frac{\partial E(v_M(r))}{\partial r}$, $\frac{\partial E(v_S(r))}{\partial r}$ as a non-negative number constantly in $(0, r_1)$, which can be shown as following.

$$\begin{aligned} [\alpha(\Phi(r) - \Phi(r_1)) + (\Phi(r) - B)] f(r) = 0 \\ [\alpha(\Phi(r) - \Phi(r_1)) + (B - C(r))] f(r) = 0 \end{aligned} \tag{11}$$

Assume that $C(r)$ is monotone increasing bivariate function, which have a direct ratio with the quality level. On the contrary, $\Phi(r)$ is a monotone increasing bivariate function with an inverse ratio with quality level. Adjust the derivatives of all the functions to intersect at the equilibrium point r^*, $\frac{\partial E(v_M(r^*))}{\partial r} = 0$, $\frac{\partial E(v_S(r^*))}{\partial r} = 0$ in $(r_1, 1)$, $\frac{\partial E(v_M(r))}{\partial r} > 0$, $\frac{\partial E(v_S(r))}{\partial r} > 0$ in (r_1, r^*), $\frac{\partial E(v_M(r))}{\partial r} < 0$, $\frac{\partial E(v_S(r))}{\partial r} < 0$ in $(r^*, 1)$. Both parties' psychological utility reaches the maximum at r^*, the expected change is shown in Fig. 4.

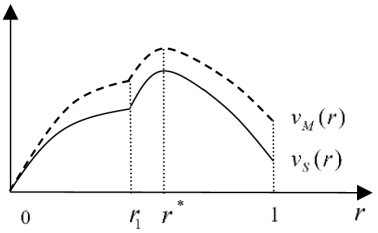

Fig. 4. The change of the participants' psychological utility.

IV. CASE STUDY

A. Case Background

A commercial aircraft company (Main manufacturer) ordered engines from an engine company (supplier). Maximum thrust is selected as a key standard of the engine quality, the

engine maximum thrust $X \in (27,34)$, which can be transferred by the Formula (1) ~ (3). Assumed that the fixed cost of a qualified engine $B = 7000$, average industry quality level $r_1 = 0.3$, the equilibrium point under the reference effects $r^* = 0.4$.

Assume that there is a linear relationship between the probability density and the quality level in ideal conditions. As shown in Fig. 5., the sum of Area 1 is 1 in $(0,1)$, l is the probability density function of the quality level in $(0.3,1)$, with a negative slope.

The expression can be obtained as following.

$$f(r) = -2r + 2 \tag{12}$$

The probability function $F(r)$ can be obtained by integrating the probability density function as following.

$$F(r) = -2r^2 + 2r \tag{13}$$

Here, $p = F(r)$.

B. *The Participants' Equilibrium Solution Without Reference Point*

In the quality cooperation without the reference point, the production cost, quality improvement profit can be shown as following.

$$\begin{aligned} C(r) &= 2r + 6999.4 \\ \Phi(r) &= -3r + 7000.9 \end{aligned} \tag{14}$$

The participants' economic profit is as below.

$$\begin{aligned} \pi_M(r) &= -3r + 0.9 \\ \pi_S(r) &= -1.5r + 0.45 \end{aligned} \tag{15}$$

The participants' expected profit is as below.

$$E(\pi_M(r)) = \int_0^r \pi_M(r) f(r) dr, (0,1) \tag{16}$$

$$E(\pi_S(r)) = \int_0^r \pi_S(r) f(r) dr, (0,1)$$

The change of the expected profit of both parties in $(0,1)$ is shown in Fig. 6. $E(\pi_M(r))$ and $E(\pi_S(r))$ decreased as the r increased. The equilibrium point is $r_1 = 0.3$, which is the industry average quality point. Besides, it should be noted that the supplier's unilateral improvement of the quality level will greatly increase the quality cost and reduce the benefits of quality cooperation a lot at the same time. As a result, it is possible for $E(\pi_S(r))$ is shown as a negative number when the quality is higher enough.

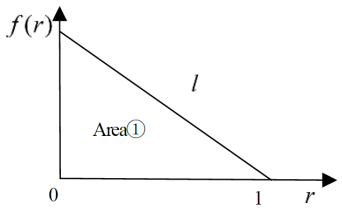

Fig. 5. The quality probability density function.

C. *The participants' equilibrium solution under reference effect*

In this section, the loss aversion coefficient is introduced to the process of cooperation. The punishment has been set for the part which has a lower quality than the industry average quality level, and related parameters are defined as $\alpha = 0.6, \beta = -0.88, C(r) = 2.5r + 6998.88, \Phi(r) = -2r + 7000.92$.

The participants' psychological utility is as below.

$$\begin{aligned} v_M(r) &= \begin{cases} \beta[\pi_M(r) - \pi_M(0.3)] + \pi_M(r), (0, 0.3) \\ \alpha[\pi_M(r) - \pi_M(0.3)]\pi_M(r), (0.3, 1) \end{cases} \\ v_S(r) &= \begin{cases} \beta[\pi_M(r) - \pi_M(0.3)] + \pi_S(r), (0, 0.3) \\ \alpha[\pi_M(r) - \pi_M(0.3)]\pi_S(r), (0.3, 1) \end{cases} \end{aligned} \tag{17}$$

The participants' expected utility is as below.

$$\begin{aligned} E(v_M(r)) &= \begin{cases} \int_0^r (\beta[\pi_M(r) - \pi_M(0.3)] + \pi_M(r)) f(r) dr, (0, 0.3) \\ \int_{0.3}^r (\alpha[\pi_M(r) - \pi_M(0.3)]\pi_M(r)) f(r) dr, (0.3, 1) \end{cases} \\ E(v_S(r)) &= \begin{cases} \int_0^r (\beta[\pi_M(r) - \pi_M(0.3)] + \pi_S(r)) f(r) dr, (0, 0.3) \\ \int_{0.3}^r (\alpha[\pi_M(r) - \pi_M(0.3)]\pi_S(r)) f(r) dr, (0.3, 1) \end{cases} \end{aligned} \tag{18}$$

The change of the expected utility of both parties in $(0,1)$ is shown in Fig. 7.

In Fig. 7. $E(v_M(r))$ and $E(v_S(r))$ decreased as the r increased. The equilibrium point is $r^* = 0.4$, The expected utility reached a maximum at that point, and then it starts to go down.

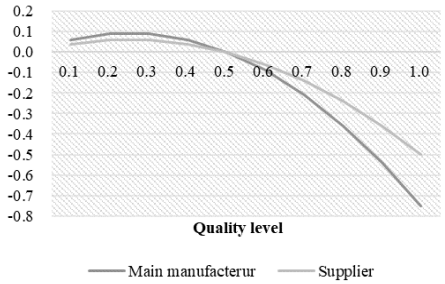

Fig. 6. The change of the expected profit of both parties.

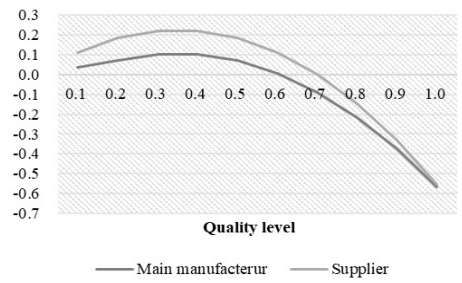

Fig. 7. The change of the expected utility of both parties.

D. Analysis and Comparison of Results

The following conclusions are found by comparing the psychological utility of both parties in the case study with a reference point and without a reference point. On the one hand, in the quality cooperation with the reference point, the suppliers tend to provide the components with industry average quality level $r_1 = 0.3$. In that case, $E(\pi_M(0.3)) = 0.09$, $E(\pi_S(0.3)) = 0.06$. On the other hand, when the psychological factors are taken into consideration, the participants' quality equilibrium point has moved to a higher level $r^* = 0.4$. At this point, the participants' have the maximum expected utility. $E(v_M(0.4)) = 0.1$, $E(v_S(0.4)) = 0.22$. By comparing the two situations have been mentioned above, it is apparent that psychological factors play a key role in quality cooperation. With the loss aversion coefficient and the expected utility function of both parties, the suppliers tend to improve the components quality level, which makes the participants' expected utility have a significant improvement.

V. CONCLUSION AND FUTURE WORKS

This paper puts forward the expected utility function of both parties in cooperation concerning the reference point, which effectively guarantees the product quality provided by the suppliers. It provides not only a new analysis idea and research mode for complex product quality contract design theoretically, but also the main manufacturer a guideline for control the supplier's product quality based on contract design practically.

There are several directions for further study. This paper assumed that there is only a single static reference point in the cooperation of the complex product supply chain. However, there may be more than one reference point will be considered by the main manufacturer. Moreover, except the static reference point, there also exists a dynamic reference point in the cooperation. Therefore, the future works can focus on the dynamic or several reference points in the quality cooperation of the complex product supply chain. How to motivate suppliers to provide higher quality components under the dynamic and various reference points is the key problem that urges to be solved in the near future.

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