# Evolution Analysis On Quality Incentives In "Main Manufacturer-Suppliers" Mode

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In the "main manufacturer-multiple suppliers" supply-demand mode, the main manufacturer and suppliers of the high-end equipment manufacturing industry are often characterized by bounded rationality and incomplete information, thus bringing challenges to the multiparty game of dynamic equipment quality control. This study models the part quality incentive with an evolutionary game between the main manufacturer and suppliers and discusses the stability of each equilibrium point. Furthermore, the impacts of the main manufacturer cost subsidies and supplier effort levels on strategy evolution are analyzed. Simulation results indicate that suppliers tend to improve the part quality as cost subsidies increase and required effort levels decrease. Additionally, the main manufacturer tends to incentivize suppliers with increased cost subsidies and decreased required effort levels. The findings define the effective range of cost subsidies and effort levels while providing theoretical references for studying the game decisions of the main manufacturer and suppliers.

**Keywords:** Main manufacturer; Evolutionary game; Quality regulation; Stability analysis



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## 1. Introduction

Crucial for strategic emerging industries, high-end equipment is customized products or systems with high technology levels and large capital investments, including aerospace equipment, high-speed trains, and semiconductor production lines. Such equipment is oriented to customer demand and manufactured collaboratively through cross-field and cross-regional organization, where the main manufacturer assembles all parts from suppliers and delivers the final product to the customer. Taking Boeing's B747 aircraft as an example, Boeing assembles the parts manufactured by 1,500 large enterprises and 15,000 small and medium enterprises and delivers the final product to the customer.

In the "main manufacturer–multiple suppliers" mode, the main manufacturer outsources non-core tasks to suitable suppliers to utilize their superior resources. Therefore, the overall quality of high-end equipment depends on not only the assembly capacity of the main manufacturer but also the part quality of the suppliers. Quality issues of key parts could cause significant losses to the main manufacturer. For instance, two Boeing 737MAX aircraft crashed successively in October 2018 and March 2019 due to the defective design of the maneuvering characteristics augmentation system and sensor failure.

The main manufacturer expects high-quality parts from suppliers for improved overall product quality and greater benefits [1]. Meanwhile, supplier profit margins narrow due to lower purchasing prices from the main manufacturer and higher raw material costs. To illustrate, the steel price rising from 1,900 yuan/ton to about 3,800 yuan/ton since 2015 poses a great risk for suppliers to improve the part quality. However, it is necessary for suppliers to invest funds to improve part quality, and the returns are heavily biased towards the manufacturer [2]. which is contradictory to the maximization of supplier benefits. Thus, the game between the main manufacturer and suppliers on part quality is becoming increasingly prominent. The main manufacturer's incentive mechanism affects suppliers' "attitude" toward collaborative cooperation [3], i.e., the effort level, and suppliers could become unwilling to improve part quality under insufficient quality incentives. Therefore, a reasonable quality incentive mechanism such as cost sharing is necessary for the main manufacturer to encourage suppliers to improve part quality [4].

Most of the existing studies on supply chain quality control and supervision are conducted from the perspective of quality improvement in the production process and enterprise collaboration [5–7], while few studies focused on part quality improvement and incentives of the main manufacturer and suppliers. The game model of quality management in the "main manufacturer-multiple suppliers" mode assumes that stakeholders are completely rational, thus incapable to describe the dynamic attributes of the participants and analyze the strategy evolution of the main manufacturer and suppliers [8]. In reality, however, the main manufacturer and suppliers have bounded rationality and incomplete information, rendering it difficult to predict the behavior of other stakeholders. Therefore, the part quality supervision strategy evolution of the main manufacturer and suppliers is analyzed through the evolutionary game theory (EGT). The evolutionary game combines the traditional game and the dynamic evolution process and constructs a decision-making process that continuously learns and revises among the stakeholders to increase benefits [9]. Finally, an evolutionarily stable strategy (ESS) is achieved [10, 11].

Based on EGT, this paper studies the part quality improvement-incentive behavior of the main manufacturer and suppliers in the "main manufacturer-multiple suppliers" mode and mainly addresses the following questions. What are the stable conditions of part quality improvement incentives? How does the supplier choose the strategy under different costsharing incentives of the main manufacturer? How does supplier effort level affect the evolution trend of supplier strategy to improve part quality?

The novelty of this paper is to explore the strategic interaction of the main manufacturer and suppliers and further analyze the impacts of the main manufacturer cost subsidies and supplier effort levels on their strategy evolution. Firstly, an evolutionary game model for the quality incentives of the main manufacturer and suppliers is constructed. Then, the stability of the equilibrium points of the game model is discussed. Finally, the impacts of cost-sharing coefficients and effort levels on the strategy evolutionary path and equilibrium state are analyzed.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature. Section 3 describes the problem and assumptions. In Section 4, an evolutionary game model for the part quality incentives of the main manufacturer and suppliers is established. Based on the replicator dynamic equation, ESS is analyzed in Section 5. Section 6 analyzes the impacts of important factors on the evolutionary paths of tripartite strategies, such as cost subsidies of the main manufacturer. Section 7 proposes the conclusions and suggestions.

## 2. Literature review

Extensive research has been conducted on supply chain quality control and regulation. Wang et al. [12] considered the uncertainty of cooperation between the main manufacturer and suppliers and studied the elasticity optimization problem based on the bilateral gray quality function. Feng et al. [13] studied the quality disclosure policy of the manufacturer in the case of consumer returns. Yet, quality incentives were not involved in the above research. Xie et al. [14] analyzed the impact of regulatory mechanisms on the production of pirated products but did not consider the interactions between manufacturers and suppliers. Kwon [15] used a lightweight model to improve the efficiency of dimensional quality management from the perspective of shipbuilding quality and analyzed the interaction among manufacturers, retailers, suppliers, and the government but not the strategy evolution process among stakeholders.

The game theory has been widely applied to supply chain quality management. Yoo and Cheong [16] established a Stackelberg game model between customers and suppliers and analyzed incentive strategies to improve product quality. Nevertheless, the quality incentive decisions with information asymmetry are not considered in these studies based on the Stackelberg game with complete information. Yi et al. [3] proposed a cooperative game model between the main manufacturer and suppliers with incomplete information. Based on the differential game theory, Pang and Tan [17] analyzed the quality equilibrium decisions in supply chains composed of one supplier and two competing manufacturers. Li et al. [18] discussed the random disturbance of quality control strategy in supply chains through the stochastic differential game. Zhao et al. [19] established a tripartite static game model of product quality supervision with incomplete information among manufacturers, distributors, and supervisory departments and analyzed the strategy selection of stakeholders. However, the dynamic decision-making processes of different stakeholders were not covered. Kong et al. [20] formulated product regulatory strategies from the perspective of enterprise clusters and analyzed the enterprise cluster evolution process but failed to consider the game behavior of other stakeholders, such as upstream and downstream enterprises.

Scholars have studied quality control in the "main manufacturer-multiple suppliers" mode, which is different from the traditional transaction. The main manufacturer plays a dominating role and can regulate supplier activities [21]. Cheng et al. [8] constructed an incentive Stackelberg game model between the main manufacturer and the suppliers. Nonetheless, these studies have not explored the strategy evolution trend of suppliers and the main manufacturer.

Most studies analyzed supply chain quality management from the static viewpoint and ignored the dynamic and complex nature of quality management. Quality management in the "main manufacturer-multiple suppliers" mode often takes the form of long-term collaborative relationships between the main manufacturer and suppliers. Due to the bounded rationality and incomplete information of the main manufacturer and suppliers, it is difficult to predict stakeholder behavior in complex and uncertain environments. Therefore, it is necessary to analyze the dynamic strategy selection of each stakeholder based on EGT.

Compared with the traditional game theory, the evolutionary game considers the bounded rationality of stakeholders and describes the decision-making process with continuous learning and revision by constructing a dynamic relationship suitable to study the long-term dynamic game among stakeholders with bounded rationality [22–24]. Parties of the evolutionary game constantly adjust and improve their benefits, finally reaching an equilibrium state, namely, the evolutionary stability strategy (ESS), where no individual party unilaterally adjusts its strategy as long as the others do not change theirs [25].

The evolutionary game has been widely applied to discuss the interaction of multiple stakeholders in supply chain management [26–28], such as environmental protection [29–31] and platform regulation [32, 33]. Chen and Hu [34] established an evolutionary game model to analyze the behavioral strategies of manufacturers and governments under various combinations of carbon taxes and subsidies. Wang et al. [32] constructed an evolutionary game model between the government and enterprises and analyzed the evolution of green technological innovations. Wu et al. [35] considered the "deceive acquaintance" behavior of e-commerce platforms and constructed an evolutionary game model from the perspective of cooperative supervision between the government and consumers. Based on the evolutionary game, Liu et al. [36] proposed a governance mechanism to prevent service platforms from the discriminatory pricing of big data. Hosseinnezhad et al. [2] analyzed the evolution process of suppliers' resource sharing under disruption scenarios. The above research provided a theoretical basis and reference for studying the decision-making evolution process of quality incentives in the "main manufacturer-multiple suppliers" mode.

Based on the above analysis, this paper studies the evolution process of quality incentives for key parts among the main manufacturer and suppliers with incomplete information and bounded rationality.

## 3. Problem description and assumptions

According to the agreement with the main manufacturer, suppliers comprehensively consider the investment cost for improving part quality and the return for supplying the parts and choose the strategy to maximize their benefits. The main manufacturer and suppliers with limited environmental cognition lack a strong ability to acquire and process information. Therefore, their strategies are not optimal in the beginning, while their final strategies are after trying different strategies in multiple games.

This paper views the main manufacturer and two types of suppliers as players in the evolutionary game and constructs an evolutionary game model for quality incentives of the main manufacturer and two types of suppliers. The schematic diagram of the model is shown in Fig. 1 Suppliers A and B are two different types, with differences in production cost, enterprise scale, production capacity, etc. Supplier A represents small and mediumsized enterprises, while supplier B represents large enterprises. Taking COMAC's C919 large aircraft as an example, 70 enterprises have become its suppliers or potential suppliers, including large enterprises such as the Aviation Industry Corporation of China (AVIC) and Baosteel as well as small and medium-sized enterprises such as Zhejiang Xizi Aviation and Boyun New Materials that focus on equipment manufacturing. Meanwhile, the main manufacturer has different cost-sharing proportions for suppliers A and B.

The following assumptions are made in this study:

1. Suppliers A and B have different production costs and investment costs for improved part quality and two strategy options: {improving part quality (I), not improving part quality (NI)}. The probability of supplier A adopting strategy I is $X, 0 \leq X \leq 1$, with $X = 1$ signifying supplier A adopting strategy I and $X = 0$ signifying supplier A not adopting strategy

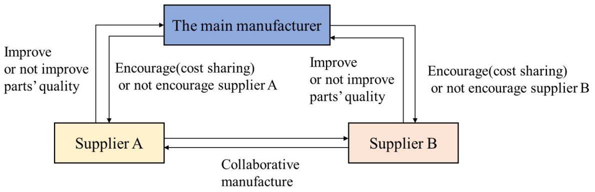



**Fig. 1.** Schematic diagram of quality incentives for the main manufacturer and suppliers.

I. The probability of supplier B adopting strategy I is $Y, 0 \leq Y \leq 1$, with $Y = 1$ signifying supplier B adopting strategy I and $Y = 0$ signifying supplier B not adopting strategy I.

2. The main manufacturer also has two strategy options: {encouraging the suppliers (E), not encouraging the suppliers (NE)}. The probability of the main manufacturer adopting strategy E is $Z, 0 \leq Z \leq 1$, with $Z = 1$ signifying the main manufacturer adopting strategy E and $Z = 0$ signifying the main manufacturer not adopting strategy E.

3. The suppliers provide parts to the main manufacturer at the price of $P_i\,(P_i > 0, i = A, B)$ and bear production costs $C_{iL}$. When supplying parts with improved quality, the suppliers bear investment costs $C_{iH}$ for purchasing advanced equipment and technology, with $C_{iH} = C_{iL} + \delta_i e_i^2/2$ [37], where $\delta_i e_i^2/2$ is the extra cost of supplier $i$ providing parts of improved quality. $e_i$ is effort level of supplier $i, e_i > 0$, and $\delta_i$ is its cost coefficient. When supplying parts of improved quality, the suppliers receive additional benefit $R_i\,(R_i > 0, i = A, B)$, such as reputation.

4. Besides assembling the parts, the main manufacturer also motivates and coordinates the suppliers. Specifically, the main manufacturer purchases parts from the suppliers at the price of $P_i$ and covers assembly cost $C_m$ and regulatory cost $C_R$. After the assembly, the product is sold to the customer at the price of $P$. The main manufacturer offers subsidy $aC_{iH}$ to suppliers adopting strategy I, with $a$ being the cost subsidy coefficient.

5. High-quality parts improve the quality of the final product and bring additional benefits to the main manufacturer, such as reputation. With suppliers A and B both adopting strategy I, the additional benefit of the main manufacturer is $G_0$. With only supplier A adopting strategy I, the additional benefit of the main manufacturer is $G_1$. With only supplier B adopting strategy I, the additional benefit of the main manufacturer is $G_2 . G_0 > G_1 > G_2$. The main parameters and their meanings are listed Table 1.

## 4. Evolutionary game model of the main manufacturer and suppliers

The eight strategy combinations are presented in Fig. 2. According to the assumptions of the model, a game payoff matrix is constructed, as shown in Table 2, where the formulas represent the payoffs of supplier A, supplier B, and the main manufacturer, respectively.

1. Expected benefits of supplier A

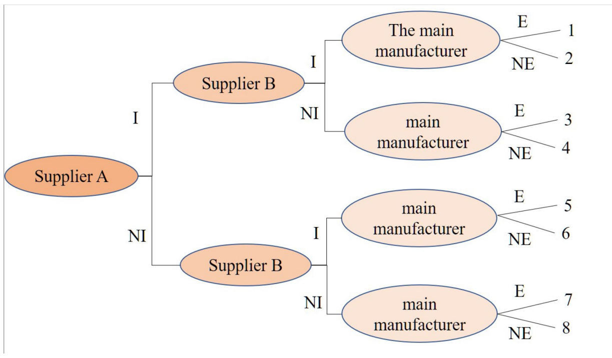



**Fig. 2.** Strategy combinations of the tripartite evolutionary game.

The expected benefits of supplier A for improving part quality can be expressed as Eq. (1).

$$\begin{aligned} U_{11} = {} & YZ\,(P_A - C_{AH} + R_A + aC_{AH}) + \\ & Y(1-Z)\,(P_A - C_{AH} + R_A) + \\ & (1-Y)Z\,(P_A - C_{AH} + R_A + aC_{AH}) + \\ & (1-Y)(1-Z)\,(P_A - C_{AH} + R_A) \\ = {} & P_A - C_{AH} + R_A + ZaC_{AH} \end{aligned} \tag{1}$$

The expected benefits of supplier A for adopting strategy NI can be calculated with Eq. (2).

$$\begin{aligned} U_{12} = {} & YZ\,(P_A - C_{AL}) + Y(1-Z)\,(P_A - C_{AL}) + \\ & (1-Y)Z\,(P_A - C_{AL}) + (1-Y)(1-Z)\,(P_A - C_{AL}) \\ = {} & P_A - C_{AL} \end{aligned} \tag{2}$$

Average expected benefits of supplier A are obtained in Eq. (3).

$$\begin{aligned} U_1 &= XU_{11} + (1-X)U_{12} \\ &= X\,(P_A - C_{AH} + R_A + ZaC_{AH}) + (1-X)\,(P_A - C_{AL}) \\ &= P_A - C_{AL} + X\,(C_{AL} - C_{AH} + R_A + ZaC_{AH}) \end{aligned} \tag{3}$$

**Table 1.** Main parameters and their meanings.

| Stakeholders | Symbols | Meanings |
|---|---|---|
| Suppliers | $P_i(i=A,B)$ | Part price of supplier $i$ |
| | $C_{iH}(i=A,B)$ | Investment costs of adopting strategy I |
| | $C_{iL}(i=A,B)$ | Investment costs of adopting strategy NI |
| | $R_i(i=A,B)$ | Additional benefits of adopting strategy I |
| Main manufacturer | $P$ | Product price |
| | $C_m$ | Assembly cost |
| | $C_R$ | Regulatory cost |
| | $G_j(j=0,1,2)$ | Additional benefits |

**Table 2.** The payoff matrix of evolutionary game model.

| Suppliers | | The main manufacturer | |
|---|---|---|---|
| | | Encourage suppliers(Z) | Not encourage suppliers(1-Z) |
| Supplier A adopts strategy I (X) | Supplier B adopts strategy I($Y$) | $P_A - C_{AH} + R_A + aC_{AH}$<br>$P_B - C_{BH} + R_B + aC_{BH}$<br>$P + G_0 - P_A - P_B - C_m - C_R - aC_{AH} - aC_{BH}$ | $P_A - C_{AH} + R_A$<br>$P_B - C_{BH} + R_B$<br>$P + G_0 - P_A - P_B - C_m - C_R$ |
| | Supplier B adopts strategy NI$(1-Y)$ | $P_A - C_{AH} + R_A + aC_{AH}$<br>$P_B - C_{BL}$<br>$P + G_1 - P_A - P_B - C_m - C_R - aC_{AH}$ | $P_A - C_{AH} + R_A$<br>$P_B - C_{BL}$<br>$P + G_1 - P_A - P_B - C_m - C_R$ |
| Supplier A adopts strategy NI $(1-X)$ | Supplier B adopts strategy I($Y$) | $P_A - C_{AL}$<br>$P_B - C_{BH} + R_B + aC_{BH}$<br>$P + G_2 - P_A - P_B - C_m - C_R - aC_{BH}$ | $P_A - C_{AL}$<br>$P_B - C_{BH} + R_B$<br>$P + G_2 - P_A - P_B - C_m - C_R$ |
| | Supplier B adopts strategy NI $(1-Y)$ | $P_A - C_{AL}$<br>$P_B - C_{BL}$<br>$P - P_A - P_B - C_m - C_R$ | $P_A - C_{AL}$<br>$P_B - C_{BL}$<br>$P - P_A - P_B - C_m - C_R$ |

Therefore, the replicator dynamic equation of supplier A can be written as Eq. (4).

$$\begin{aligned} F(X) &= X\left(U_{11}-U_1\right) = X(1-X)\left(U_{11}-U_{12}\right) \\ &= X(1-X)\left(C_{AL}-C_{AH}+R_A+ZaC_{AH}\right) \end{aligned} \tag{4}$$

where $F(X)$ represents the change rate of supplier A to improve part quality. With $F(X) > 0$, supplier A tends to adopt strategy I. With $F(X) < 0$, supplier A is unwilling to adopt strategy I.

2. Expected benefits of supplier B

The expected benefits of supplier B for improving part quality can be expressed as Eq. (5).

$$\begin{aligned} U_{21} &= XZ\left(P_B - C_{BH} + R_B + aC_{BH}\right) + X(1-Z)(P_B \\ &\quad - C_{BH} + R_B) + (1-X)Z\left(P_B - C_{BH} + R_B + aC_{BH}\right) \\ &\quad + (1-X)(1-Z)\left(P_B - C_{BH} + R_B\right) \\ &= P_B - C_{BH} + R_B + ZaC_{BH} \end{aligned} \tag{5}$$

The expected benefits of supplier B for adopting strategy NI can be calculated with Eq. (6).

$$\begin{aligned} U_{22} &= XZ\left(P_B - C_{BL}\right) + X(1-Z)\left(P_B - C_{BL}\right) + \\ &\quad (1-X)Z\left(P_B - C_{BL}\right) + (1-X)(1-Z)\left(P_B - C_{BL}\right) \\ &= P_B - C_{BL} \end{aligned} \tag{6}$$

Average expected benefits of supplier B are calculated in Eq. (7).

$$\begin{aligned} U_2 &= YU_{21} + (1-Y)U_{22} \\ &= Y\left(P_B - C_{BH} + R_B + ZaC_{BH}\right) + (1-Y)\left(P_B - C_{BL}\right) \\ &= P_B - C_{BL} + Y\left(C_{BL} - C_{BH} + R_B + ZaC_{BH}\right) \end{aligned} \tag{7}$$

Therefore, the replicator dynamic equation of supplier B can be written as Eq. (8).

$$\begin{aligned} F(Y) &= Y\left(U_{21}-U_2\right) = Y(1-Y)\left(U_{21}-U_{22}\right) \\ &= Y(1-Y)\left(C_{BL}-C_{BH}+R_B+ZaC_{BH}\right) \end{aligned} \tag{8}$$

Where $F(Y)$ denotes the change rate of supplier B to improve part quality. When $F(Y) > 0$, supplier B tends to adopt strategy I. When $F(Y) < 0$, supplier B is unwilling to adopt strategy I.

3. Expected benefits of the main manufacturer

The expected benefits of the main manufacturer incentivizing suppliers are calculated in Eq. (9).

$$\begin{aligned} U_{31} &= XY\left(P+G_0-P_A-P_B-C_m-C_R-aC_{AH}-aC_{BH}\right) \\ &+X(1-Y)\left(P+G_1-P_A-P_B-C_m-C_R-aC_{AH}\right)+ \\ &(1-X)Y\left(P+G_2-P_A-P_B-C_m-C_R-aC_{BH}\right)+ \\ &(1-X)(1-Y)\left(P-P_A-P_B-C_m-C_R\right) \\ &=P-P_A-P_B-C_m-C_R+XY\left(G_0-G_1-G_2\right)+ \\ &X\left(G_1-aC_{AH}\right)+Y\left(G_2-aC_{BH}\right) \end{aligned} \tag{9}$$

The expected benefits of the main manufacturer choosing NE strategy are obtained in Eq. (10).

$$\begin{aligned} U_{32} &= XY\left(P+G_0-P_A-P_B-C_m-C_R\right)+ \\ &X(1-Y)\left(P+G_1-P_A-P_B-C_m-C_R\right)+ \\ &(1-X)Y\left(P+G_2-P_A-P_B-C_m-C_R\right)+ \\ &(1-X)(1-Y)\left(P-P_A-P_B-C_m-C_R\right) \\ &=P-P_A-P_B-C_m-C_R-XY \\ &\left(G_0+G_1+G_2\right)+XG_1+YG_2 \end{aligned} \tag{10}$$

Average expected benefits of the main manufacturer are calculated in Eq. (11).

$$\begin{aligned} U_3 &= ZU_{31}+(1-Z)U_{32} \\ &=P-P_A-P_B-C_m-C_R-XY\left(G_0+G_1+G_2\right) \\ &+XG_1+YG_2+2XYZG_0-XZaC_{AH}-YZaC_{BH} \end{aligned} \tag{11}$$

The replicator dynamic equation of the main manufacturer is obtained in Eq. (12).

$$\begin{aligned} F(Z) &= Z\left(U_{31}-U_3\right)=Z(1-Z)\left(U_{31}-U_{32}\right) \\ &=Z(1-Z)\left(2XYG_0-XaC_{AH}-YaC_{BH}\right) \end{aligned} \tag{12}$$

where $F(Z)$ represents the change rate of the main manufacturer motivating the suppliers.$F(Z)>0$ indicates that the main manufacturer tends to incentivize part suppliers. $F(Z)<0$ indicates that the main manufacturer is unwilling to incentivize the suppliers.

With $C_{iH}=C_{iL}+\delta_i e_i^2/2$, a three-dimensional dynamic system composed of supplier A, supplier B, and the main manufacturer can be constructed, as expressed in Eq. (13).

$$\left\{\begin{array}{l} F(X)=X(1-X)\left(-\delta_A e_A^2/2+R_A+ZaC_{AH}\right) \\ F(Y)=Y(1-Y)\left(-\delta_B e_B^2/2+R_B+ZaC_{BH}\right) \\ F(Z)=Z(1-Z)\left(2XYG_0-XaC_{AH}-YaC_{BH}\right) \end{array}\right. \tag{13}$$

## 5. Stability analysis

According to Eq. (13), equilibrium points in the game among supplier A, supplier B, and the main manufacturer are (0,0,0), (0,1,0), (0,0,1), (0,1,1), (1,0,0), (1,1,0), (1,0,1), (1,1,1), and $(X^*,Y^*,Z^*)$. Since the asymptotic stability of pure-strategy equilibria is only discussed in an asymmetric game [35], the asymptotic stability of $(X^*,Y^*,Z^*)$ is not discussed here. An equilibrium point is stable when all eigenvalues of the Jacobian matrix of each equilibrium are below 0 . When all eigenvalues are above 0 , the equilibrium point is unstable. The equilibrium point is a saddle point if all eigenvalues are positive or negative. The Jacobian matrix of the game system is expressed in Eq. (14).

$$\begin{aligned} J &= \begin{bmatrix} \frac{dF(X)}{dX} & \frac{dF(X)}{dY} & \frac{dF(X)}{dZ} \\ \frac{dF(Y)}{dX} & \frac{dF(Y)}{dY} & \frac{dF(Y)}{dZ} \\ \frac{dF(Z)}{dX} & \frac{dF(Z)}{dY} & \frac{dF(Z)}{dZ} \end{bmatrix} \\ &= \begin{bmatrix} (1-2X)a & 0 & X(1-X)aC_{AH} \\ 0 & (1-2Y)b & Y(1-Y)aC_{BH} \\ Z(1-Z)\left(2YG_0-aC_{AH}\right) & Z(1-Z)c & (1-2Z)d \end{bmatrix} \end{aligned} \tag{14}$$

where $a=-\delta e_A^2/2+R_A+ZaC_{AH}, b=-\delta e_B^2/2+R_B+ZaC_{BH}, c=2XG_0-aC_{BH}, d=2XYG_0-XaC_{AH}-YaC_{BH}$.

The Jacobian matrix of equilibrium point (0,0,0) can be expressed as Eq. (15).

$$J=\begin{bmatrix} -\delta_A e_A^2/2+R_A & 0 & 0 \\ 0 & -\delta_B e_B^2/2+R_B & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{15}$$

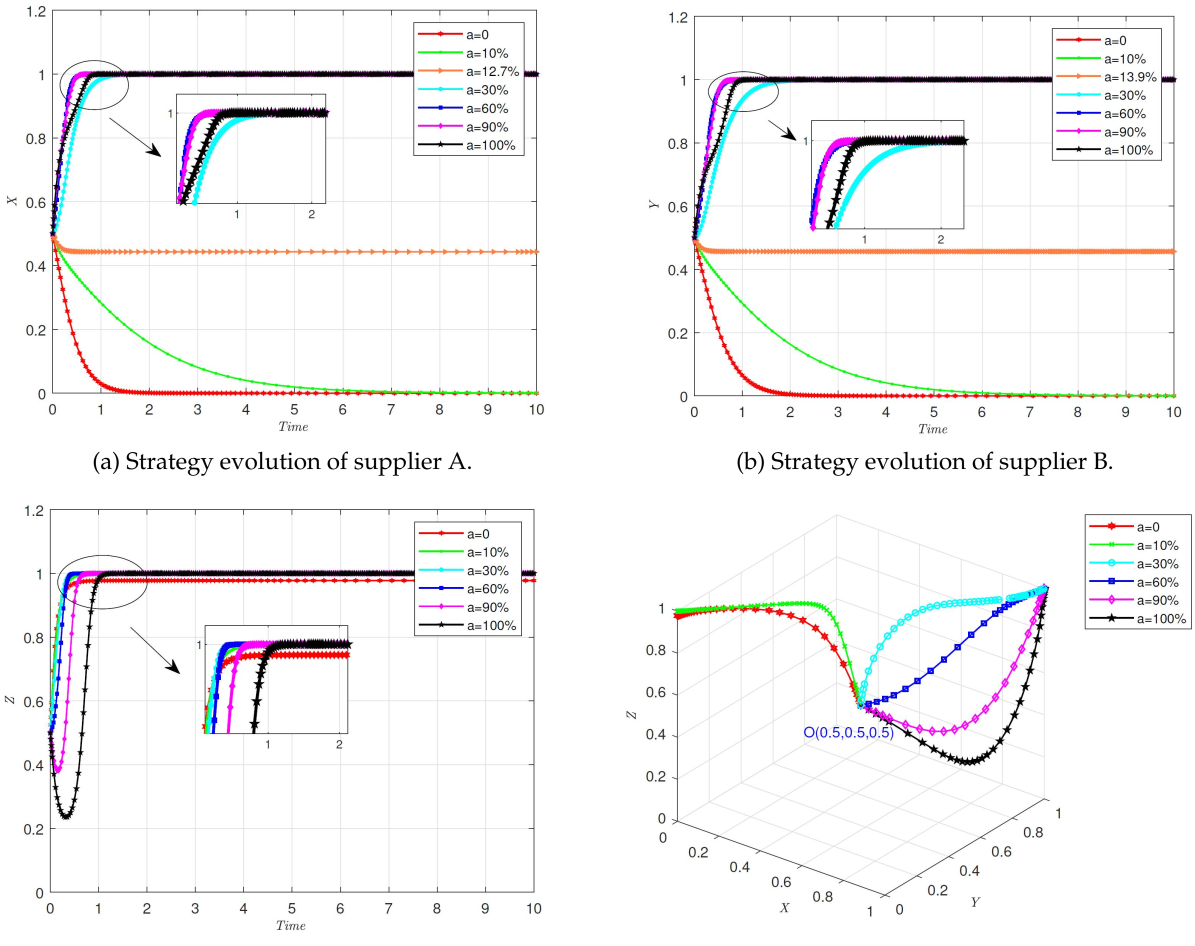
The eigenvalues of the matrix are $-\delta_A e_A^2/2+R_A, -\delta_B e_B^2/2+R_B, 0$.

Similarly, the eigenvalues and stability analyses of other equilibrium points are shown in Table 3.

As $E_1(0,0,0), E_3(0,0,1), E_4(0,1,1)$, and $E_7(1,0,1)$ are not stable, $E_2(0,1,0), E_5(1,0,0), E_6(1,1,0)$, and $E_8(1,1,1)$ are analyzed.

1. With $R_A<\delta_A e_A^2/2, R_B>\delta_B e_B^2/2$, the extra benefit of supplier A adopting strategy I is below its effort cost, and the extra benefit of supplier B adopting strategy I is above its effort cost. $E_2(0,1,0)$ is an ESS, and the strategies are {supplier A adopting strategy NI, supplier B adopting strategy I, the main manufacturer adopting strategy NE}. With higher required effort levels for supplier A and lower required effort levels for supplier B, it is easier for the system to stabilize to this state.

2. With $R_A>\delta_A e_A^2/2, R_B<\delta_B e_B^2/2$, the extra benefit of supplier A adopting strategy I is above its effort cost, and the extra benefit of supplier B adopting strategy I is below its effort cost. $E_5(1,0,0)$ is an ESS, and the




(a) Strategy evolution of supplier A.

(b) Strategy evolution of supplier B.

(c) Strategy evolution of the manufacturer.

(d) Tripartite strategy evolution.

**Fig. 3.** The effect of cost subsidy coefficient on the tripartite strategy evolution.

strategies are {supplier A adopting strategy I, supplier B adopting strategy NI, the main manufacturer adopting strategy NE}. With lower required effort levels for supplier A and higher required effort levels for supplier B, the system finally converges to this state.

3. With $R_A > \delta_A e_A^2/2, R_B > \delta_B e_B^2/2$, and $2G_0 < aC_{AH} + aC_{BH}$, the extra benefit of suppliers A and B adopting strategy I is above their effort cost, and the double extra benefits of the main manufacturer are below its cost subsidies to supplier A and B. $E_6(1,1,0)$ is an ESS, and the system tends to stabilize to the state: {supplier A adopting strategy I, supplier B adopting strategy I, the main manufacturer adopting strategy NE}. With lower required effort levels for suppliers A and B and higher cost subsidy coefficients of the main manufacturer, the system stabilizes to the state.

4. With $R_A + aC_{AH} > \delta_A e_A^2/2, R_B + aC_{BH} > \delta_B e_B^2/2$, and $2G_0 > aC_{AH} + aC_{BH}, E_8(1,1,1)$ is an ESS, and the system tends to stabilize to the state: {supplier A adopting strategy I, supplier B adopting strategy I, the main manufacturer adopting strategy E}. To converge to this state, the required effort levels for suppliers A and B should be lower, and the cost subsidy of the main manufacturer should be appropriate. $E_8(1,1,1)$ is the expected state in this study and is focused on in the simulation, as described in the next section.

## 6. Simulation analysis

According to actual data of shipbuilding enterprises in the literature [37], the following parameters are set: $P = 3000000$ dollars, $C_m = 130000$ dollars, $C_{AL} = 230000$ dollars, $\delta_A = 100$, $e_A = 30$, $C_{AH} = 275000$ dollars. Additionally, $E_8(1,1,1)$ is the expected state in this study and is focused on in the simulation. Therefore, other parameters of the payoff matrix

**Table 3.** Stability analysis of equilibrium points.

| Equilibrium points | $\lambda_1, \lambda_2, \lambda_3$ | Stability |
|---|---|---|
| $E_1(0,0,0)$ | $\lambda_1 = -\delta_A e_A^2/2 + R_A$<br>$\lambda_2 = -\delta_B e_B^2/2 + R_B$<br>$\lambda_3 = 0$ | Saddle point |
| $E_2(0,1,0)$ | $\lambda_1 = -\delta_A e_A^2/2 + R_A$<br>$\lambda_2 = \delta_B e_B^2/2 - R_B$<br>$\lambda_3 = -aC_{BH} < 0$ | $\lambda_1 < 0, \lambda_2 < 0$, stable point<br>Others, saddle point |
| $E_3(0,0,1)$ | $\lambda_1 = -\delta_A e_A^2/2 + R_A + aC_{AH}$<br>$\lambda_2 = -\delta_B e_B^2/2 + R_B + aC_{BH}$<br>$\lambda_3 = 0$ | Saddle point |
| $E_4(0,1,1)$ | $\lambda_1 = -\delta_A e_A^2/2 + R_A + aC_{AH}$<br>$\lambda_2 = \delta_B e_B^2/2 - R_B - aC_{BH}$<br>$\lambda_3 = aC_{BH} > 0$ | $\lambda_1 > 0, \lambda_2 > 0$,unstable point<br>Others, saddle point |
| $E_5(1,0,0)$ | $\lambda_1 = \delta_A e_A^2/2 - R_A$<br>$\lambda_2 = -\delta_B e_B^2/2 + R_B$<br>$\lambda_3 = -aC_{AH} < 0$ | $\lambda_1 < 0, \lambda_2 < 0$, stable point<br>Others, saddle point |
| $E_6(1,1,0)$ | $\lambda_1 = \delta_A e_A^2/2 - R_A$<br>$\lambda_2 = \delta_B e_B^2/2 - R_B$<br>$\lambda_3 = 2G_0 - aC_{AH} - aC_{BH}$ | $\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$, stable point<br>$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > 0$, unstable point<br>Others, saddle point |
| $E_7(1,0,1)$ | $\lambda_1 = \delta_A e_A^2/2 - R_A - aC_{AH}$<br>$\lambda_2 = -\delta_B e_B^2/2 + R_B + aC_{BH}$<br>$\lambda_3 = aC_{AH} > 0$ | $\lambda_1 > 0, \lambda_2 > 0$, unstable point<br>Others, saddle point |
| $E_8(1,1,1)$ | $\lambda_1 = \delta_A e_A^2/2 - R_A - aC_{AH}$<br>$\lambda_2 = \delta_B e_B^2/2 - R_B - aC_{BH}$<br>$\lambda_3 = aC_{AH} + aC_{BH} - 2G_0$ | $\lambda_1 < 0, \lambda_2 < 0, \lambda_3 < 0$, stable point<br>$\lambda_1 > 0, \lambda_2 > 0, \lambda_3 > 0$, unstable point<br>Others, saddle point |

are assigned according to the above parameters and stability condition $(\delta_A e_A^2/2 - R_A - aC_{AH} < 0, \lambda_2 = \delta_B e_B^2/2 - R_B - aC_{BH} < 0, aC_{AH} + aC_{BH} - 2G_0 < 0)$ of equilibrium point $E_8(1,1,1)$ in Table 3. Other parameters of payoff matrix are assigned: $P_A = 320000$ dollars, $P_B = 240000$ dollars, $C_{BH} = 190000$ dollars, $C_{BL} = 160000$ dollars, $\delta_B = 120, e_B = 23, R_A = 10000$ dollars, $R_B = 5000$ dollars, $G_0 = 300000$ dollars, $G_1 = 180000$ dollars, $G_2 = 120000$ dollars, $C_R = 50000$ dollars, $a = 0.5$.

Stakeholders of the game have bounded rationality, and the initial probability is set as (0.5,0.5,0.5). The main manufacturer and suppliers constantly compare benefits and dynamically change their strategies. Cost subsidy coefficients and effort levels are the main factors affecting the tripartite strategy evolution process. Therefore, the impacts of cost subsidy coefficients and effort levels on the evolution process are analyzed.

### 6.1. The impact of cost subsidy coefficient on the tripartite strategy evolution and expected benefits

The impact of the cost subsidy coefficient on the strategy evolution of supplier A is shown in Fig. 3 (a) When the cost subsidy coefficient is 0% and 10%, i.e., below 12.7% $\left(\left(\delta_A e_A^2/2 - R_A\right)/C_{AH}\right)$, the strategy equilibrium state of supplier A is " 0 ", i.e., supplier A is unwilling to improve part quality. As the cost subsidy coefficient increases, the stabilization toward equilibrium state "1" accelerates, i.e., the higher the cost subsidy coefficient, the quicker supplier A stabilizes to equilibrium state "1". When the cost subsidy coefficient exceeds 30%, the strategy evolution speed of supplier A is essentially unchanged.

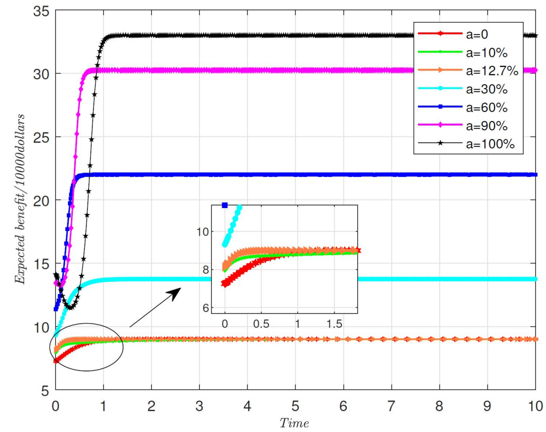
The impact of the cost subsidy coefficient on the strategy evolution of supplier B is shown in Fig. 3 (b) Compared with Fig. 3 (a), the cost-sharing coefficient demarcation point of supplier B adopting different strategies is $a = 13.9\%$ $\left(\left(\delta_B e_B^2/2 - R_B\right)/C_{BH}\right)$, and the stabilization toward equilibrium state "1" decelerates under the same cost subsidy coefficient due to the different production costs and effort levels of suppliers A and B, as listed in Table 3.

The impact of the cost subsidy coefficient on the strategy evolution of the main manufacturer is shown in Fig. 3 (c). The convergence to equilibrium state "1" accelerates as the cost subsidy coefficient decreases. With small cost subsidy coefficients, the main manufacturer tends to adopt strategy E.

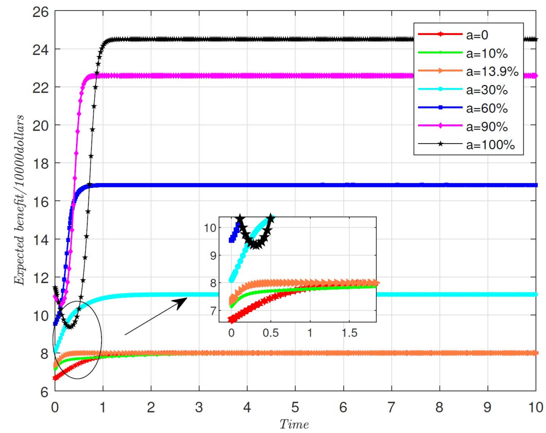
The impact of the cost subsidy coefficient on the tripartite strategy evolution process is shown in Fig. 3 (d). With $a = 0\%$ and $a = 10\%$, suppliers and the main manufacturer finally converge to ESS $(0,0,1)$, i.e., suppliers A and B are unwilling to improve part quality, while the main manufacturer tends to encourage them. When $a$ is above 13.9%, the stability condition of ESS $(1,1,1)$ is met. Therefore, the system eventually converges to ESS $(1,1,1)$. According to the above analysis, cost subsidies promote suppliers A and B to improve part quality but inhibit the main manufacturer from adopting strategy E.

The impact of the cost subsidy coefficient on tripartite expected benefits is shown in Fig. 4. When $a > 12.7\%$ and $a > 13.9\%$, the expected benefits of suppliers A and B increase with the increasing cost subsidies. When $a < 12.7\%$ and $a < 13.9\%$, the expected benefits of suppliers A and B show slight changes with the cost subsidy. With the same subsidy coefficient, the expected benefit of supplier A is much higher than that of supplier B.

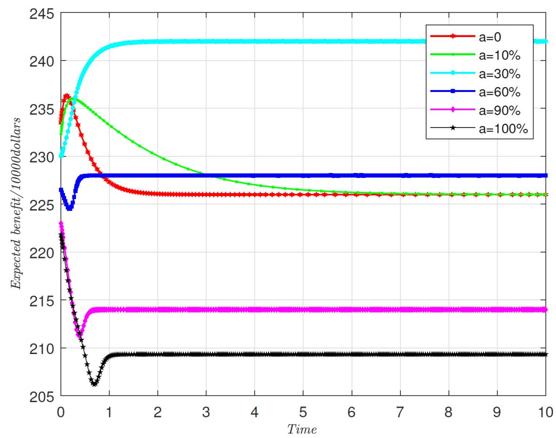
When $a \geq 30\%$, increasing the cost subsidies gradually decreases the expected benefit of the main manufacturer. When $a = 0\%$ and $10\%$, the benefit of the main manufacturer remains essentially unchanged and falls below that with $a = 30\%$. This is because when $a = 0$ and $10\%$, suppliers A and B adopt strategy NI, and the main manufacturer cannot receive additional benefits.




(a) Expected benefits of supplier A.




(b) Expected benefits of supplier B.




(c) Expected benefits of the main manufacturer.

**Fig. 4.** The effect of cost subsidy coefficient on tripartite expected benefits.

### 6.2. The impact of supplier A's effort levels on tripartite strategy evolution and expected benefits

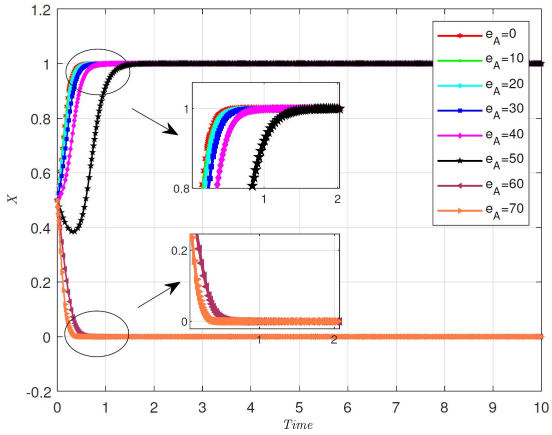
The impact of required effort levels for supplier A on its strategy evolution is plotted in Fig. 5 (a). With smaller $e_A$, supplier A tends to evolve toward equilibrium state "1", which takes longer with increasing $e_A$. With $e_A$ above 60 , supplier A tends to evolve toward equilibrium state "0", i.e., supplier $A$ is unwilling to improve part quality, and the time to evolve to state "0" shortens with increasing $e_A$.

The impact of supplier A's effort levels on the evolution process of supplier B is presented in Fig. 5 (b). With smaller $e_A$, supplier B tends to evolve toward equilibrium state "1", i.e., adopting strategy I, while the evolution speed is not significantly affected by $e_A$. With $e_A$ above 60 , supplier B reaches equilibrium state "0", i.e., unwilling to adopt strategy I. Increasing $e_A$ accelerates suppliers' stabilization to the equilibrium state "0".

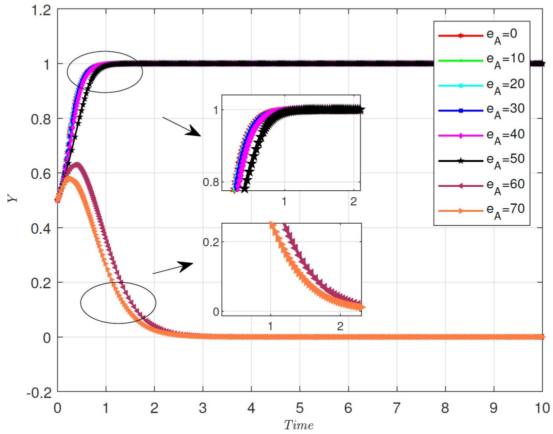
The effect of $e_A$ on the evolution process of the main manufacturer is illustrated in Fig. 5 (c). As $e_A$ increases, the main manufacturer tends to evolve from equilibrium state " 1 " to equilibrium state " 0 ", i.e., the increase in $e_A$ inhibits the main manufacturer from encouraging the suppliers. The higher the required effort levels for supplier A, the greater the unwillingness of the main manufacturer to motivate supplier A.

The impact of $e_A$ on the tripartite strategy evolution is shown in Fig. 5 (d). When $e_A = 60$ and $70$ , the system eventually converges to ESS $(0,0,0)$. As $e_A$ decreases, the system converges to ESS $(1,1,1)$, and the final strategy is (I, I, E).

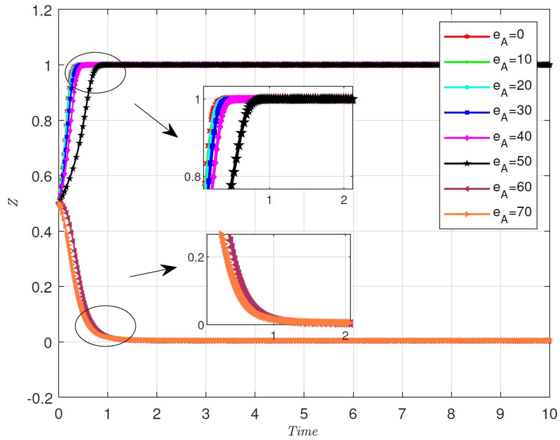
The impact of supplier A's effort levels on tripartite expected benefits is illustrated in Fig. 6. Supplier A's effort levels have a greater effect on the benefits of supplier A and the main manufacturer. As the effort levels increase from 0 to 50, the expected benefits of supplier A and the main



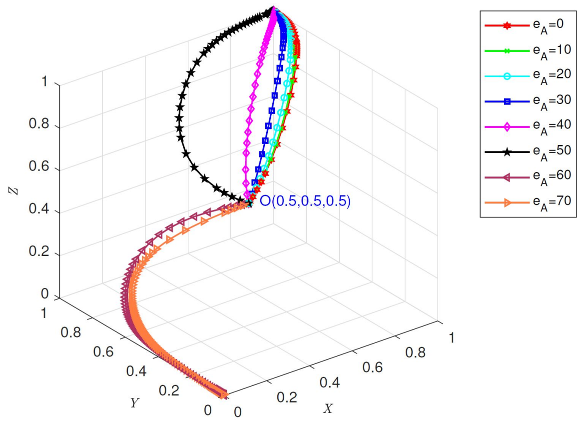

(a) Strategy evolution of supplier A.




(b) Strategy evolution of supplier B.




(c) Strategy evolution of the manufacturer.




(d) Tripartite strategy evolution.

**Fig. 5.** The effect of supplier A's effort levels on tripartite strategy evolution.

manufacturer gradually decrease with increasing magnitudes, while effort levels have no effect on the expected benefit of supplier B. When $e_A = 60$ and 70, the tripartite expected benefits decrease sharply and remain essentially unchanged, respectively. This is because the ESS is (0,0,0), i.e., (NI, NI, NE). Suppliers cannot obtain cost subsidies from the main manufacturer, and the main manufacturer cannot acquire additional benefits from improved part quality.

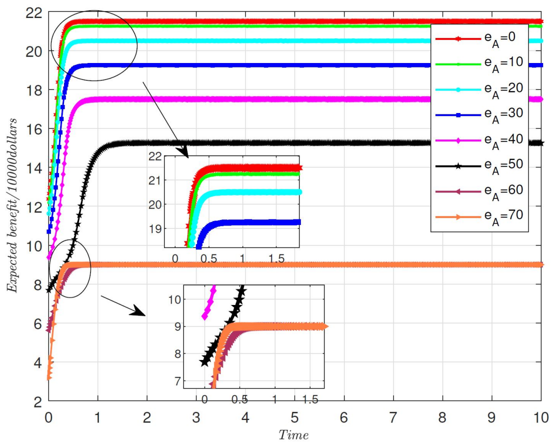
### 6.3. The impact of supplier B's effort levels on the strategy evolution and expected benefits

The impact of required effort levels for supplier B on the strategy evolution of supplier A is shown in Fig. 7 (a). With smaller $e_B$, supplier A evolves toward equilibrium state "1", and the evolution is not significantly impacted by $e_B$. As $e_B$ increases from 60 to 70 , the strategy converges to equilibrium state " 0 ", and the convergence rate accelerates.

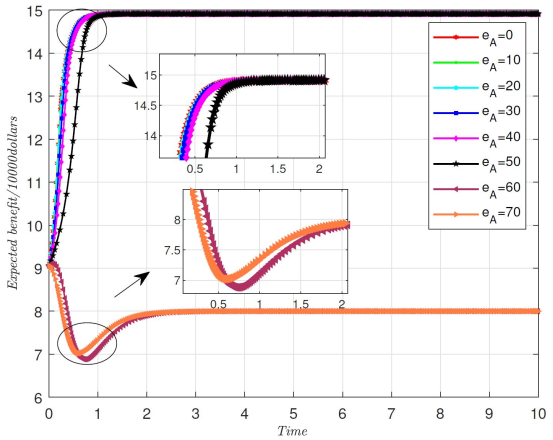
The effect of $e_B$ on the evolution process of supplier B is shown in Fig. 7 (b). As $e_B$ increases, supplier B tends to evolve towards equilibrium state " 0 " from equilibrium state " 1 ", indicating its willingness to adopt strategy NI. With smaller and decreasing $e_B$, the evolution to equilibrium state " 1 " shortens, and supplier B tends to improve part quality.

The effect of $e_B$ on the evolutionary path of the main manufacturer is shown in Fig. 7 (c). As $e_B$ increases, the main manufacturer evolves toward equilibrium state " 0 " from equilibrium state "1". With lower required effort levels for supplier B, the main manufacturer is more enthusiastic about adopting strategy E.

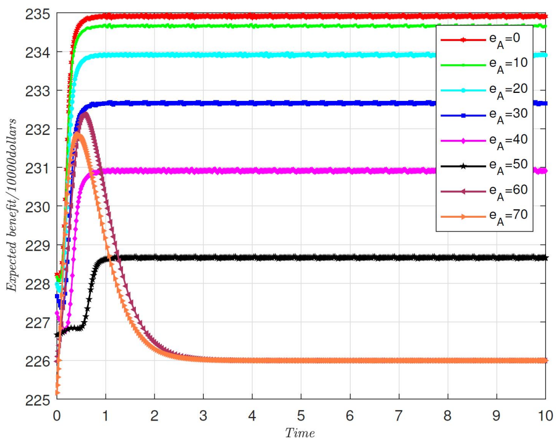
The impact of the required effort levels for supplier B on the tripartite strategy evolution is presented in Fig. 7 (d). When $e_B = 60$ and 70, the system trends toward ESS $(0, 0, 0)$, and the final strategy is (NI, NI, NE). As $e_B$ decreases, the system eventually converges to ESS (1,1,1) from ESS (0,0,0), and the final strategy is (I, I, E).




(a) Expected benefits of supplier A.




(b) Expected benefits of supplier B.




(c) Expected benefits of the main manufacturer.

**Fig. 6.** The effect of supplier A's effort levels on tripartite expected benefits.

Likewise, the impact of supplier B's effort levels on the tripartite expected benefits is illustrated and analyzed in Fig. 8.

## 7. Conclusion

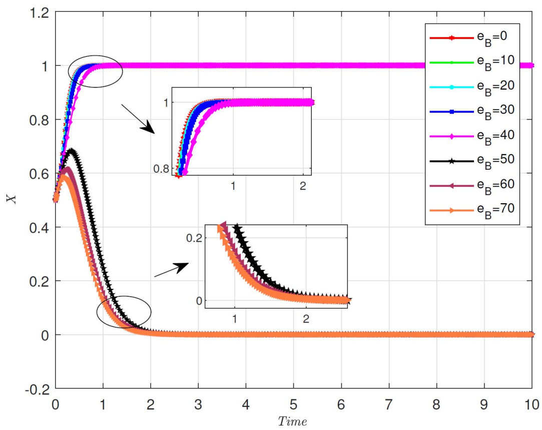
This paper establishes a tripartite evolutionary game among supplier A, supplier B, and the main manufacturer in the "main manufacturer-multiple suppliers" mode and discusses the stability of the equilibrium points of the evolutionary game model. Finally, the impacts of cost subsidy coefficients and effort levels on the tripartite evolution process are analyzed.

The main conclusions are as follows:

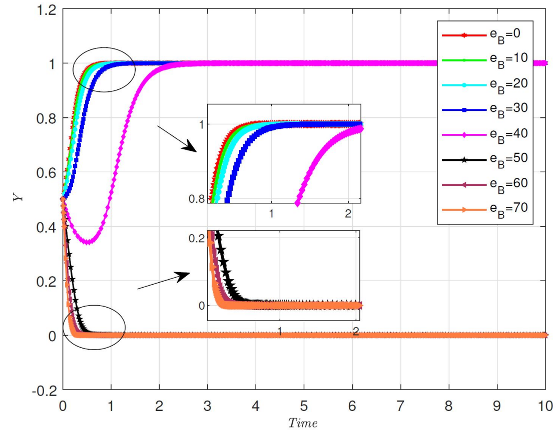
1. As the cost subsidy coefficient increases, suppliers tend to improve part quality, and the strategy evolution speed of the suppliers to equilibrium state "1" shows essentially no change. The smaller the cost subsidy coefficient, the more enthusiastic the main manufacturer is to motivate suppliers to adopt strategy I. Meanwhile, the cost subsidy coefficient has a positive impact on the expected benefits of the suppliers. With the increase in cost subsidy, the expected benefit of the main manufacturer decreases.

2. As the required effort levels for the suppliers decrease, the system evolves from the equilibrium state of {supplier A adopting strategy NI, supplier B adopting strategy NI, the main manufacturer adopting strategy NE} to {supplier A adopting strategy I, supplier B adopting strategy I, the main manufacturer adopting strategy E}. With low required effort levels, the suppliers tend to improve part quality, and the main manufacturer tends to adopt strategy E. As the required effort levels increase, the suppliers become unwilling to improve part quality, and the main manufacturer becomes unwilling to motivate them. This is because the main manufacturer must cover higher cost subsidies when motivating suppliers to improve part quality. The required effort levels for the suppliers should be reduced as much as possible to entice them into adopting strategy I. Effort levels negatively impact the expected benefits of the suppliers and the main manufacturer.

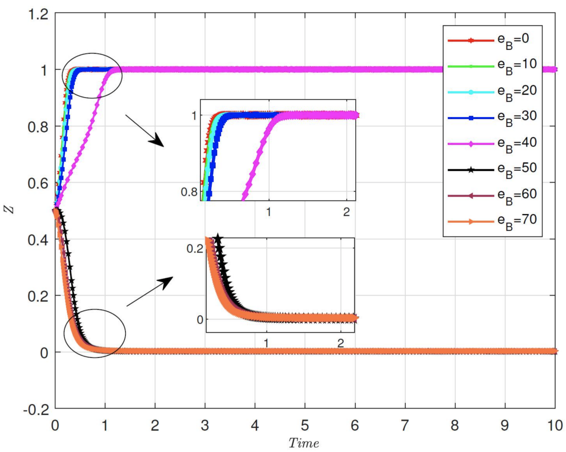
Some suggestions can be proposed through the above analysis. Considering that the main manufacturer plays a leading role in part quality improvement and that its cost subsidy coefficients positively impact part quality improvement, the main manufacturer should encourage the suppliers to improve part quality through appropriate cost subsidies. To ensure the benefits of the main manufacturer, however, the cost subsidies should not be too high. From the perspective of the suppliers, the required effort



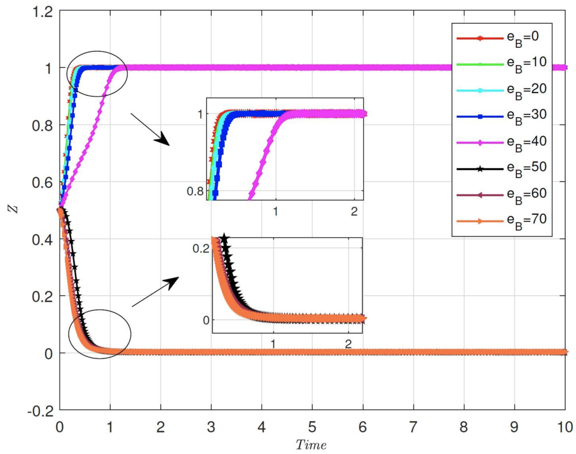

(a) Strategy evolution of supplier A.




(b) Strategy evolution of supplier B.




(c) Strategy evolution of the manufacturer.




(d) Tripartite strategy evolution.

**Fig. 7.** The effect of supplier B' effort levels on tripartite strategy evolution.

levels negatively impact part quality improvement, which should, therefore, be reduced through measures such as introducing advanced production technology.

The study can be extended in future research.

(1) This paper establishes a quality incentive model for the main manufacturer and the suppliers based on EGT. However, the role of customersis also important in high-end equipment manufacturing, and an evolutionary game model involving the customers can be established in the future.

(2) This study analyzes suppliers' strategy from the perspective of part quality, while part price and delivery time can be considered in the future.

(3) This reach only discusses the impacts of cost subsidy coefficients and effort levels on the evolution process, whereas the impacts of other factors should also be analyzed in future studies, such as supplier production costs and main manufacturer assembly costs.

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## Competing interests statement

No potential competing interest was reported by the authors.

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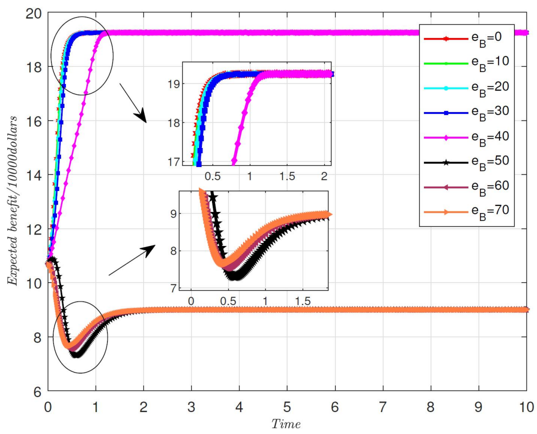
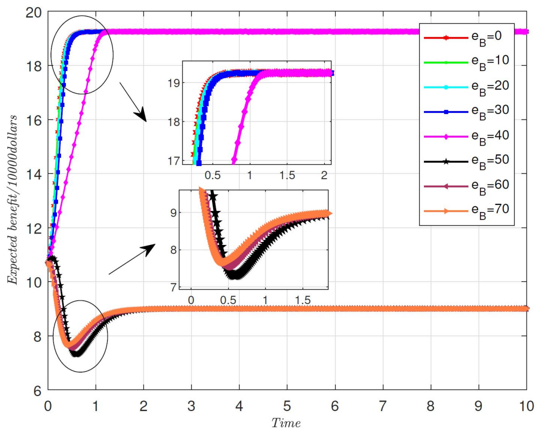
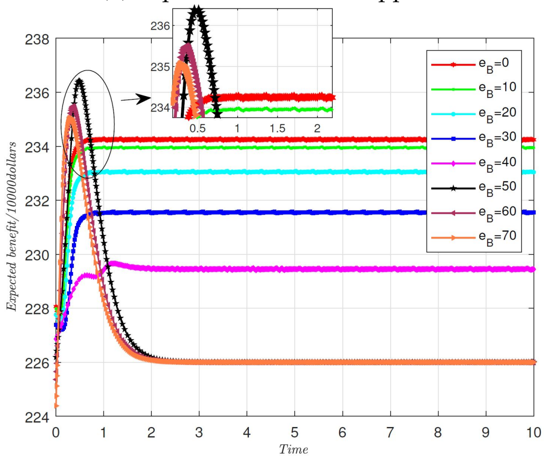



(a) Expected benefits of supplier A.




(b) Expected benefits of supplier B.




(c) Expected benefits of the main manufacturer.

**Fig. 8.** The effect of supplier B's effort levels on the tripartite expected benefits.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