Research on Civil Aircraft Spare Parts Pooling Evolutionary Game based on Supervision and Incentive Mechanism

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Abstract. In order to promote the cooperation of spare parts pooling alliance among airlines, an evolutionary game model of willingness to cooperate based on third-party supervision and incentive mechanism is established in this paper. The evolutionary stable conditions of the alliance members under different decision-making behaviors are analyzed by simulation, and the influence of relevant parameters on evolutionary results are determined. The results indicate that with certain constraints satisfied, the strategy choices of game parties can be brought to a cooperative state by adopting third-party supervision and incentive method. When the level of willingness to cooperate in a low state, the larger airline more tends to adopt non-cooperative strategy relative to the other. Meanwhile, increasing the level of supervision and penalty intensity can avoid free-rider behavior of airlines. Increasing the level of incentive can motivate airlines to adopt positive game strategies effectively. Expanding the size of spare parts pooling alliance can help to increase the incremental profit and shorten the time for evolving to the cooperation state.

Keywords: Alliance Cooperative Control, Evolutionary Computation, Sensitivity Analysis, Cooperative Game Theory

1. INTRODUCTION

In recent years, civil aviation transport has been booming, the growth of transport scale and the lack of resource guarantee capacity have become the main contradiction faced by the civil aviation industry. In order to meet the requirements of the spare parts fill rate, airlines usually stock an excessive amount of inventory on each maintenance base, resulting in the problem of high costs and low turnover rate in the allocation of spare parts resources. The inventory control capacity directly affects the economics of airline spare parts supply management, a redundant inventory will cause significant economic pressure on the airline, while an inadequate inventory will result in Aircraft-on-Ground(AOG) and reduce aircraft dispatch rates. Multiple studies have shown that spare parts pooling among airlines can help coordinate network resources and reduce operating costs [1], [2], [3]. However, the decision making of the members in spare parts pooling alliance (SPPA) is often influenced by the changing environment, and they need to constantly weigh up the relationship between competitive and cooperative responses. To

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address this problem, this paper carries out a study on the game of cooperation intention among members of the SPPA. By analyzing the evolutionary game process and results of cooperation intention under different control strategies, the paper provides a theoretical basis and controllability method for promoting alliance cooperation.

At present, most scholars' research on SPPA mainly focuses on the allocation of resource for spare parts pooling [4], spare parts supply chain management [5], cooperation revenue allocation game [6], and cooperation cost allocation game [7]. However, additional research is needed on strategies to promote multi-airline game players to reach alliances. In general, game players are usually in a more complex interest relationship and not fully rational. A complex alliance can be split into multiple two-person partnerships, with the end of the relationship between any two representing the dissolution of the entire alliance. Thus, the game stability analysis of a large alliance can be converted into two-person game analysis of multiple small alliances [8]. In the study of airline alliance game problem, Zhu *et al.* explored the evolutionary game problem of corporate competition and cooperation with multiple situations strategic decision-making approach [9]. Zhang *et al.* analyzed the impact of external uncertainties on the stability of air cargo alliances based on evolutionary game theory [10]. Yan *et al.* analyzed the impact on the evolutionary trend of airline alliance cooperation when the participants adopted different decision-making behaviors based on loss aversion prospect theory [11]. In the study of resource pooling game guided by the third-party, Arslan *et al.* explored the model of spare parts integrated supply with third-party involvement and proposed a cost allocation model [12]. Jia *et al.* studied shared parking behavior with government incentives and demonstrated that third-party incentives can promote the sharing of travel resources [13]. Chen *et al.* showed that by increasing the cost of penalties can increase the level of trust between firms, thus promoting the willingness of alliance members to adopt cooperative strategies [14]. Meng *et al.* developed an evolutionary game model among "government–port–third-party" organization, demonstrating that third-party can facilitate government regulation and control enforcement in port development [15]. In addition, as a mutually beneficial organization, the game members of SPPA inevitably generate free-rider behavior in cooperation [16]. Jiang *et al.* [17] established an evolutionary game model with the participation of government regulators for airline logistics infrastructure investment, the paper proved that the reward and punishment mechanism can effectively reduce the free-rider behavior of the game parties.

In order to further study the strategies to promote the development of SPPA cooperation, the main contributions made in this paper are summarized as follows. First, in order to avoid the impact of free-rider behavior on the cooperation of SPPA, this paper applies the third-party supervision and incentive mechanism to the process of cooperation among airlines and establishes an evolutionary game model of cooperative willingness for spare parts pooling. Second, this paper analyzes the benefit matrix of SPPA members under different decision-making behaviors to determine the influence of relevant parameters on the process and outcome of alliance evolution, so as to derive a controllable method to promote alliance cooperation.

2. MODEL ASSUMPTIONS AND DESCRIPTION

The set of strategies for airlines is S={cooperation, non-cooperation}. If there is a value of cooperation between two airlines, there will be a series of game behaviors between the two parties on how to further develop the spare parts pooling. In the process of airlines two-person willingness game, the level of cooperative willingness of the players varies with the time, size, profitability, and credibility of the alliance development. Both sides of the game make decisions based on factors such as the spare parts support capacity provided by the game object, the variation of revenue before and after spare parts pooling and the construction cost. The decision -making results of both parties determine the respective expected profit.

The phenomenon of free-rider in SPPA is when one party requests spare parts support, but the other party does not support even though they are in stock. The behavior emerges from loss aversion and bounded will on the one hand. In early stage of the SPPA, the level of scale effect and trust among members are low, and it is difficult for alliance members to have high expectation on cooperation profits, so they can keep base inventory and reduce the risk of AOG through free-rider behavior. On the other hand, the strategy of the alliance members tends to maximize short-term profits. Under the premise of bounded will, the short-term free-rider profits of alliance members are greater than the expected profits of cooperation, so they cannot make choice of optimal solution for long-term cooperation. Therefore, in order to avoid this free-rider behavior, this paper introduces a supervision and incentive mechanism to promote the SSPA cooperation, and the assumptions of SSPA cooperative willingness evolutionary game model are as follows.

Assumption 1: The set of strategy choices for airline A is S_A={cooperation, non-cooperation}, the probabilities of taking cooperative and uncooperative strategy intentions are x and 1-x, respectively. The set of strategy choices for airline B is S_B={cooperation, non-cooperation}, the probabilities of taking cooperative and uncooperative strategy intentions are y and 1-y, respectively.

Assumption 2: The profit of airlines A, B before SSPA cooperation is V_A, V_B, respectively, and the increased profit after SSPA cooperation is ΔV. At this time, the increased profits obtained by airline A, B based on contribution are $\alpha\Delta V$ and $(1-\alpha)\Delta V$, respectively, where $\alpha\in(0, 1)$.

Assumption 3: After SSPA establishment, the extra operating costs resulting from the cooperative strategy of one airline and the uncooperative free-rider strategy of the other are β_A, β_B, and the profits from the free-rider behavior are g_A, g_B, respectively.

Assumption 4: The third-party government organization supervises the cooperative behavior of both parties, and the increased operating costs of airlines A, B are ΔC_A, ΔC_B, respectively.

Assumption 5: The supervision intensity of third-party government organization for free-rider behavior is p, $p\in(0, 1)$, and the penalty intensity for free-rider behavior is ϑ. When both parties adopt the cooperative strategy, the incentive made by the third-party government organization is In, and the incentives obtained by airlines A, B based on contribution are In, $(1-\alpha)In$, respectively.

Based on the above assumptions, the payment matrix of the game between airlines is obtained as shown in Table I.

TABLE I AIRLINES SPARE PARTS POOLING GAME PAYMENT MATRIX

Airline A	Airline B: Cooperation	Airline B: Non-cooperation
Cooperation	$(V_A + \alpha\Delta V - \Delta C_A + \alpha In,$ $V_B + (1-\alpha)(\Delta V + In) - \Delta C_B)$	$(V_A - \Delta C_A - \beta_A + \vartheta p,$ $V_B - \Delta C_B - \vartheta p + g_B)$
Non-Cooperation	$(V_A - \Delta C_A - \vartheta p + g_A,$ $V_B - \Delta C_B - \beta_B + \vartheta p)$	(V_A, V_B)

3. EVOLUTIONARY GAME ANALYSIS OF COOPERATIVE WILLINGNESS IN SPARE PARTS POOLING

Based on the profit function of SPPA members when they adopt different strategy combinations, the replicated dynamic equation of cooperative willingness game can be established, which can dynamically investigate the evolution process and results of decision-making ratio within the game group.

The expected profit when airline A adopts a cooperative strategy, U'_A, as shown in (1). The expected profit when airline A adopts an uncooperative strategy, U''_A, as shown in (2). The average profit of airline A, $\bar{U}_A$, as shown in (3).

$$U'_A = y(V_A + \alpha\Delta V - \Delta C_A + \alpha In) + (1-y)(V_A - \Delta C_A - \beta_A + \vartheta p) \quad (1)$$

$$U''_A = y(V_A - \Delta C_A - \vartheta p + g_A) + (1-y)V_A \quad (2)$$

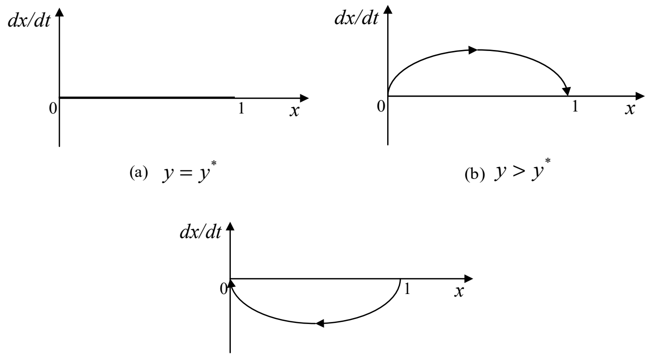
$$\bar{U}_A = xU'_A + (1-x)U''_A \quad (3)$$

According to evolutionary game theory, the replicated dynamic equation for airline A's strategy choice is shown in (4).

$$\begin{aligned} F(x) = \dot{x} = \frac{dx}{dt} &= x(U'_A - \bar{U}_A) = x(1-x)(U'_A - U''_A) \\ &= x(1-x)\begin{bmatrix} y(\alpha\Delta V + \alpha In + \beta_A + \Delta C_A - g_A) \\ +\vartheta p - \Delta C_A - \beta_A \end{bmatrix} \end{aligned} \quad (4)$$

The probability of airline A adopting the cooperative strategy, x, varies between [0,1] with the level of cooperative intention. If $U'_A > \bar{U}_A$, the trend of airline A's strategy choice will be toward cooperation, and if $U'_A < \bar{U}_A$, then the trend will be toward non-cooperation. Further, let $F(x) = 0$ to derive $x'_1 = 0$ and $x'_2 = 1$. Therefore, the stable points of the replicated dynamic equation for airline A's strategy choice are $x = x'_1$ and $x = x'_2$. The dynamic evolutionary trends of airline A's willingness to cooperate are shown in Fig. 1.

When $y^* = \frac{\Delta C_A + \beta_A - \vartheta p}{\alpha\Delta V + \alpha In + \beta_A + \Delta C_A - g_A}$, $F(x) \equiv 0$ in (4). It implies when $y = y^*$, airline A gains the same profits whatever changes in strategy choices at this time. When $y > y^*$, airline A gets stable states at $x = x'_1$ and $x = x'_2$, where the evolutionarily stable strategy (ESS) is at $x = x'_2$. When $y < y^*$, airline A gets stable states at $x = x'_1$ and $x = x'_2$ as well, where the ESS is at $x = x'_1$.



(a) $y = y^*$ (b) $y > y^*$

(c) $y < y^*$

Fig. 1. Dynamic evolutionary trends of airline A's willingness to cooperate

Similarly, the expected profit when airline B adopts a cooperative strategy, U'_B, as shown in (5). The expected profit when airline B adopts an uncooperative strategy, U''_B, as shown in (6). The average profit of airline B, $\bar{U}_B$, as shown in (7).

$$\begin{aligned} U'_B = &x[V_B + (1-\alpha)\Delta V - \Delta C_B + (1-\alpha)In] \\ &+(1-x)(V_B - \Delta C_B - \beta_B + \vartheta p) \end{aligned} \tag{5}$$

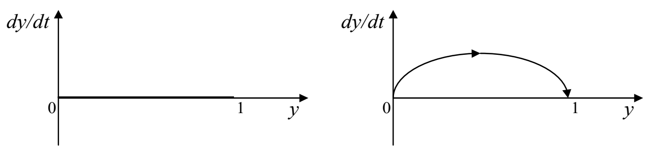
$$U''_B = x(V_B - \Delta C_B - \vartheta p + g_B) + (1-x)V_B \tag{6}$$

$$\bar{U}_A = xU'_A + (1-x)U''_A \tag{7}$$

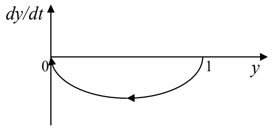
The replicated dynamic equation for airline A's strategy choice is shown in (8).

$$\begin{aligned} F(y) = \dot{y} = \frac{dy}{dt} &= y(U'_B - \bar{U}_B) = y(1-y)(U'_B - U''_B) \\ &= y(1-y)\begin{Bmatrix} x[(1-\alpha)\Delta V + (1-\alpha)In + \beta_B + \Delta C_B - g_B] \\ +\vartheta p - \Delta C_B - \beta_B \end{Bmatrix} \end{aligned} \tag{8}$$

Let $F(y) = 0$ to derive $y'_1 = 0$ and $y'_2 = 1$.The stable points of the replicated dynamic equation for airline B's strategy choice are $y = y'_1$ and $y = y'_2$. The dynamic evolutionary trends of airline B's willingness to cooperate are shown in Fig. 2. When $x^* = \frac{\Delta C_B + \beta_B - \vartheta p}{(1-\alpha)\Delta V + (1-\alpha)In + \beta_B + \Delta C_B - g_B}$, $F(y) \equiv 0$ in (8). It implies when $x = x^*$, airline B gains the same profits whatever changes in strategy choices at this time. When $x > x^*$, airline B gets stable states at $y = y'_1$ and $y = y'_2$, where the ESS is at $y = y'_2$. When $x < x^*$, airline B gets stable states at $y = y'_1$ and $y = y'_2$ as well, the ESS is at $y = y'_1$.



(a) $x = x^*$ (b) $x > x^*$



(c) $x < x^*$

Fig. 2. Dynamic evolutionary trends of airline B's willingness to cooperate

The equilibrium points of the evolutionary game for SPPA willingness to cooperate are obtained as $O(0,0)$, $Q(1,0)$, $P(0,1)$, $M(1,1)$, $E(x^*, y^*)$. The Jacobian matrix, J, is established in (9) to determine the stability of the equilibrium points [18].

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} \tag{9}$$

The determinant, *detJ*, and trace, *trJ*, of the Jacobian matrix are derived, and the stability criterion of the five equilibrium points are obtained with the method of local stability analysis. Therefore, *detJ* and *trJ* are composed of multiple parameters, when $\alpha\Delta V + \alpha In + \vartheta p > g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p > g_B$, i.e. the profit of the airline's cooperative strategy is greater than the free-rider strategy. The phase diagrams of dynamic evolution within the SPPA under different constraints are shown in Fig. 3. Similarity, when $\alpha\Delta V + \alpha In + \vartheta p < g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p < g_B$, i.e. the profit of the airline's cooperative strategy is less than the free-rider strategy. The phase diagrams of dynamic evolution within the SPPA under different constraints are shown in Fig. 4.

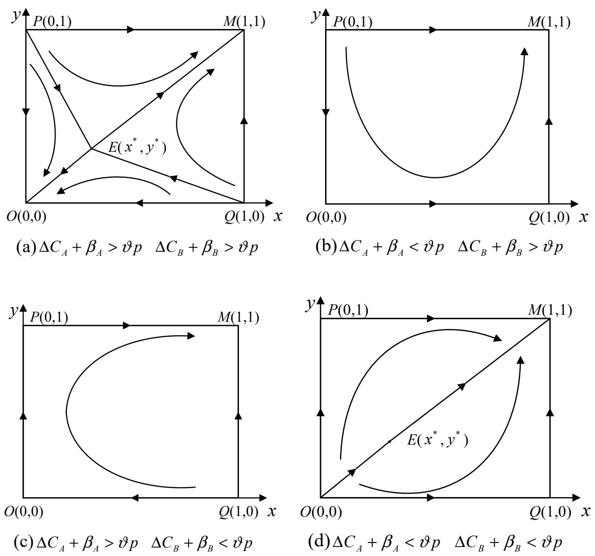
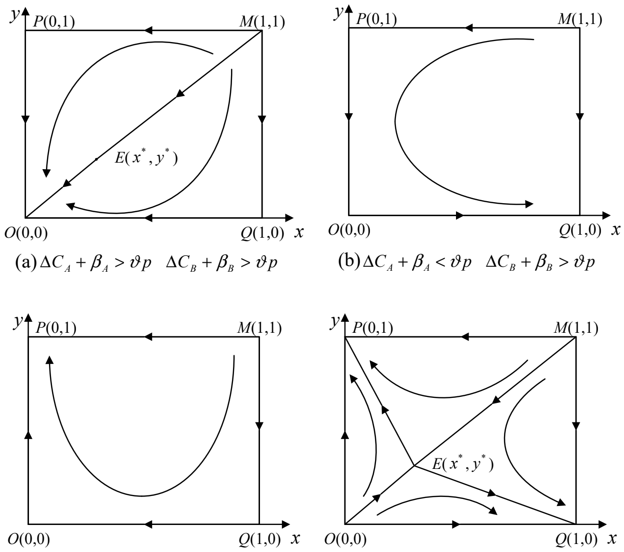


Fig. 3. The phase diagrams of dynamic evolution within the SPPA with $\alpha\Delta V + \alpha In + \vartheta p > g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p > g_B$



(a) $\Delta C_A + \beta_A > \vartheta p \quad \Delta C_B + \beta_B > \vartheta p$ (b) $\Delta C_A + \beta_A < \vartheta p \quad \Delta C_B + \beta_B > \vartheta p$

(c) $\Delta C_A + \beta_A > \vartheta p \quad \Delta C_B + \beta_B < \vartheta p$ (d) $\Delta C_A + \beta_A < \vartheta p \quad \Delta C_B + \beta_B < \vartheta p$

Fig. 4. The phase diagram of dynamic evolution within the SPPA with $\alpha\Delta V + \alpha In + \vartheta p < g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p < g_B$

In Fig. 3 (a), $\Delta C_A + \beta_A > \vartheta p$ and $\Delta C_B + \beta_B > \vartheta p$ i.e., the cost of airlines adopting cooperative strategy is greater than the penalty for their respective free-rider behavior. Among the equilibrium points, O(0,0) and M(1,1) are ESS. In Fig. 3 (b), $\Delta C_A + \beta_A < \vartheta p$ and $\Delta C_B + \beta_B > \vartheta p$ i.e., the cost of airline A adopting cooperative strategy is less than the penalty for free-rider behavior, while airline B does the opposite. Among the equilibrium points, only M(1,1) is ESS at this time. In Fig. 3 (c) and (d), among the equilibrium points, only M(1,1) is ESS as well. As a result, when $\alpha\Delta V + \alpha In + \vartheta p > g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p > g_B$, keeping the cost of either airline adopting cooperative strategy is less than the penalty for free-rider behavior will ensure that the SPPA eventually evolves to a cooperative state.

In Fig. 4 (a), among the equilibrium points, O(0,0) is ESS. In Fig. 4 (b), among the equilibrium points, Q(1,0) is ESS. In Fig. 4 (c), among the equilibrium points, P(0,1) is ESS. In Fig. 4 (d), among the equilibrium points, Q(1,0) and P(0,1) are ESS. As a result, when $\alpha\Delta V + \alpha In + \vartheta p < g_A$, $(1-\alpha)(\Delta V + In) + \vartheta p < g_B$, whatever the relationship between the cost of adopting cooperative strategy and the penalty for free-rider behavior, there is no way to ensure that the SPPA eventually evolves to the cooperative state.

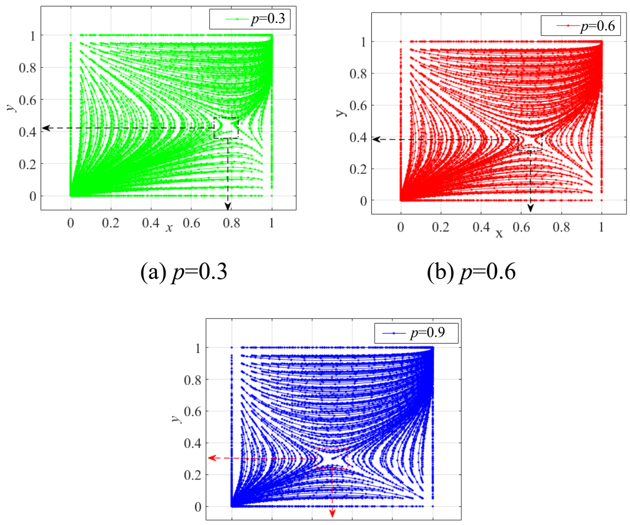
4. PARAMETERS SENSITIVITY SIMULATION ANALYSIS OF EVOLUTIONARY GAME

As previously mentioned, when $\alpha\Delta V + \alpha In + \vartheta p < g_A$ and $(1-\alpha)(\Delta V + In) + \vartheta p < g_B$, there is no way to ensure that the SPPA eventually evolves to a cooperative state. Therefore, this section conducts a parametric sensitivity simulation analysis with $\alpha\Delta V+\alpha In+\vartheta p>g_A$, $(1-\alpha)\Delta V+(1-\alpha)In+\vartheta p>g_B$ to explore the controllability method for the evolution of SPPA to cooperative state. The parameter settings under the change of third-party supervision intensity are shown in Table II.

TABLE II PARAMETER SETTINGS OF GAME SYSTEM UNDER THE CHANGE OF THIRD-PARTY SUPERVISION INTENSITY

				p=0.3, p=0.6, p=0.9					
α	ΔV	β_A	β_B	g_A	g_B	ΔC_A	ΔC_B	ϑ	In
0.7	200	70	65	50	70	55	30	50	50

Input Table II and (1)-(8) into MATLAB for simulation, the evolutionary game phase diagrams with the change of third-party supervision intensity are obtained as shown in Fig. 5.



(a) p=0.3 (b) p=0.6

(c) p=0.9

Fig. 5. The evolutionary game phase diagrams with the change of third-party supervision intensity

As shown in Fig. 5 (a)-(c), keeping other parameters constant, the area of the game evolving to (1,1) gets larger as p increases, which implies that the game tends to evolve toward cooperative strategy between two parties. In this case, the evolutionary rates and results of the game between two airlines are shown in Fig. 6.

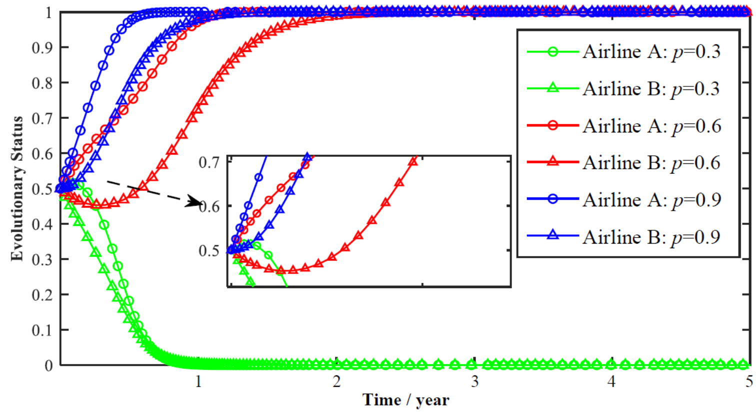


Fig. 6. The evolutionary sensitivity simulation of airlines game under different levels of supervision intensity

In Fig. 6, initially, both airlines put 50% level of willingness to cooperate into the game. When p=0.3, the game strategies of both airlines A and B eventually evolve to the non-cooperation state, (0, 0). When p=0.6 and p=0.9, the game strategies eventually evolve to the cooperation state, (1, 1). Meanwhile, the evolution time of game strategies to (1,1) state is significantly shortened as p increases, which proves that increased supervision intensity can avoid free-rider behavior of airlines and effectively promote the development of SPPA cooperation. While keeping p=0.6 and other initial conditions the same, the evolutionary rates and results of the game under three different levels of penalty intensity are shown in Fig. 7.

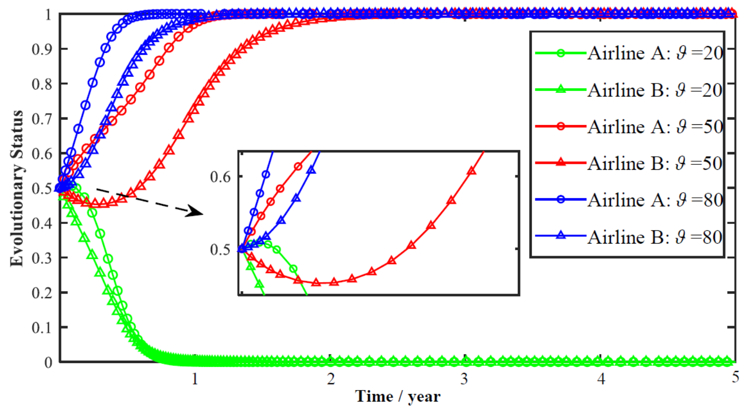


Fig. 7. The evolutionary sensitivity simulation of airlines game under different levels of penalty intensity

In Fig. 7, while ϑ=20, the game strategies of both airlines A and B eventually evolve to the non-cooperation state, (0, 0). Comparing with Fig. 6, it follows that the change of ϑ also affects the strategy choice of airlines when p is the same. The lower level of ϑ will cause the game to evolve towards non-cooperation of both parties, while the higher level of ϑ will promote the cooperation process of both parties to the game. When the p of SPPA has already achieved a high level, in fact, the further increase of supervision intensity needs to consume more costs, including technical and human costs, or even cannot be further increased. At this point to improve ϑ from another perspective can also promote the development of SPPA cooperation.

While keeping p=0.6 and other initial conditions the same, the evolutionary rates and results of the game under three different levels of incentive are shown in Fig. 8.

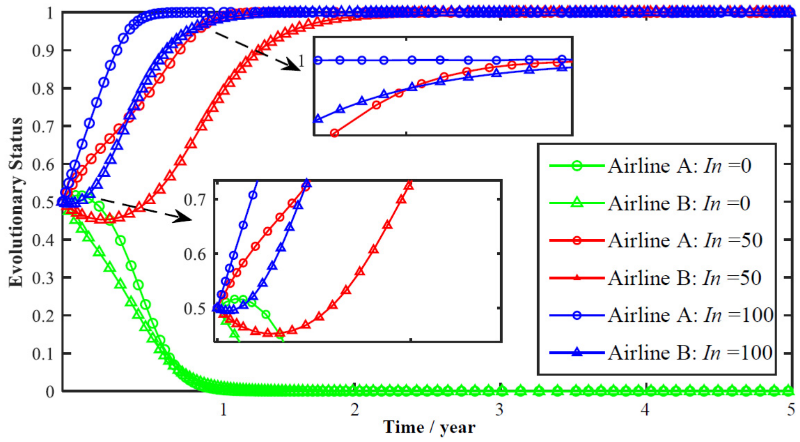


Fig. 8. The evolutionary sensitivity simulation of airlines game under different levels of incentive

In Fig. 8, when In=0, i.e., there is no external condition to motivate the cooperation of SPPA, the game strategies of both airlines A and B eventually evolve to the non-cooperation state, (0,0). After the levels of incentive are increased to In=50 and In=100, the game strategies eventually evolve to (1,1). Therefore, external Incentive is an effective method to promote alliance cooperation, and airlines will adopt different game strategies according to the level of incentive. A higher level of incentive tends to attract airlines to adopt a positive game strategy, making it easier for both parties to achieve alliance cooperation. The evolutionary sensitivity of SPPA game with different levels of incentive affecting willingness to cooperate is simulated in Fig. 9.

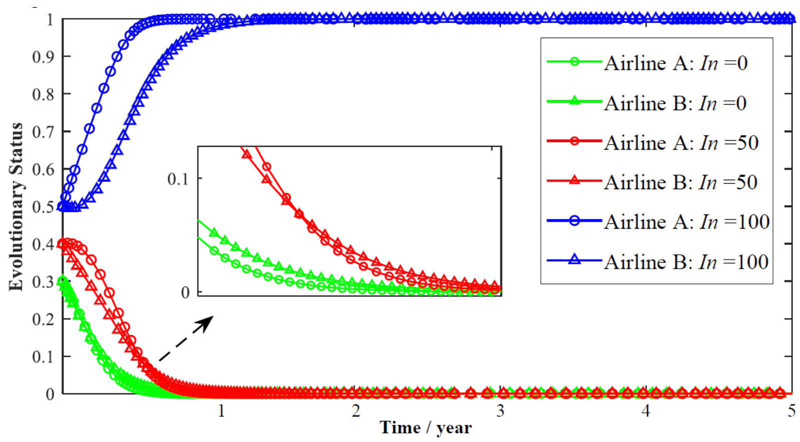


Fig. 9. The evolutionary sensitivity simulation of SPPA game with different levels of incentive affecting willingness to cooperate

As shown in Fig 9, a higher level of *In* is conducive to a more positive willingness to cooperate between airlines and beneficial to alliance cooperation, while a lower willingness to cooperate is more likely to cause the partnership termination. Moreover, Table II shows that the size of airline A is larger than airline B, which plays a dominant role in the game process. Comparing Fig. 8 with the high level of willingness to cooperate, airline A tends to adopt a more positive game strategy relative to airline B. However, at a lower level of willingness, airline B takes more free-rider behavior, resulting in airline A to pay more operating costs to maintain alliance cooperation. Therefore, in a state of low willingness to cooperate, the larger party tends to adopt non-cooperation strategy relative to the other. Finally, keeping p=0.6 and other initial conditions the same, the evolutionary rates and results of the game under three different levels of incremental profit are further explored as shown in Fig. 10.

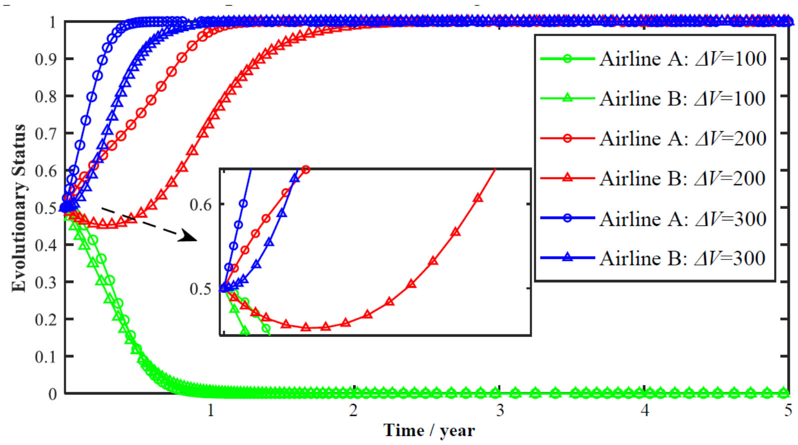


Fig. 10. The evolution sensitivity simulation of airlines game under different levels of incremental profit

In Fig. 10, when ΔV=100, the game strategies of both airlines A and B eventually evolve to (0,0). The game strategies eventually evolve to (1,1) while ΔV=200 and ΔV=300. Meanwhile, the time for both sides evolve to (1,1) state is significantly shortened as ΔV increased, which indicates that the increase of ΔV can accelerate the evolution process to (1,1). Due to the size of SPPA directly affects the scale of route network for spare parts assistance, which determines the ΔV of spare parts pooling cooperation. Therefore, combining the spare parts demands of all SPPA members to construct a pooling network and unify the allocation of base inventory can effectively reduce airlines operating costs and promote alliance pooling cooperation.

5. Conclusion

In order to promote SPPA and avoid free-rider behavior of airlines in the process of cooperation, this paper establishes an evolutionary game model of willingness to cooperate for spare parts pooling based on supervision and incentive mechanisms, and investigates the cooperative willingness problem among SPPA members by analyzing the cooperative conditions and parameter sensitivities that affect the evolutionary results of the game. The following conclusions are drawn. Firstly, when $\alpha\Delta V + \alpha In + \vartheta p > g_A$ and $(1-\alpha)(\Delta V + In) + \vartheta p > g_B$ are satisfied, keeping the cost of either airline adopting cooperative strategy is less than the penalty for free-rider behavior will ensure that the SPPA eventually evolves to a cooperative state. Secondly, when $\alpha\Delta V+\alpha In+\vartheta p>g_A$ and $(1-\alpha)(\Delta V+In)+\vartheta p>g_B$ are satisfied, whatever the relationship between the cost of adopting cooperative strategy and the penalty for free-rider behavior, there is no way to ensure that the SPPA eventually evolves to a cooperative state. Thirdly, increasing p and ϑ can avoid free-rider behavior of airlines, increasing In can effectively motivate airlines to adopt positive game strategies, increasing ΔV can significantly shorten the time for evolving to the state of alliance pooling cooperation. Finally, when the level of willingness to cooperate in a low state, the larger airline more tends to adopt non-cooperative strategy relative to the other.

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