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# Supply Chain Logistics Information Collaboration Strategy Based on Evolutionary Game Theory

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**ABSTRACT** Supply chain logistics information collaboration (SCLIC) is the basis and premise of supply chain logistics collaboration. An effective logistics information collaboration strategy can improve enterprises' chances of success in a new partnership in the supply chain. However, SCLIC is usually difficult to be achieved because of the complexity of the impact factor, strategy evolution process, and stability strategies. We propose an evolutionary game theory-based SCLIC strategy to solve this problem. Firstly, we build an evolutionary game model of SCLIC based on a two-echelon supply chain composed of suppliers and manufacturers. The strategy evolution game of suppliers, manufacturers, and the combination of manufacturers and suppliers are analyzed based on benefit maximization. The evolutionary stability strategy (ESS) is determined. Secondly, we analyze the impact of the relevant parameters on the strategy evolution process. And we use a comprehensive simulation to examine the efficiency of the proposed model. Finally, some managerial insights are presented for the supply chain enterprises to promote the realization of SCLIC.

**INDEX TERMS** Supply chain logistic information collaboration, evolutionary game theory, evolutionary stability strategy.

## ABBREVIATIONS

| | |
|---|---|
| EGT | Evolutionary game theory |
| ESS | Evolutionarily stable strategy |
| NIS | Neighborhood invader strategy |
| SCIS | Supply chain information sharing |
| SCLIC | Supply chain logistics information collaboration |
| SCM | Supply chain management |

## I. INTRODUCTION

With the rapid changes in global market demand and the uncertainty of economic priorities among trading partners, manufacturing enterprises have encountered major challenges [1]. Enterprises realize that gaining competitive advantage in the new market environment alone is almost impossible. Enterprises must expand cooperation and coordination to co-produce, share risks, and increase profits [2]. Therefore, competition venues are transforming from enterprises to supply chains [3]. The supply chain mainly focuses on how to coordinate the individual players to work together as a unit to pursue the same goals [4], while the supply chain system includes interrelated structures such as logistics, capital flow, and information flow among supply chain individuals [5], [6]. Thus, effective information sharing, collaboration, and coordination among supply chain partners are key to successful supply chain management (SCM) [4], [5], [7].

Supply chain information collaboration is the integration, coordination, and development of resources, business processes and organizational relationships by sharing and exchanging operational data, market data and other information among partners to respond faster to end customers' needs with the help of advanced information technology [3]. As a critical part of the supply chain, logistics is a significant part of the cost and performance of the supply chain. The logistics collaboration happens mainly in transportation and spreads to other distribution fields including delivery and storage [8]. So, it's good for supply chain partners to work on logistics

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collaboration for mutual benefits [9]. The effectiveness of the logistics collaboration is proved in many forms and adopted in many parts positively [8]. Modern logistics emphasizes information collaboration, which provides detailed supporting data to explain why and how supply chain individuals benefit from integrating separated logistics as a whole through collaboration [10]. Therefore, supply chain logistics information collaboration (SCLIC) is not only an important part of supply chain information collaboration but also the basis and premise of supply chain logistics collaboration.

Manufacturing enterprises often suffer from shutting down due to waiting for materials and failure to deliver goods on time because of the incoordination of separate logistics information: both suppliers and manufacturers cannot get information between each other. Suppliers are not able to collect demand information from downstream manufacturers on time so that adequate supply preparation is almost impossible. Meanwhile, manufacturers fail to obtain the supply information of suppliers, resulting in the mismatch between the logistics capacity provided by manufacturers and the quantity supplied by suppliers. Incoordination makes the whole supply chain inefficient. For example, agricultural machinery manufacturing enterprises, according to our investigation, are in urgent need of effective SCLIC in order to improve the ability of logistics coordination and competition level of the supply chain.

In reality, it is difficult for supply chain enterprises to adopt SCLIC. Firstly, many factors, such as collaborative cost, benefits, risks, would influence the establishment of information collaborative behavior. Secondly, information collaboration is a dynamic process, during which enterprises carry out exploratory collaborative behavior. Finally, it usually takes a long time to get benefits from SCLIC.

Information sharing and collaboration between supply chain individuals are effective strategies for improving performance. Most researchers only emphasize the level, effect, and performance of information sharing and collaboration [7] instead of a collaboration strategy. This paper focuses on the SCLIC strategy based on evolutionary game theory (EGT) to address this gap. The paper's contributions are threefold. First, we provide a conceptual framework illustrating how supply chain enterprises achieve benefit maximization with SCLIC based on EGT in the context of a two-echelon supply chain composed of supplier and manufacturer. Second, we present the evolution of the SCLIC strategy and analyze the evolutionary strategies in different scenarios. Third, we analyze the impacts on the evolution process of SCLIC strategies by using a mathematic method and verify by simulation.

The remainder of this paper is structured as follows. In Section 2, we briefly reviewed the literature on information collaboration, information sharing, and EGT in the supply chain. Section 3 defines the research question, assumptions, and relevant notations, and builds an evolutionary game model of SCLIC, analyzes detailed evolutionary game scenarios and processes, and determined evolutionary stability strategy (ESS) in different scenarios. The impacts on ESS are analyzed by mathematical analysis and simulation in Section 4. Section 5 provides managerial insights. The last section presents the conclusion, limitations, and directions for further research.

## II. LITERATURE REVIEW

### A. SUPPLY CHAIN INFORMATION COLLABORATION OR INFORMATION SHARING

Nowadays, SCM has become one of the focal points in the competition. Information sharing and coordination between supply chain individuals are considered an effective strategy for improving performance [5], [7]. Researchers believe that information sharing has positive effects on operational performance [11] in terms of improving efficiency and limiting unbalanced behaviors in the context of supply chain [12], which mainly depends on retailers' operational factors [13]. With the development of information technology, supply chain members are able to use an all-channel communication network through cloud computing and smart devices to increase the information sharing performance [14]. In addition, reference [15] suggests the relationship between information sharing and organizational performance is mediated by collaboration practice with supply chain partners. Though essential, information sharing alone is insufficient to make significant performance improvements. In the supply chain with multiple suppliers, information sharing might also intensify the competition among them [16].

The positive relationship between information sharing and supply chain performance is also supported by many empirical works [5]. Data from 617 Chinese manufacturing firms are used to investigate the relationships among competitive environments, supply chain information sharing (SCIS), and supply chain performance and the results show that internal information sharing and information sharing with customers are positively related to superior supply chain performance [17]. Reference [18] experimentally shows that the levels of trust and trustworthiness in the supply chain and supplier's capability to determine the optimal production quantity affect the efficacy of forecast sharing and the resulting profits. Reference [19] indicates that supplier innovativeness positively affects information sharing and supply chain agility by using a survey to 272 supply and purchasing executives and managers in the manufacturing industry.

Information sharing is regarded as valuable except when demand follows a random walk and the retailer is slow to react [20]. It is believed that the values gained by upstream and downstream enterprises in the supply chain are different [21] because the value of inventory information sharing in supply chain and supply chain information sharing with the seasonal demand process is analyzed respectively [22]. Generally, the upstream players are more powerful than the downstream players because upstream supply chain player determines the value of information sharing from the parameters of the neighboring downstream players' orders [23].

Whereas the value of downstream sales information to the upstream firm stems from improving upstream order fulfillment forecast accuracy in the two-echelon supply chain [24]. In addition, information sharing becomes more important for upstream firms when demand correlation over a period is high, or when lead times are high, or both [25].

Information sharing is key to supply chain cost reduction [26] by saving buyers' inventory costs [16], [27] and total costs of the suppliers [16], especially in successive periods. To be more specific, reference [20] proves that demand information sharing can significantly reduce bullwhip effect/inventory cost. Moreover, the ratios of order costs and transport costs between suppliers and buyers have a greater impact on the cost savings of buyers, suppliers and the whole system.

The mismatch between supply and demand often exists within the supply chain and among retail stores [14]. For example, poor demand and inventory visibility in the healthcare sector would result in demand and supply mismatch of healthcare products, which may cause disastrous economic and patient care consequences [28]. Information sharing allows a manufacturer's wholesale price to respond properly to the demand signal, which benefits the supply chain if the manufacturer is efficient in cost reduction, or hurts it otherwise [29]. When demand information is shared between two competing supply chains, the shared information might enable the manufacturer's wholesale prices to respond to demand signals, which can benefit the supply chain if the manufacturer is efficient in reducing costs and otherwise inefficient [30]. Information sharing results in better annual profit with a drop-in buyer's price in sustainable supply chains [31]. Public information sharing can benefit all firms in the market as well as consumers [32]. Sharing forecast information helps supply chain parties to better match demand and supply [33]. In order to better forecast the seasonal demand, the supplier would initiate the information sharing process by offering incentives to the retailer which are proportional to the degree of information sharing [34]. Sharing demand forecast voluntarily in a supply chain benefits the manufacturer but hurts the retailer. However, whether supply chains benefit from information sharing depends on competition intensity and forecast error [35].

However, information sharing is not beneficial to all supply chain enterprises. If partial information sharing occurs only between distributors and retailers, rather than between distributors and manufacturers, it does not always benefit manufacturers, and in some cases, information sharing may harm manufacturers [36]. Moreover, the research results of reference [27] show that information sharing will lead to the loss of suppliers. Although information sharing among the supply chain network partners is a key strategy to address the availability of inventory [37], the main beneficiary of the information sharing is usually the warehouse, which receives approximately two-thirds of the benefit. Thus, incentives and revenue sharing contracts should be implemented to motivate and balance the benefits between supply chain partners [38].

In a supply chain composed of one group purchasing organizations and two manufacturers competing in quantity, the manufacturers' horizontal competition and information incompletion are identified as two determinants of supply chain inefficiency under individual purchasing. In this case, both manufacturers have no incentive to share information so that group purchasing damages the supply chain. Under group purchasing, information sharing partially from the lower-precision manufacturer rather than both can benefit the supply chain [39]. In a supply chain where the contract manufacturer is both the upstream partner and downstream competitor of the original equipment manufacturer. When the wholesale price is exogenously given, information sharing is beneficial for the original equipment manufacturer but hurts the contract manufacturer. When the wholesale price is a decision variable, the contract manufacturer benefits from information sharing whereas the original equipment manufacturer does not [40].

Information sharing in the supply chain can also pose risks. The firms, especially those upstream parties in the supply chain, may face a significant risk of over-estimating the value of information sharing if they ignore substitution, demand correlation, and partial information sharing effects [41]. Qualitative research is conducted to investigate how managers perceive risks associated with sharing information with trading partners, and how they attempt to mitigate them [42]. Comparative analysis also shows that the retailer is reluctant to share his private information on the disrupted demand with his partner because of the fear of information leakage [30]. The retailer has an incentive to voluntarily share the information with the make-to-stock manufacturer if the magnitude of demand uncertainty is intermediate [43]. Moreover, the possibility of information sharing in the make-to-stock scenario is higher than that of in the make-to-order scenario [44]. Therefore, members in a supply chain must sign a coordinative contract in order to ensure that they share their information [45].

Though there're lots of successful, mutually beneficial collaborations in supply chains, the failure rate is surprisingly high [4]. In reference [46], the value of limited collaboration or information visibility is identified by investigating the interaction of collaboration and coordination in a four-echelon supply chain under different scenarios of information sharing level. In reference [47], the influencing factors and system model of supply chain information collaboration are identified in the cloud- computing environment. In reference [28], cloud computing is regarded as an enabler of the electronic SCM system by improving information sharing.

In summary, abundant research has been done on information sharing and information collaboration. They have already reached a consensus that both information sharing and information collaboration strategies are good for improving supply chain or business performance. However, information collaboration is different from information sharing. Information collaboration is a typical application of the collaboration theory in information science. It refers to the orderly transmission and sharing of related information by multiple information sources in the specified time and space according to unified rules. Information collaboration emphasizes collaboration, which is the sharing of relevant information in a specific time and space. So, information sharing is the basis of information collaboration. Good information sharing can effectively improve information collaboration. Effective information collaboration strategies can also help promote the level of information collaboration. SCLIC is not only an important part of supply chain information collaboration but also the basis and premise of supply chain logistics collaboration. However, currently relevant research on SCLIC, especially in collaboration strategy, is relatively less, and the core problem of exploring SCLIC in the supply chain has not been addressed. The practical importance of this focuses on helping enterprises improve their chances of success in a new partnership in the supply chain.

### *B. EGT AND SUPPLY CHAIN*

The game theory originally addresses problems confronted by decision-makers with diverging interests (for instance, firms competing for a market) [48]. It is an effective quantitative method exploring strategic behavior between/among two or more players when their interests are in conflict, but actions are interactive [49], [50]. The classic game theory assumes that players would show perfect rational behaviors. In reality, it's impossible because of the lack of acquaintance with others' information [49]. Game theory is widely used in the modeling of social interaction in the supply chain field, providing effective decision-making guidance for players on SCM, distribution channels, pricing and manufacturer-retailer games [49].

EGT is developed from the strong requirements of irrationality, knowledge of the game and information sharing [50]. EGT extends the ideas of the classic game theory by introducing population ecology [48] and is an essential component of a mathematical and computational approach to biology [51]. It assumes both players to be bounded and rational when seeking to achieve game equilibrium based on a trial-and-error method, which is in line with the principles of biological evolution [51].

EGT provides a reasonably efficient tool for understanding adaptation without getting bogged down by complications [48] and has significant potential for modelling substantive economic problems [52]. Nowadays, EGT is used to analyze different social and economic systems in various fields such as economy, sociology, mathematics and anthropology [53].

EGT has three main concepts related to stability: evolutionarily stable strategy (ESS), convergence stability, and neighborhood invader strategy (NIS) [54]. ESS refers to a strategy of the population that cannot be invaded by any alternative strategy which is initially rare. It presents a framework for predicting the results of competing strategies of a population [53]. Thus, the strategies of both players eventually would eventually converge to an ESS [55]. Researchers often use the replicator equation to mathematically describe the idea that individuals with better performance would have more offspring, and thus their frequency in the population would increase [56].

Recently, EGT is widely used in supply chain coordination [57]. Reference [58] proposes a mixed performance measurement system using a combination of EGT and the balanced score card in environmental SCM. The measurement system evaluates business operations using four different perspectives of finance, customer, internal business process, and learning and growth. In reference [59], an EGT model is used to observe the cooperation tendency of multi-stakeholders (suppliers and manufacturers) when establishing long-term green purchasing relationships. Reference [60] uses EGT to explain and predict social and economic sustainability (in tandem) for a public health insurance supply chain. In reference [61], the two populations EGT approach is used to model the performance of supply chain members under different government scenarios. Reference [62] develops an evolutionary game model with a two-echelon closed-loop supply chain to study ESS of manufacturers and retailers and finds out two possible evolutionary results affected by the profits of manufacturers. Reference [63] develops an evolutionary game model to capture emission reduction and low-carbon promotion actions, which are typically conducted by one manufacturer and one retailer in every two-echelon supply chain, respectively. In reference [64], an EGT model is developed between a population of suppliers and a population of manufacturers under a government subsidy mechanism. Then, the strategies of both players eventually for suppliers and manufacturers are discussed. Reference [65] uses an evolutionary game framework to investigate how to optimize the strategy of low carbon investment for suppliers and manufacturers in supply chains, and discusses the impacts on ESS. Using two-population EGT, reference [66] models the performance of supply chain members under the financial risk environment, and uses the proposed model to simulate the case of the global supply chain. Reference [67] probes into the coordination of service quality of the port service supply chain by establishing an evolutionary game model. In reference [68], EGT is used to analyze the relationships of stakeholders such as government, enterprises, and consumers in the green supply chain.

Though EGT is effective in establishing a collaboration strategy of supply chain enterprises, few studies have been done in SCLIC. This paper uses EGT to construct a model of SCLIC and tries to find out the formation process and influences of ESS, which would emphasize the importance of effective strategies for nodal enterprises in SCLIC.

## III. EVOLUTIONARY GAME MODEL OF SCLIC

### *A. PROBLEM DESCRIPTION AND ASSUMPTIONS*

This paper considers a two-echelon supply chain composed of two groups: manufacturer group M and supplier group S. Enterprises in both groups are bounded rational, so they usually choose certain strategies and conduct exploratory behavior according to their own conditions and abilities to predict and analyze. Generally, short term strategies are not optimal, while stable and optimal status needs multiple evolutionary games. We select the factors which affect the value of the benefit function of SCLIC and discuss the enterprises' behavior process of choosing SCLIC strategy based on benefit maximization.

The information on the game group of both parties is asymmetric. Suppliers and manufacturers are randomly matched when cooperative trading behavior occurs. Manufacturer's information on parts inventory, product inventory and sales demand is shared with upstream suppliers. Suppliers can use this information to predict and adjust their production capacity, supply quantity, order quantity and logistics activities, which result in inventory optimization. Upstream suppliers' information of product, raw material, and supply logistics enables downstream manufacturers to adjust production environment and conditions in a timely manner and respond quickly to equipment replacement when product changes occur.

In this paper, the following questions are addressed:

(1) Do the population of suppliers and manufacturers tend to evolve toward SCLIC?

(2) What is the ESS of SCLIC?

(3) How do the relevant factors affect ESS?

(4) How to make supply chain enterprises better coordinate supply chain logistics information?

The proposed evolutionary game model of SCLIC is established upon the following assumptions:

(1) Both manufacturer and supplier groups are bounded rational. They continuously learn from multiple games and seek to achieve the optimal equilibrium with ESS.

(2) In SCLIC, the respective behavior strategy sets of suppliers and manufacturers are only {collaboration, non-collaboration}.

(3) Incentive and punishment mechanisms are introduced to encourage participation in SCLIC. When all nodal enterprises in the supply chain coordinate logistics information and adopt an incentive mechanism, the benefits of nodal enterprises would be improved. On the contrary, when each nodal enterprise takes speculative behavior, it adopts the punishment mechanism.

(4) If both groups choose to carry out SCLIC, they would gain additional benefits. Thus, the benefit of the supply chain would be maximized. However, in the two paired enterprises, if only one party carried out SCLIC while the other didn't, only the non-SCLIC party gains additional benefits, which would be less than those when both parties participate. When neither party carries out SCLIC, nobody would gain additional benefits.

We explicitly set up parameters for a single enterprise in both groups in order to establish respective benefit functions. It would help to extend the knowledge on the evolution process of SCLIC strategy. If a single enterprise's selection changes, the proportion of the individuals choosing a certain strategy in the group would change. Parameters used in this paper are defined in Table 1.

### B. EVOLUTIONARY GAME MODEL

According to the above assumptions and conditions, enterprises participating in the game only have two pure strategies {collaboration, non-collaboration}. Therefore, the manufacturer has two pure strategies,

$M_1$: The strategy in which the manufacturer collaborates logistics information.

$M_2$: The strategy that the manufacturer does not collaborate with logistics information.

Similarly, the supplier also has two pure strategies,

$S_1$: The strategy in which the supplier collaborates logistics information.

$S_2$: The strategy that the supplier does not collaborate with logistics information.

The benefits pertaining to the combinations of pure strategies of the manufacturers and suppliers are presented in Table 2.

### C. REPLICATOR DYNAMIC EQUATION

According to the replicator dynamic equation, the expected benefits of the logistics information collaboration or not in the two groups are obtained. When manufacturer group M is in a state of selecting a certain proportion of information collaboration members, the expected benefits obtained by individuals adopting logistics information collaboration strategy are as follows.

$$\begin{aligned} E_{m1} &= x\left[A_2 + (1-b)B - \beta f_2 - (1-a)C\right] \\ &\quad + (1-x)\left[A^2 - \beta f^2 - (1-a)C\right] \end{aligned} \tag{1}$$

The expected benefits obtained by the individuals who do not adopt the SCLIC strategy are as follows.

$$E_{m2} = x\left(A_2 + B_2 - Pf_1\right) + (1-x)A_2 \tag{2}$$

The proportion of collaborative logistics information in group enterprises is combined with their respective expected benefits. Then, the average expected benefits of manufacturer group M are as follows.

$$\bar{E}_m = yE_{m1} + (1-y)E_{m2} \tag{3}$$

The replicator dynamic differential equation of the proportion of the manufacturer choosing to adopt SCLIC strategy changing with time are as follows.

$$\begin{aligned} F(y) &= \frac{dy}{dt} \\ &= y\left(E_{m1} - \bar{E}_m\right) \\ &= y(1-y)\left[x\left(B - bB - B_2 + Pf_1\right)\right. \\ &\quad \left. -\ \left(\beta f_2 + C - aC\right)\right] \end{aligned} \tag{4}$$

Equation (4) indicates that when the proportion of suppliers choosing SCLIC strategy is $x$, manufacturer group M will change $y$. The manufacturer group eventually achieves

**TABLE 1.** Parameters and their meanings.

| Parameters | Meaning |
|---|---|
| $A_i$ | The basic benefits, namely, the benefits obtained by supply chain enterprises when they do not coordinate logistics information. $i = 1,2$, $A_1$ and $A_2$, are the benefits obtained by supplier and manufacturer respectively. |
| $C$ | The total cost of SCLIC, $C > 0$. The funds occupied by the equipment and human resources invested in information collaboration. Normally, the total cost of SCLIC shall be shared by all supply chain enterprises. |
| $f$ | The coefficient of information collaboration degree, $f \geq 0$, represents the information amount of collaboration. Similar to the degree of information sharing[69], the coefficient of information collaboration degree indicates the accuracy of the collaboration information which the supply chain enterprise is willing to provide, and $f$ will depend on the size of the collected sample. When one party in the game collaborates more information, the other party gains more additional benefits. |
| $a$ | Cost allocation coefficient, $a \in (0,1)$. In the two paired enterprises, if the cost of supplier is $aC$, the cost of the manufacturer is $(1-a)C$. |
| $B$ | The additional benefit from SCLIC, $B > 0$. When both groups adopt SCLIC, the supply chain as a whole will gain extra benefits, which makes coordinated benefits exceeds the uncoordinated benefits of logistics information. |
| $b$ | Additional benefit allocation coefficient, $b \in (0,1)$. If the additional benefit of the supplier group S is $bB$, then the additional benefit of the manufacturer group M is $(1-b)B$. When only individuals in the supplier group participate in the matching of collaborative logistics information, then the additional benefit of individual manufacturers who do not collaborate logistics information is $B_2 > 0$. Similarly, when only individuals in the manufacturer group participate in the matching of collaborative logistics information, then the additional benefit of individual suppliers who do not collaborate logistics information is $B_2 > 0$. Set $B_2 < bB$ and $B_2 < (1-b)B$. |
| $\beta$ | Risk coefficient, $\beta > 0$. Risk means that the enterprise is facing the harm of benefit reduction. Therefore, it is set that $\beta$ is positively correlated with $f$. $\beta f_1$ is risk benefit damage quantity when individuals in supplier group S choose information collaboration. And $\beta f_2$ is risk benefit damage quantity when individuals in manufacturer group M choose information collaboration. |
| $P$ | Penalty coefficient, $P > 0$. If the value of penalty benefit received by the party who doesn't take part in logistics information collaboration is positively correlated with the logistics information collaboration degree of the party who takes part in logistics information collaboration. Then the penalty benefit received by the party who doesn't take part in logistics information collaboration is $-Pf$. |
| $x$ | The proportion of suppliers that choose SCLIC in the initial state of the supplier group, $x \in [0,1]$, then the proportion of suppliers who do not choose SCLIC is $1-x$. |
| $y$ | The proportion of manufacturers that choose SCLIC in the initial state of the manufacturer group, $y \in [0,1]$, then the proportion of manufacturers who do not choose SCLIC is $1-y$. |

**TABLE 2.** Game model encompassing the strategies of manufacturers and suppliers.

| | | Manufacturers | |
|---|---|---|---|
| | | $M_1(y)$ | $M_2(1-y)$ |
| Suppliers | $S_1(x)$ | $\{A_1 + bB - \beta f_1 - aC,$<br>$A_2 + (1-b)B - \beta f_2 - (1-a)C\}$ | $\{A_1 - \beta f_1 - aC,$<br>$A_2 + B_2 - Pf_2\}$ |
| | $S_2(1-x)$ | $\{A_1 + B_2 - Pf_2,\ A_2 - \beta f_2 - (1-a)C\}$ | $\{A_1,\ A_2\}$ |

stability by learning to change the strategies of individuals of the group. In this process, both the proportion of the supplier group choosing SCLIC strategy (corresponding to different $x$ and $y$, $F(y) = 0$) and the benefit of individuals within the manufacturer group M under different strategies (corresponding to different $x$ and $y$, $F'(y) < 0$) should be considered.

Similarly, when supplier group S is in the state of reaching a certain proportion of individuals selecting SCLIC, the expected benefits obtained by individuals using SCLIC strategy are as follows.

$$E_{s1} = y(A_1 + bB - \beta f_1 - aC) + (1-y)(A_1 - \beta f_1 - aC) \quad (5)$$

When supplier group S is in the state of reaching a certain proportion of individuals selecting SCLIC, the expected benefits obtained by the individuals who do not adopt the SCLIC strategy are as follows.

$$E_{s2} = y(A_1 + B_2 - Pf_2) + (1-y)A_1 \tag{6}$$

According to the proportion of suppliers selecting SCLIC and their respective expected benefits, the average expected benefits of supplier group S can be obtained with follows.

$$\bar{E}_s = xE_{s1} + (1-x)E_{s2} \tag{7}$$

The replicator dynamic equation of the proportion of suppliers choosing SCLIC strategy changing with time is as follows.

$$\begin{aligned} F(x) &= \frac{dx}{dt} \\ &= x\left(E_{s1} - \bar{E}_s\right) \\ &= x(1-x)\,[y(bB - B_2 + Pf_2) \\ &\quad - (\beta f_1 + aC)] \end{aligned} \tag{8}$$

Equation (8) indicates that when an individual manufacturer chooses SCLIC ratio as $y$, the proportion of supplier group S individuals choosing SCLIC strategy would change to $x$.

### D. EVOLUTIONARY GAME MODEL ANALYSIS

When $F(y)$ is analyzed, it needs to meet $F(y^*) = 0$, then all $y^*$ values can be solved when the replicator dynamic equation is stable, that is, the trend direction of population strategy change adjustment.

This stable result has such a property in the group: when small variation occurs, breaking the stable equilibrium state, the evolution of the population would continue to eliminate this variation, and finally reach a stable state. So, when the variation occurs, the replicator dynamics will weaken it and the variation will cause the dynamic change to converge to the steady state $y$. Therefore, for group enterprises to make all adjusted strategies stable, they need to meet $F(y^*) = 0$, and at $y^*$, $F'(y^*) < 0$, $y^*$ is the stable result of group tendency. $F(x)$ and $F(y)$ form a dynamic evolution system of game adjustment for supplier group S and manufacturer group M.

When the proportion $x$ of individual suppliers choosing SCLIC strategy changes, the proportion $y$ of individual manufacturers choosing SCLIC strategy would change accordingly. Both sides influence each other until both groups stop changing. Then, the game reaches a stable equilibrium state. At this time, $F(x) = 0$ and $F(y) = 0$, and the most important condition is to meet $F'(x) < 0$, $F'(y) < 0$.

#### 1) EVOLUTIONARY GAME ANALYSIS OF SUPPLIER

The process of strategy evolution adjustment analysis is based on the comparison between the value of the game benefit function of SCLIC and non-SCLIC under stable evolution state. According to (8), $F'(x)$ is shown in the following.

$$F'(x) = (1-2x)\,[y(bB - B_2 + Pf_2) - (\beta f_1 + aC)] \tag{9}$$

Then $F(x) = 0$, the solution of (8) is as follows: $x_1^* = 0, x_2^* = 1, y^* = (\beta f_1 + aC)/(bB - B_2 + Pf_2)$.

(1) When $y^* \in (0, 1)$, that is, $(bB - B_2 + Pf_2) > (\beta f_1 + aC) > 0$, the evolutionary stability results of supplier group S can be analyzed as follows.

① When $y = y^* = (\beta f_1 + aC)/(bB - B_2 + Pf_2)$, $F(x) = 0$. It means that the proportion of individuals in the manufacturer group M choosing collaborative logistics information is $y^*$, and all $x$ values reach a stable state for the supplier group S. That is, $x \in [0, 1]$. At this point, $\forall x, \exists F'(x) = 0$, however, it is not in conformity with $F'(x) < 0$, so at this time, it is not a stable strategy.

When $y \neq y^*$, let $F(x) = 0$, then, $x_1 = 0$ or $x_2 = 1$. Now, we need to make $F'(x) < 0$, therefore, $F'(x)$ should be analyzed as $y$ changes.

② When $y > y^*$, then $F'(x_1 = 0) > 0$ and $F'(x_2 = 1) < 0$. Therefore, $x_2 = 1$ is the individual proportion when supplier group S evolves into a logistics information collaboration strategy. In this case, it is necessary to ensure that the proportion of manufacturer group individuals choosing SCLIC is greater than $y^*$, and the final evolutionary result of supplier group S is that all enterprises tend to choose SCLIC. According to the formula of $y^*$, if the cost of SCLIC borne by supplier group S is smaller, the potential risks it faces are smaller, the additional benefits it gains are larger, the external penalties are larger, and the additional benefits without collaborative logistics information are smaller, $y^*$ can become smaller. The evolution result of supplier group S is that the higher the proportion of collaborative logistics information.

③ When $y < y^*$, then $F'(x_1 = 0) < 0$ and $F'(x_2 = 1) > 0$. Therefore, $x_1 = 0$ is the individual proportion when the supplier group S evolves to obtain the logistics information coordination strategy. In this case, the proportion of manufacturer group individuals choosing SCLIC strategy is smaller than $y^*$, and the evolution result of the supplier group is that enterprises tend to non-SCLIC. From the formula of $y^*$, when $y^*$ gets bigger, the cost borne by the supplier group and the potential risks would increase, while the additional benefits of SCLIC and the punishment would decrease, the additional benefits of non-SCLIC would grow bigger, and the evolution of the supplier group would result in a higher proportion of non-SCLIC.

(2) Let's think about $y^* \notin (0, 1)$. When $y^* = 0$, that is, $\beta f_1 + aC = 0$.

① When $(bB - B_2 + Pf_2) > 0$, for $y \in (0, 1]$, $F'(x_1 = 0) > 0$, $F'(x_2 = 1) < 0$. Therefore, the evolution stable result of supplier group S is all logistics information synergy. At this point, for manufacturer group M, the proportion of logistics information coordination strategy in the group is (0,1], which makes supplier group S reach the stable strategy of coordination logistics information.

If $y = 0$, the proportion of the collaborative logistics information strategy of the evolution of manufacturer group M is 0. If $x \in [0, 1]$, then $F'(x) = 0$ has been established.

② When $(bB - B_2 + Pf_2) < 0$, for $y \in (0, 1]$, $F'(x_1 = 0) < 0$, $F'(x_2 = 1) > 0$. Therefore, $x_1 = 0$ is the proportion of individuals when supplier group S evolves into logistics information collaborative strategy, and the evolution results show that supplier group S all tends to be a non-collaborative logistics information strategy. At this point, for manufacturer group M, the proportion of logistics information coordination strategy in the group is (0,1], which makes supplier group S reach the stable strategy of non-coordination logistics information.

If $y = 0$, the proportion of the collaborative logistics information strategy of the evolution of manufacturer group M is 0. Meet $x \in [0, 1]$, $F'(x) = 0$, so at this time no stable results.

③ When $(bB - B_2 + Pf_2) = 0$, for $x, y \in [0, 1]$, $F'(x) = 0$ is always valid. This case does not meet the conditions for the evolution into a stable case, and in fact $(\beta f_1 + aC) > 0$, this case does not exist.

(3) When $y^* = 1$, namely $(bB - B_2 + Pf_2) = (\beta f_1 + aC)$. For $y \in [0, 1]$ and $y < y^*$, $F'(x_1 = 0) < 0$, $F'(x_2 = 1) > 0$ are always true. Therefore, $x_1 = 0$ is the individual proportion when supplier group S evolves into logistics information collaborative strategy, and the evolution results show that supplier group S all tends to be a non-collaborative logistics information strategy. For manufacturer group M, the proportion of logistics information coordination strategy in the group is $y \in [0, 1)$. It is guaranteed here that $(\beta f_1 + aC) > 0$ and $(bB - B_2 + Pf_2) > 0$.

If $y = y^* = 1$, the proportion of collaborative logistics information strategy of the evolution of manufacturer group M is all, and for $x \in [0, 1]$, $F'(x) = 0$ is always true. So, there's no stable result.

(4) When $y^* < 0$, that is, $(\beta f_1 + aC) > 0$ and $(bB - B_2 + Pf_2) < 0$. For $y \in [0, 1]$, $y > y^*$ is true, then, $F'(x_1 = 0) < 0$ and $F'(x_2 = 1) > 0$. Therefore, $x_1 = 0$ is the individual proportion when supplier group S evolves into logistics information collaborative strategy, and the evolution results show that supplier group S all tends to be a non-collaborative logistics information strategy. The collaborative logistics information strategy proportion of manufacturer group M is $y \in [0, 1]$. However, the environment of this paper is on $(bB - B_2 + Pf_2) > 0$, which will not be considered later.

Or $(\beta f_1 + aC) < 0$, $(bB - B_2 + Pf_2) > 0$, such that $y^* < 0$. But $(\beta f_1 + aC) \geq 0$. So, it doesn't really exist.

(5) When $y^* > 1$, that is $(\beta f_1 + aC) > (bB - B_2 + Pf_2) > 0$, at this time, $y < y^*$. For $y \in [0, 1]$, $F'(x_1 = 0) < 0$, $F'(x_2 = 1) > 0$. Therefore, $x_1 = 0$ is the individual proportion when supplier group S evolves into logistics information collaborative strategy, and the evolution results show that supplier group S all tends to be a non-collaborative logistics information strategy. The collaborative logistics information strategy proportion of manufacturer group M is $y \in [0, 1]$.

The above analysis can be shown in Table 3. Based on the above analysis, on the basis of $y^* \in [0, 1]$, it's only when the proportion of manufacturer group individuals choosing SCLIC strategy is greater than $y^*$ that the stable evolution result of the supplier group is SCLIC. And the smaller $y^*$ is (up to 0), the proportion of supplier group individuals choosing SCLIC strategy would be more significant. This means that when the proportion of manufacturer group members choosing SCLIC is larger than a certain $y^*$, supplier group individuals tend to choose SCLIC.

**TABLE 3. Evolutionary stability result of supplier group S.**

| $y^*$ | $y$ | $F'(0)$ | $F'(1)$ | Stability point |
|---|---|---|---|---|
| $0 \le y^* \le 1$ | $y = y^*$ | $= 0$ | $= 0$ | − |
| | $y^* < y \le 1$ | $> 0$ | $< 0$ | $x = 1$ |
| | $0 \le y < y^*$ | $< 0$ | $> 0$ | $x = 0$ |
| $y^* < 0$ | $0 \le y \le 1$ | $< 0$ | $> 0$ | $x = 0$ |
| $y^* > 1$ | $0 \le y \le 1$ | $< 0$ | $> 0$ | $x = 0$ |

### 2) EVOLUTIONARY GAME ANALYSIS OF MANUFACTURER

According to (4), the first partial derivative of $F(y)$ with respect to $y$ is obtained as follows:

$$F'(y) = (1 - 2y)\left[x\left(B - bB - B_2 + PBf_1\right) - \left(\beta f_2 + C - aC\right)\right] \quad (10)$$

When $F(y) = 0$, the solution of (4) is as follows: $y_1^* = 0$, $y_2^* = 1$, $x^* = (\beta f2 + C - aC)/(B - bB - B2 + Pf1)$.

(1) When $x^* \in [0, 1]$, that is, $(B - bB - B2 + Pf1) \geq (\beta f2 + C - aC) \geq 0$

① When $x = x^* = (\beta f2 + C - aC)/(B - bB - B2 + Pf1)$, $F(y) = 0$. At this time, the proportion of choosing collaborative logistics information strategy in supplier group S is $x^*$, and all $y$ values reach a stable state for manufacturer group M, that is, $y \in [0, 1]$. But this is not in conformity with $F'(y) = 0$.

② When $x > x^*$, $F'(y_1 = 0) > 0$, $F'(y_2 = 1) < 0$. Therefore, $y_2 = 1$ is the stable results of the manufacturer group M. In this case, when the proportion of collaborative logistics information selected by supplier group S is greater than $x^*$, the final evolution result of manufacturer group M is collaborative logistics information. According to the formula of $x^*$, the smaller $x^*$ is, the more significant is the proportion of manufacturers choosing SCLIC.

③ When $x < x^*$, $F'(y_1 = 0) < 0$, $F'(y_2 = 1) > 0$. Therefore, $y_1 = 0$ is the stable results of the manufacturer group M. In this case, when the proportion of supplier group individuals choosing SCLIC is less than $x^*$, the evolution result of the manufacturer group would be no SCLIC. If $x^*$ becomes larger until 1, the proportion of manufacturer group evolving into completely non-SCLIC would be more significant.

(2) When $x^* < 0$, at this time, $x \in [0, 1]$, $x > x^*$

① When $(B - bB - B2 + Pf1) > 0$ and $(\beta f2 + C - aC) < 0$, $F'(y_1 = 0) > 0$, $F'(y_2 = 1) < 0$. The final evolution result of the manufacturer group M is all cooperative logistics information. At this time, the proportion of supplier group S choosing logistics information cooperation strategy is $x \in [0, 1]$, namely, there is no stable evolution result.

**TABLE 4.** **Evolution stable result of the manufacturer group M.**

| $x^*$ | $x$ | $F'(0)$ | $F'(1)$ | Stable point |
|---|---|---|---|---|
| $0 \le x^* \le 1$ | $x = x^*$ | $= 0$ | $= 0$ | – |
| | $x^* < x \le 1$ | $> 0$ | $< 0$ | $x = 1$ |
| | $0 \le x < x^*$ | $< 0$ | $> 0$ | $x = 0$ |
| $x^* < 0$ | $0 \le x \le 1$ | $< 0$ | $> 0$ | $x = 0$ |
| $x^* > 1$ | $0 \le x \le 1$ | $< 0$ | $> 0$ | $x = 0$ |

② When $(B - bB - B2 + Pf1) < 0$ and $(\beta f2 + C - aC) > 0$, $F'(y_1 = 0) < 0, F'(y_2 = 1) > 0$. The evolution result of manufacturer group M is that there is no cooperative logistics information. At this time, the proportion of supplier group S choosing logistics information cooperation strategy is $x \in [0, 1]$, namely, there is no stable evolution result. On the actual situation $(B - bB - B2 + Pf1) > 0, (\beta f2 + C - aC) > 0$. So, there's no way that $x^*$ is less than 0.

(3) When $x^* > 1$, that is, $(\beta f2 + C - aC) > (B - bB - B2 + Pf1) > 0$. For $x \in [0, 1]$, $F'(y_1 = 0) < 0, F'(y_2 = 1) > 0$. Therefore, $y_1 = 0$ is the individual proportion when manufacturer group M evolves into logistics information collaborative strategy, and the evolution results show that manufacturer group M tends to be a non-collaborative logistics information strategy. The strategy proportion of supplier group S evolving into collaborative logistics information is $x \in [0, 1]$.

The above analysis can be shown in Table 4. On the basis of the condition of $x^* \in [0, 1]$, it's only when the proportion of suppliers choosing SCLIC strategy is greater than $x^*$ that the stable evolution result of the manufacturer group is SCLIC. Thus, when the proportion of suppliers choosing SCLIC is larger than a certain value of $x^*$, manufacturers tend to choose SCLIC strategy.

### 3) EVOLUTIONARY GAME ANALYSIS OF SUPPLIER AND MANUFACTURER

In the last two sections, ESS of manufacturer group M and supplier group S are discussed respectively. The combination of $x^*$ and $y^*$ with different values will have different evolutionary results. The equilibrium solution is obtained by the replicator dynamics equations of both groups, and the stable solution of the model can be known by using the equilibrium solution and the Jacobian matrix of the model system.

### 4) EVOLUTIONARY GAME ANALYSIS OF SUPPLIER AND MANUFACTURER

In the last two sections, ESS of manufacturer group M and supplier group S are discussed respectively. The combination of $x^*$ and $y^*$ with different values will have different evolutionary results. The equilibrium solution is obtained by the replicator dynamics equations of both groups, and the stable solution of the model can be known by using the equilibrium solution and the Jacobian matrix of the model system.

Let $M = bB - B_2 + Pf_2, N = \beta f_1 + aC, O = B - bB - B2 + Pf1, S = \beta f2 + C - aC$. The Jacobian matrix of the above model is as (11). The determinant and trace of (11) are calculated as (12) and (13), respectively.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)(yM-N) & x(1-x)M \\ y(1-y)O & (1-2y)(xO-S) \end{bmatrix} \tag{11}$$

$$Det(J) = (1-2x)(yM-N)(1-2y)(xO-S) - y(1-y)Ox(1-x)M \tag{12}$$

$$Tr(J) = (1-2x)(yM-N) + (1-2y)(xO-S) \tag{13}$$

According to (4) and (8), the equilibrium solution of equation group which is constituted by $F(x)$ and $F(y)$ is $(0, 0), (1, 0), (0, 1)$ and $(1, 1)$. When $0 < x^* < 1$ and $0 < y^* < 1$, $(x^*, y^*)(x^* = S/O, y^* = N/M)$ is also an equilibrium solution. The special cases include: When $S = O$, namely, $x^* = 1$, the equilibrium solution is $(1, \sim)y \in (0, 1)$. Or when $M = N$, namely, $y^* = 1$, the equilibrium solution is $(\sim, 1)x \in (0, 1)$. Substitute these equilibrium solutions into (12) and (13). When $Det(J) > 0$ and $Tr(J) < 0$, the equilibrium solution is a stable solution, which is also a stable evolution result. The results are shown in Table 5.

In different conditions of $x^*$ and $y^*$, the process of convergence and change of strategy of both groups to reach stability is shown in Fig. 1, and the evolutionary equilibrium stability of the solution is analyzed as follows.

Scenario 1 (Fig. 1a): When $0 < x^* < 1$ and $y^* > 1$, namely, $(B - bB - B2 + Pf1) > (\beta f2 + C - aC) > 0(O > S > 0)$ and $(\beta f_1 + aC) > (bB - B_2 + Pf_2) > 0(N > M > 0)$. The stability of the equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6. At this time, the stable solution of the game system of both groups is $(0, 0)$. So, both groups tend to choose non-SCLIC. The initial game is an equilibrium state at unstable points or saddle points and will converge to the stable solution $(0, 0)$ when is disturbed.

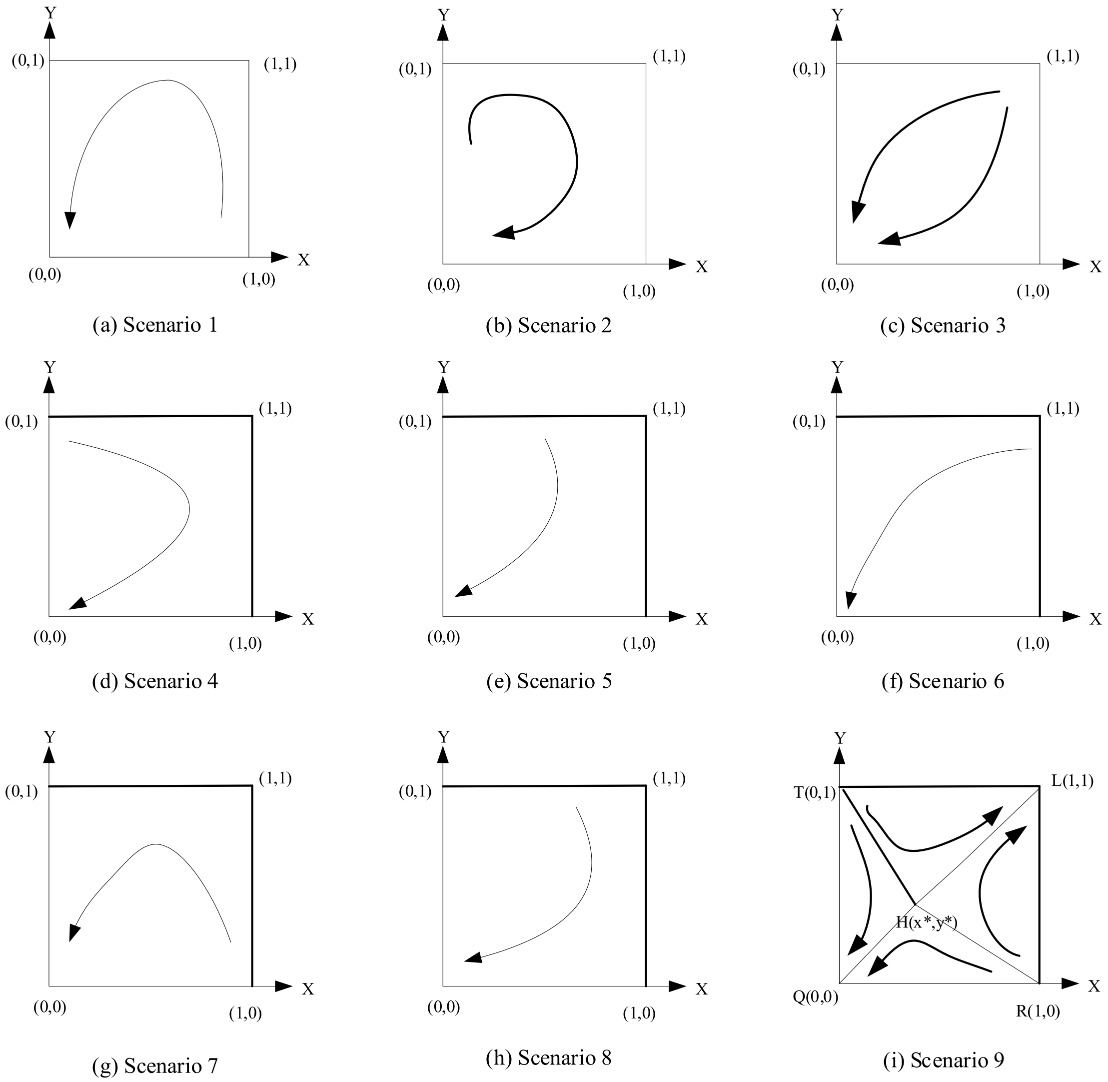
Scenario 2 (Fig. 1b): When $x^* > 1$ and $0 < y^* < 1$, namely, $0 < (B - bB - B2 + Pf1) < (\beta f2 + C - aC)(0 < O < S)$ and $0 < (\beta f_1 + aC) < (bB - B_2 + Pf_2)(0 < N < M)$. The stability of the equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6. So, Scenario 2 is the same as Scenario 1, namely, the stable solution is $(0, 0)$.

Scenario 3 (Fig. 1c): When $x^* > 1$ and $y^* > 1$, namely, $0 < (B - bB - B2 + Pf1) < (\beta f2 + C - aC)(0 < O < S)$, $(\beta f_1 + aC) > (bB - B_2 + Pf_2) > 0(N > M > 0)$. The stability of the equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6.

Scenario 4 (Fig. 1d): When $x^* = 1$ and $0 < y^* < 1$, namely, $O = S$ and $0 < N < M$, the stability of equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6. The stable solution is still $(0, 0)$. When $x = 1$, the equilibrium solution $(1, \sim)$ is a saddle point or unstable solution. In this case, the two-party group strategy may converge to $(1, \sim)$ under special initial conditions. It means that all individuals in

**TABLE 5.** Determinant and trace of each equilibrium solution.

| Equilibrium solution | $Det(J)$ | $Tr(J)$ |
|---|---|---|
| (0,0) | $NS$ | $-N-S$ |
| (0,1) | $S(M-N)$ | $M-N+S$ |
| (1,0) | $N(O-S)$ | $N+O-S$ |
| (1,1) | $(N-M)(S-O)$ | $(N-M)+(S-O)$ |
| $(1,\sim)$ | $(2y-1)(yM-N)(O-S)$ | $N-yM+(1-2y)(O-S)$ |
| $(\sim,1)$ | $(2x-1)(M-N)(xO-S)$ | $S-Ox+(1-2x)(M-N)$ |
| $(x^*,y^*)$ | $N(N/M-1)S(1-S/O)$ | 0 |



(a) Scenario 1
(b) Scenario 2
(c) Scenario 3
(d) Scenario 4
(e) Scenario 5
(f) Scenario 6
(g) Scenario 7
(h) Scenario 8
(i) Scenario 9

**FIGURE 1.** Evolutionary stable phase diagram.

the supplier group would choose SCLIC, and the proportion of manufacturers choosing SCLIC is from 0 to 1 in the group.

Scenario 5 (Fig. 1e): When $x^* = 1$ and $y^* = 1$, namely, $O = S$ and $N = M$, the stability of the equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6, where $(\sim, 1)x \in (0, 1)$ and $(1, \sim)y \in (0, 1)$. In this case, the stable solution is still (0, 0). In a special initial state, the direction of the game may be $(1, \sim)$, $(\sim, 1)$.

Scenario 6 (Fig. 1f): When $x^* = 1$ and $y^* > 1$, namely, $O = S$ and $N > M > 0$, the stability of equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6, where

**TABLE 6.** Equilibrium solution judgement.

| Equilibrium solution | $Det(J)$ | $Tr(J)$ | Judgement result | Equilibrium solution | $Det(J)$ | $Tr(J)$ | Judgement result |
|---|---|---|---|---|---|---|---|
| Scenario 1 | | | | | | | |
| (0,0) | + | − | Stable point | (1,0) | + | + | Unstable point |
| (0,1) | − | Uncertain | Saddle point | (1,1) | − | Uncertain | Saddle point |
| Scenario 2 | | | | | | | |
| (0,0) | + | − | Stable point | (1,0) | − | Uncertain | Saddle point |
| (0,1) | + | + | Unstable point | (1,1) | − | Uncertain | Saddle point |
| Scenario 3 | | | | | | | |
| (0,0) | + | − | Stable point | (1,0) | − | Uncertain | Saddle point |
| (0,1) | − | Uncertain | Saddle point | (1,1) | + | + | Unstable point |
| Scenario 4 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | 0 | − | Saddle point |
| (0,1) | + | + | Unstable point | $(1,\sim)$ | 0 | Uncertain | Saddle point or Unstable point |
| (1,0) | 0 | + | Unstable point | | | | |
| Scenario 5 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | 0 | 0 | Saddle point |
| (0,1) | 0 | + | Unstable point | $(1,\sim)$ | 0 | + | Unstable point |
| (1,0) | 0 | + | Unstable point | $(\sim,1)$ | 0 | + | Unstable point |
| Scenario 6 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | 0 | + | Unstable point |
| (0,1) | − | Uncertain | Saddle point | $(1,\sim)$ | 0 | + | Unstable point |
| (1,0) | 0 | + | Unstable point | | | | |
| Scenario 7 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | 0 | − | Saddle point |
| (0,1) | 0 | + | Unstable point | $(\sim,1)$ | 0 | Uncertain | Saddle point or Unstable point |
| (1,0) | + | + | Unstable point | | | | |
| Scenario 8 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | 0 | + | Unstable point |
| (0,1) | 0 | + | Unstable point | $(\sim,1)$ | 0 | + | Unstable point |
| (1,0) | − | Uncertain | Saddle point | | | | |
| Scenario 9 | | | | | | | |
| (0,0) | + | − | Stable point | (1,1) | + | − | Stable point |
| (0,1) | + | + | Unstable point | $(x^*,y^*)$ | − | 0 | Saddle point |
| (1,0) | + | + | Unstable point | | | | |

$(1,\sim)y \in (0,1)$. This case is similar to Scenario 4, with a special initial state, which converges at $x = 1$, unstable.

Scenario 7 (Fig. 1g): When $y^* = 1$ and $0 < x^* < 1$, namely, $N = M$ and $O > S > 0$, the stability of equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6, where $(\sim,1)x \in (0,1)$. This scenario is similar to Scenario 4, with a special initial state, which converges at $x = 1$, unstable. When the initial game is in a special state, the two groups converge at $(\sim,1)$, unstable.

Scenario 8 (Fig. 1h): When $y^* = 1$ and $x^* > 1$, namely, $N = M$ and $0 < O < S$, the stability of equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6, where $(\sim,1)x \in (0,1)$. This scenario is similar to Scenario 7, with a special initial state, which converges at $y = 1$, unstable. In other cases, it will still converge to the stable solution (0, 0) where both groups do not choose SCLIC.

Scenario 9 (Fig. 1i): When $0 < x^* < 1$ and $0 < y^* < 1$, namely, $(B - bB - B2 + Pf1) > (\beta f2 + C - aC) > 0(O > S > 0)$ and $0 < (\beta f_1 + aC) < (bB - B_2 + Pf_2)(0 < N < M)$. The stability of the equilibrium solution of $F(x)$ and $F(y)$ are shown in Table 6, where $x^* = S/O$ and $y^* = N/M$. The stable solution is (0, 0) or (1, 1). Suppose $Q(0,0)$, $T(0,1)$, $R(1,0)$, $L(1,1)$, $H(x^*,y^*)$. The initial state of the game is at the upper right of the broken line $THR$, so the proportion of SCLIC selected by both sides tends to (1, 1) in the process of constant change. When the initial state of the game is at the

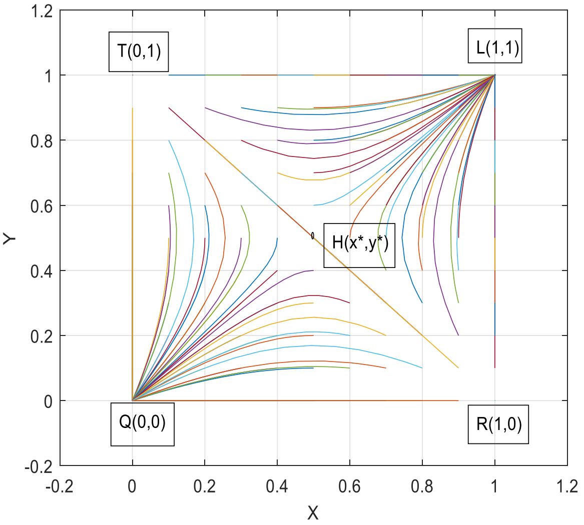


**FIGURE 2.** **Evolutionary simulation results of scenario 9.**

lower left of the broken line THR, the proportion of SCLIC selected by the two group members tends to be (0, 0) in the process of constant change. The evolution simulation result of Scenario 9 is shown in Fig. 2 using MATLAB R2017a. In Fig. 2, let $x^* = 0.5$ and $y^* = 0.5$. The simulation result tends to (0, 0) or (1, 1).

By analyzing the equilibrium solution and describing the strategy convergence phase diagram, we can obtain two influencing conditions that enable both groups to coordinate logistics information (namely (1, 1)). One is the proportion of individuals in the initial selection of cooperative logistics information strategy by the two groups in the game, which is random and uncertain. Secondly, the location of the saddle point $(x^*, y^*)$ impacts the initial point of the game in the quadrilateral *THRL*, and further impacts the probability of collaborative logistics information of both groups. When $x^* \in (0, 1)$ and $y^* \in (0, 1)$, the saddle point $H(x^*, y^*)$ appears in the evolutionary phase diagram. Obviously, when $x^*$ and $y^*$ have different values, the position of the saddle point will change.

In this case, there is a certain probability that the proportion of individuals choosing SCLIC in both groups tend to be (1, 1). At the beginning of the game, the proportion of each group of individuals choosing SCLIC is an uncertain random value. If $S_{THRL}$ increases, the probability that the game situation belongs to this quadrilateral range at the beginning will increase, and two groups will reach a stable state finally. Thus, the probability of individuals choosing SCLIC in the two groups will be (1, 1). At this time, $S_{THRL}$ is closely related to the position of the saddle point $H(x^*, y^*)$.

In the following section, we will analyze the different results owing to the parameter changes in detail.

## IV. EVOLUTIONARY EQUILIBRIUM STABILITY ANALYSIS

### *A. MATHEMATIC ANALYSIS*

From the above analysis and Fig. 2, it can be seen that in the initial game, the proportion of individuals choosing SCLIC in the group is uncertain and unstable random, which is represented as a random point in the phase diagram. When the requirement of Scenario 9 is met, there is a certain probability that all individuals in both groups tend to choose SCLIC. Moreover, the larger $S_{THRL}$ is, the greater the probability that the game evolution of individuals in both groups eventually tends to choose SCLIC. $S_{THRL}$ is closely related to the location of saddle point $H(x^*, y^*)$. Next, we use the partial derivative of the area function with respect to each parameter to discuss the impact of each parameter on the area of the region, and find the countermeasures to increase $S_{THRL}$. The formula for calculating $S_{THRL}$ and the partial derivatives of the area function with respect to the relevant parameters are as follows.

$$\begin{aligned} S_{THRL} &= S_{THL} + S_{RHL} = \frac{(1-y^*)}{2} + \frac{(1-x^*)}{2} \\ &= \frac{(2-x^*-y^*)}{2} = 1 - \frac{(x^*+y^*)}{2} \\ &= 1 - \frac{\frac{\beta f_2+C-aC}{B-bB-B_2+Pf_1} + \frac{\beta f_1+aC}{bB-B_2+Pf_2}}{2} \end{aligned} \tag{14}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial b} &= \frac{1}{2}\left\{\frac{B(aC+\beta f_2)}{(bB-B_2+Pf_1)^2} - \frac{B[(1-a)C+\beta f_1]}{[(1-b)B-B_2+Pf_2]^2}\right\} \end{aligned} \tag{15}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial b^2} &= -\left\{\frac{(bB-B_2+Pf_1)(aC+\beta f_2)B^2}{(bB-B_2+Pf_1)^4}\right. \\ &\quad \left. + \frac{[(1-b)B-B_2+Pf_2][(1-a)C+\beta f_1]B^2}{[(1-b)B-B_2+Pf_2]^4}\right\} \end{aligned} \tag{16}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial B} &= \frac{1}{2}\left\{\frac{(1-b)[\beta f_2+C-aC]}{[B-bB-B_2+Pf_1]^2} + \frac{b(\beta f_1+aC)}{(bB-B_2+Pf_2)^2}\right\} \end{aligned} \tag{17}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial a} &= \frac{1}{2}\left[\frac{C}{B-bB-B_2+Pf_1} - \frac{C}{bB-B_2+Pf_2}\right] \end{aligned} \tag{18}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial f_1} &= \frac{1}{2}\left[\frac{P(\beta f_2+C-aC)}{(B-bB-B_2+Pf_1)^2} - \frac{\beta}{bB-B_2+Pf_2}\right] \end{aligned} \tag{19}$$

$$\begin{aligned} \frac{\partial S_{THRL}}{\partial f_1^2} &= -\frac{P^2(\beta f_2+C-aC)}{(B-bB-B_2+Pf_1)^3} \end{aligned} \tag{20}$$

$$\frac{\partial S_{THRL}}{\partial f_2} = \frac{1}{2}\left[\frac{P(\beta f_1 + aC)}{(bB - B_2 + Pf_2)^2} - \frac{\beta}{B - bB - B_2 + Pf_1}\right] \quad (21)$$

$$\frac{\partial S_{THRL}}{\partial f_2^2} = -\frac{P^2(\beta f_1 + aC)}{(bB - B_2 + Pf_2)^3} \quad (22)$$

According to (14), $S_{THRL}$ is closely related to $b$, $B$, $\beta$, $f$, $a$, $C$, $B_2$, and $P$.

### 1) THE IMPACT OF *b*

According to (15), the impact of $b$ on $S_{THRL}$ cannot be determined. Then, take the second partial derivative of the area function with respect to $b$, and get (16), where the second partial derivative is less than 0. That is when the first partial derivative is 0, the benefit distribution coefficient $b^*$ at this time makes $S_{THRL}$ have a maximum value. That is, the proportion of the two groups members choosing SCLIC strategy tends to $(1, 1)$ have a greater probability. When $b < b^*$, $S_{THRL}$ is positively correlated with $b$. When $b > b^*$, $S_{THRL}$ is negatively correlated with $b$. When $b = b^*$, $S_{THRL}$ is maximum, at which time $b$ is optimal.

### 2) THE IMPACT OF *B*

From (14), when the parameter $B$ is getting larger, the denominator of $x^*$ and $y^*$ would be larger, $x^*$ and $y^*$ will be smaller, and the saddle point $(x^*, y^*)$ would be closer to $(0, 0)$, $S_{THRL}$ will be larger. Therefore, increasing B is more conducive to the selection of SCLIC strategies by both groups.

### 3) THE IMPACT OF *β*

According to (14), the larger $\beta$ is, the larger the molecules of $x^*$ and $y^*$ will be, and the larger $x^*$ and $y^*$ will be, and the closer the saddle point $(x^*, y^*)$ is to $(1, 1)$, the smaller $S_{THRL}$ will be. In other words, the higher the risk is, the lower the proportion of SCLIC will be.

### 4) THE IMPACT OF *f*

The first partial derivative of (14) with respect to $f_1$ is obtained by (19), and the first partial derivative of (14) with respect to $f_2$ is obtained by (21). It is difficult to determine the impact of $f_1$ and $f_2$ on $S_{THRL}$ from (19) and (21). Therefore, the second partial derivative of (14) with respect to $f$ is calculated, and equation (20) with respect to $f_1$ and (22) with respect to $f_2$ are obtained. Both are less than 0. Therefore, when the first partial derivatives (19) and (21) are 0, there is a special value of SCLIC level $f^*$ that maximizes $S_{THRL}$.

### 5) THE IMPACT OF *a*

Similarly, the formula of $S_{THRL}$ is used to obtain the first partial derivative of $a$, as shown in (18). When $(B - bB - B_2 + Pf_1) > (bB - B_2 + Pf_2)$, equation (18) is less than 0. That is, the larger $a$ is, the smaller $S_{THRL}$ is, and the stable evolution result of the final population is (1,1). When $(B - bB - B_2 + Pf_1) < (bB - B_2 + Pf_2)$, equation (18) is greater than 0. At this time, the larger $a$ is, the larger $S_{THRL}$ will be. In this case, $a$ should be as large as possible.

**TABLE 7.** Impact of the relevant parameter on $S_{THRL}$.

| | Restrict condition | Parameters change | $S_{THRL}$ | Impact |
|---|---|---|---|---|
| $b$ | $b < b^*$ | Increase | Increase | Positive |
| | $b > b^*$ | Increase | Decrease | Negative |
| $B$ | | Increase | Increase | Positive |
| $\beta$ | | Increase | Decrease | Negative |
| $f_1$ | $f_1 < f_1^*$ | Increase | Increase | Positive |
| | $f_1 > f_1^*$ | Increase | Decrease | Negative |
| $f_2$ | $f_2 < f_2^*$ | Increase | Increase | Positive |
| | $f_2 > f_2^*$ | Increase | Decrease | Negative |
| $a$ | $O > M$ | Increase | Decrease | Negative |
| | $O < M$ | Increase | Increase | Positive |
| $C$ | | Increase | Decrease | Negative |
| $B_2$ | | Increase | Decrease | Negative |
| $P$ | | Increase | Increase | Positive |

### 6) THE IMPACT OF *C*

According to (14), the larger $C$ is, the larger the numerator of $x^*$ and $y^*$ will be, and the larger $x^*$ and $y^*$ will be. As a result, the saddle point $(x^*, y^*)$ is closer to $(1, 1)$, and $S_{THRL}$ will be smaller. Therefore, for a lower value of $C$, it can be considered that the promotion effect of members in both groups choosing SCLIC strategy is better, and the proportion of members in both groups choosing SCLIC strategy is higher in the process of continuous evolution.

### 7) THE IMPACT OF $B_2$

From (14), it is easy to see that the larger $B_2$ is, the smaller the denominator of $x^*$ and $y^*$ is, and the larger $x^*$ and $y^*$ will be, and the closer the saddle point $(x^*, y^*)$ is to (1,1), the smaller $S_{THRL}$ will be, which is not conducive to the formation of SCLIC behavior between the two groups.

### 8) THE IMPACT OF *P*

From (14), it is easy to see that the larger $P$ is, the larger the denominator of $x^*$ and $y^*$ is, the smaller $x^*$ and $y^*$ will be, and the closer the saddle point $(x^*, y^*)$ is to (0,0), the larger $S_{THRL}$ will be. Therefore, when $P$ is larger, the amount of punishment is higher, which might promote individuals in both groups to actively choose SCLIC strategy.

The impact of the relevant parameter on $S_{THRL}$ is shown in Table 7. When $\frac{\partial S_{THRQ}}{\partial b} = 0$, $b = b^*$. When $\frac{\partial S_{THRQ}}{\partial f_1} = 0$, $f_1 = f_1^*$. When $\frac{\partial S_{THRQ}}{\partial f_2} = 0, f_2 = f_2^*$. $O = B - bB - B_2 + Pf_1$, $M = bB - B_2 + Pf_2$.

**TABLE 8.** The specific parameter value of enterprise.

| $b$ | $B$ | $\beta$ | $f_1$ | $f_2$ | $a$ | $C$ | $B_2$ | $P$ |
|---|---|---|---|---|---|---|---|---|
| 0.6 | 150 | 6 | 6 | 5 | 0.6 | 30 | 50 | 5 |

### B. SIMULATION ANALYSIS

In the last section, the impact of each parameter on $S_{THRL}$ is analyzed using a mathematic method, and the process of the proportion of information collaboration strategy adopted by both groups changing with the parameter is discussed. In this section, different value ranges of each parameter are assumed according to the actual situation, and all numerical simulations are run using MATLAB R2017a.

The agricultural machinery manufacturing industry in Luoyang, China mainly consists of upstream parts suppliers and downstream agricultural machinery manufacturers, in which we have conducted many interviews with top-level managers and industrial experts about SCLIC. Combined with literatures [49], [50], [64] and the interviews, it is assumed that $b \in (0, 1)$, $B \in [80, 150]$, $\beta \in [1, 10]$, $C \in [10, 50]$, $a \in (0, 1)$, $B_2 \in [30, 70]$, $f \in [0, 10]$, $P \in [1, 10]$. Now given the specific values of each parameter, then $x^* \in (0, 1)$ and $y^* \in (0, 1)$ are valid. As a result, the proportions of supplier group and manufacturer group members adopting SCLIC strategy can converge to (1, 1). $S_{THRL}$ is analyzed by changing the value of one parameter when others remain constant. The specific values are shown in Table 8, then:

$$\begin{cases} \dfrac{\partial S_{THRQ}}{\partial b} = 0 \\ b^* = 0.5 \\ \dfrac{\partial S_{THRQ}}{\partial f_1} = 0 \\ f_1^* = 7.28 \\ \dfrac{\partial S_{THRQ}}{\partial f_2} = 0 \\ f_2^* = 0.48 \end{cases} \tag{23}$$

Let $O = B - bB - B_2 + Pf_1 = 40$, $M = bB - B_2 + Pf_2 = 65$, at this time, $O < M$.

The simulation results of MATLAB are shown in Fig. 3 to 10. The simulation results are consistent with the above mathematics theoretical analysis results, respectively. In Fig. 3, when $b^* = 0.5$, there is a peak value, and $b$ is optimal. In Fig. 6, when $f_1^* = 7.28$, $S_{THRL}$ gets the peak value, at this time, $f_1$ is optimal. And when $f_2^* = 0.48$, $S_{THRL}$ gets the peak value, at this time, $f_2$ is also optimal. In Fig. 8, let $b = 0.4$, then $O = 70$, $M = 35$, $O > M$. The larger $a$ is, the smaller $S_{THRL}$ will be.

Combined with the theoretical analysis in the previous section and Fig. 3 to 10, the following results are determined.

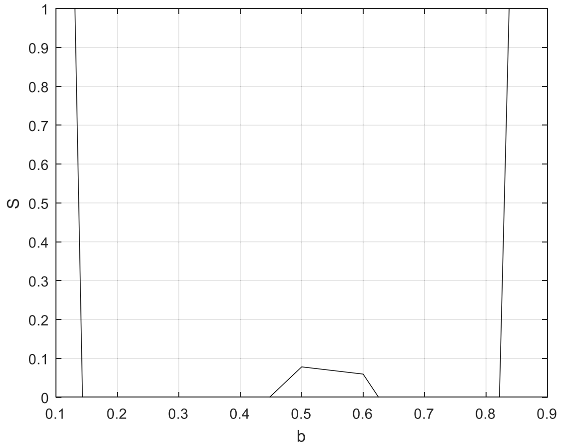


**FIGURE 3.** The impact of b on $S_{THRL}$.

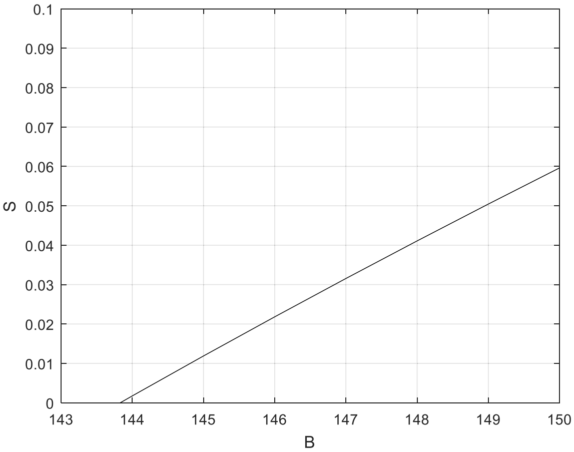


**FIGURE 4.** The impact of B on $S_{THRL}$.

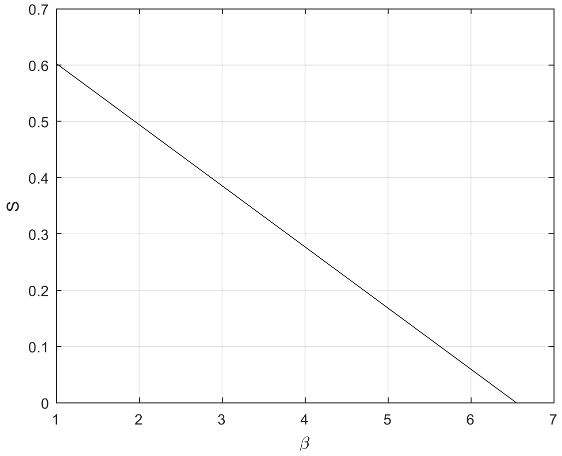


**FIGURE 5.** The impact of $\beta$ on $S_{THRL}$.

(1) Reasonable distribution of benefits obtained because SCLIC makes the proportions of the two group members adopting SCLIC strategy become higher. Therefore, the supply chain should determine the appropriate allocation coefficient according to the actual situation and the method proposed in this paper.

(2) The additional benefits can help to promote supply chain enterprises to choose SCLIC strategy. Moreover,

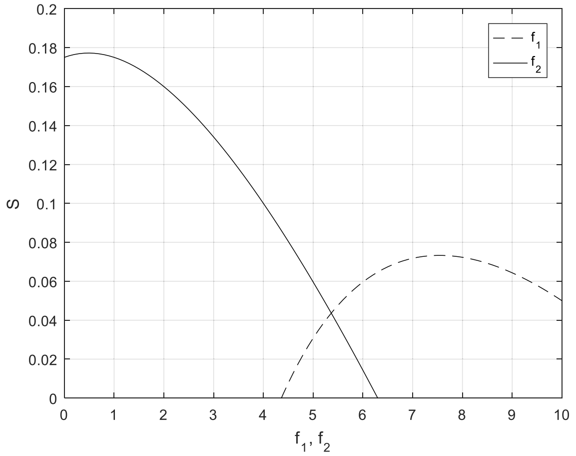


**FIGURE 6.** The impact of *f* on $S_{THRL}$.

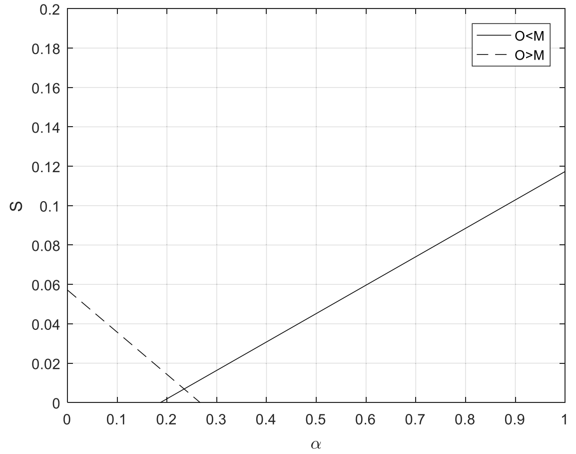


**FIGURE 7.** The impact of a on $S_{THRL}$.

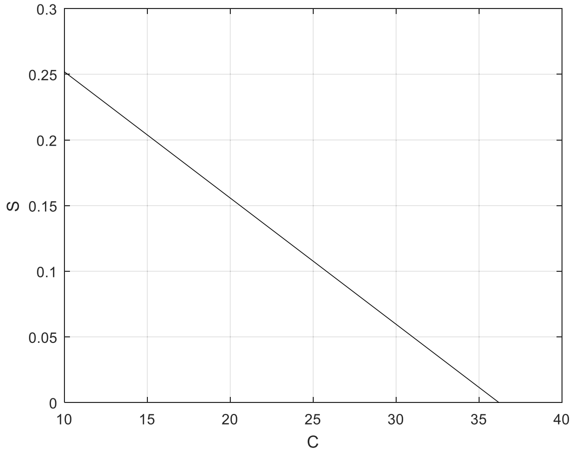


**FIGURE 8.** The impact of *C* on $S_{THRL}$.

the greater the benefit is, the more possibilities the supply chain enterprises would choose SCLIC strategy. If the benefit is small, they should find out the reasons and take certain actions to increase the benefit.

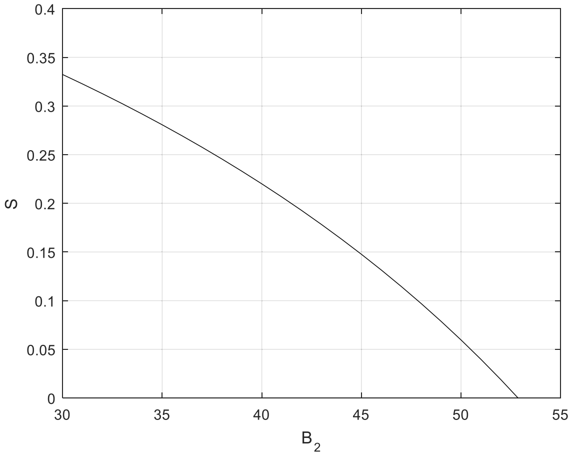


**FIGURE 9.** The impact of $B_2$ on $S_{THRL}$.

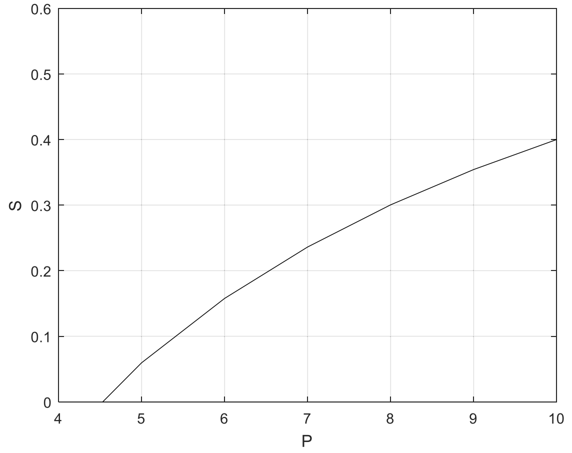


**FIGURE 10.** The impact of *P* on $S_{THRL}$.

(3) The higher the risk, the lower the proportion of SCLIC strategy would be adopted.

(4) The degree of SCLIC is related to the proportion of the two group members adopting SCLIC strategy, but SCLIC would not be achieved if any member lacks the ability and support to SCLIC. Therefore, the supply chain enterprises should collaborate reasonably their information, so as to maximize their benefits.

(5) The greater the cost of SCLIC is, the less willing for supply chain enterprises to adopt SCLIC strategy. On the one hand, the total cost of SCLIC should be as small as possible. On the other hand, in specific circumstances, the increase in the cost allocation coefficient will also promote SCLIC. Therefore, the impact of other parameters such as the additional total benefits from SCLIC, the benefit of the non-SCLIC alone, and the loss under the penalty mechanism on it should be considered.

(6) If the non-SCLIC supply chain enterprises can obtain enough benefits, other supply chain enterprises will not coordinate logistics information.

(7) When the punishment coefficient is getting larger, the amount of punishment capital would be higher, which can promote individuals in both groups to actively choose the SCLIC strategy.

## V. MANAGERIAL INSIGHTS

SCLIC is the basis and premise of supply chain logistics collaboration. According to the above research results, in order to promote the SCLIC, the following managerial insights for supply chain enterprises are given.

### A. BUILDING COLLABORATION MECHANISMS OF SCLIC

The supply chain is a dynamic alliance made up of both independent and interrelated individuals. They always try to avoid risks and costs and maximize benefits in the process of SCLIC. Therefore, mechanisms are necessary to ensure the SCLIC strategy of supply chain members [70]. On one hand, the additional benefits should be clearly defined rather than simply attributed to the total profits increase of manufacturing enterprises. In addition, benefits should be known by their partners and be distributed at a reasonable distribution coefficient [71]. On the other hand, risk should be identified and prevented to further ensure SCLIC through efficient control mechanisms and barriers [72]. However, this is not easy especially in supply chains without the core or leading companies. There should be a supply chain manager or leader. The leader may be the core or leading companies, or whoever wants to determine the mechanisms for the whole supply chain's sake, adjust it in time according to the actual situation, and encourage suppliers and manufacturers to choose SCLIC.

### B. ENHANCING MUTUAL TRUST

When many enterprises combine into a supply chain to meet the market demand, they should trust each other [73]. Mutual trust is the basis of SCLIC. Supply chain members should change the traditional zero-sum competition into a new multi-win situation through open cooperation and communication based on mutual trust [74]. Besides, communication between suppliers and manufacturers could be strengthened for both parties to achieve efficient logistics coordination and meet the market demand in time by providing reliable data truly reflecting the additional benefits generated by SCLIC. Unprecise data might eventually cause loss by transferring wrong information of additional benefit and ruin mutual trust.

### C. IMPROVING CONSCIOUSNESS AND ABILITY OF COLLABORATION

Supply chain enterprises should enhance their sense of coordination. With a strong consciousness of collaboration, supply chain members would be able to respond to the market demand quickly, reduce the cost, increase the logistics efficiency and enhance the competitiveness of the supply chain by avoiding the delay and distortion of logistics information sharing. Information collaboration is more than information sharing. SCLIC emphasizes providing the right amount of accurate logistics information at the right time [28]. Although the degree of SCLIC is related to the proportion of the two group members adopting SCLIC strategy, SCLIC would not be achieved if any member lacks the ability and support to SCLIC.

## VI. CONCLUSION

In this paper, ESS and replicator dynamic equations of the EGT method are used to analyze the dynamic change of the population proportion of members in supplier and manufacturer groups participating in SCLIC. Based on the value of SCLIC between enterprises, this paper studies the proportion change of members in supplier and manufacturer group choosing SCLIC strategy and the conditions affecting the change.

It can be concluded that when $0 < x^* < 1$ and $0 < y^* < 1$ are established at the same time, the supply chain enterprises will constantly adjust their strategies in practice so that the proportion of individuals in both groups adopting SCLIC will be likely to be (1, 1). On the evolutionary phase diagram, this probability varies with $S_{THRL}$. The larger $S_{THRL}$ is, the larger the proportion of both supplier and manufacturer group individuals adopting SCLIC tends to be (1, 1), and vice versa. The impact of each parameter on $S_{THRL}$ is discussed by mathematical analysis, and the impact process of enterprises choosing SCLIC strategy is discussed. According to the actual situation and numerical simulation requirements, we assume that the value range of each parameter remains the same. We change a single variable at a time and use MATLAB to verify the results of each parameter's impact on the evolution of SCLIC behavior. Managerial implications are given.

Relying upon the research results of this paper, the enterprises of supply chain can clearly understand the importance of SCLIC to supply chain competitiveness, and insight into the formation mechanism of SCLIC strategy. It is helpful to improve their supply chain logistics information collaborative awareness and collaborative behavior. Besides, with the growing focus on the supply chain, the research covered in the paper provides galvanizing and motivating insights into the practice of SCLIC of manufacturing enterprises. The supply chain manager can formulate specific measures to improve the collaborative environment of supply chain logistics information and motivate the enterprises of supply chain to implement the collaborative behavior of logistics information, so as to realize SCLIC and improve the market competitiveness of supply chain in the long run.

Although some research results have been obtained in this paper, there are still some restrictions. (1) Assumptions in the modelling might not be fully met in practice. (2) More impact factors of SCLIC might be involved in practice except for the ones we analyzed. (3) Our result needs to be further verified in reality.

Future directions of research are as follows. First, other game models could be used to determine equilibrium strategies. Second, assumptions can be further modified and improved so that the model would be closer to reality. Third, we could increase or change the factors that affect the equilibrium strategy so as to construct the benefit function of SCLIC. Fourth, researchers could put some effort into the formation process of SCLIC strategies, and compare with our results to verify the practicability of the model. Fifth, we could do further research on the related influencing factors (such as incentive mechanism, punishment mechanism, etc.). Finally, SCLIC between manufacturer and retailer group would also be an interesting topic.

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