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The Optimal Strategy of Enterprise Key Resource Allocation and Utilization in Collaborative Innovation Project Based on Evolutionary Game

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Abstract: The rational allocation and utilization of key corporate resources is the key to the success of collaborative innovation projects. Finding an optimal strategy for the allocation and utilization of key resources is of great significance for promoting the smooth progress of cooperative both innovation parties and increasing project returns. Therefore, from the perspective of the repeated games of the project participants, this article studies the optimal allocation and utilization of key resources of the enterprise in collaborative innovation projects. In this study, nine scenarios and eighteen strategic combinations of resources allocation and utilization by collaborative innovation partners are explored. Explicit expressions for the components of sixteen equilibrium points in terms of parameters are derived. Among these equilibrium points, four stable solutions are determined. These stable solutions correspond to the optimal strategies for enterprises allocating key resources and A&R parties to use these resources in different scenarios, and these strategies enable partners to maximize their interests. On this basis, some suggestions are put forward to promote cooperation and improve project performance.

Keywords: evolutionary game; equilibrium; optimal strategy; industry-university-research cooperation; key resource allocation



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1. Introduction

For enterprises to remain competitive in fierce competition, product and technology innovation is indispensable [1]. To this end, many enterprises have formulated innovation strategies, and innovative projects are an important carrier for implementing innovation strategies. However, many enterprises lack knowledge and technical advantages, which makes the implementation of innovative projects difficult. To overcome this disadvantage, companies cooperate with universities and research institutes (hereinafter referred to as A&R) to implement innovation projects. Such projects are called Collaborative Innovation Projects (CIP). This refers to projects in which enterprises cooperate with universities, research institutes, and other enterprises to develop new technologies and processes, including general research and development (R&D) projects, achievements transformation projects. Similar to the description of CIP by Wu et al. [2], these projects involve new ideas, products, and materials and specific systems or processes projects that companies and public research institutions (such as institutes and universities) or other companies (suppliers, customers, competitors, and other companies) collaborate to create [2]. At present, the importance of such projects is increasingly recognized and used. Its success helps enterprises to obtain innovative products and technologies and improve their core competitiveness.

For a larger, innovation-focused enterprise, several different collaborative innovation projects are being implemented at the same time over a period. For example, from the

information released by listed companies in China, some companies implement dozens of innovative projects at the same time, and many of them are cooperative innovation projects [3].

The successful implementation of collaborative innovation projects is inseparable from the utilization of key resources of enterprises. Key resources are essential for collaborative innovation projects, including the corporate talent [4], technology [5], and critical equipment [6]. However, companies have very limited resources of this kind. Moreover, there are often conflicts in the allocation and utilization of key resources between multiple projects within an enterprise, which is more common in collaborative innovation projects. This is often because the allocation and utilization of resources need to meet the needs of all parties [7] and improve the efficiency of resource allocation [8].

Therefore, how do companies allocate critical resources to projects, and how do project stakeholders utilize these resources to make resource allocation and utilization more efficient? The core of these problems lies in finding a reasonable strategy for the allocation and utilization of key resources, which is conducive to the smooth progress of collaborative innovation and the improvement of project returns.

From the perspective of the game, there is an iterative game process between the innovative entities of the project (enterprises and A&R parties) in the allocation and utilization of key resources. Companies allocate limited critical resources to projects based on their importance and probability of success [9]. In the face of different resource allocation strategies of enterprises, A&R will take corresponding resource utilization countermeasures, resulting in changes in cooperation benefits. At this point, the company will reconsider the change in revenue and change the strategy in line with the change in strategy on the A&R side. Parties involved in collaborative innovation projects will repeat the game process until a stable state is reached [10].

Although academics have studied issues related to resource allocation, most of them do not use game theory as a tool. For example, Wang et al. [11] proposed a new multi-criteria decision-making method for analyzing water resource allocation problems. The conclusions reached are centered around the efficiency of resource allocation. Even when using game theory, most are static games. The use of dynamic gaming methods for the allocation of resources is limited. The game analysis is carried out for the cooperative subjects of the project, mainly to design the distribution of benefits, and the results obtained are the distribution scheme of interests. There is less research on the allocation of resources. This is difficult to meet the needs of the enterprise's key resource allocation practices in project implementation.

Therefore, this paper studies the balanced allocation and utilization of enterprises' key resources during the implementation of collaborative innovation projects from the perspective of a repeated game between all parties. In different scenarios, the appropriate strategies for allocating key resources and A&R party to use these resources are obtained, and these strategies enable partners to maximize their interests.

The main contributions of this paper are as follows: (1) Different from the single perspective in the past, from the perspective of the game between the two parties involved in the project, it studies the rational allocation and utilization of the key resources of the enterprise in the collaborative innovation project. (2) Explicit expressions of 16 equilibrium solutions of the evolutionary game for resource allocation and utilization by innovation partners are derived, among which 5 stable solutions are found. (3) It was found that among the factors that affect resource allocation and utilization performance, in addition to the distribution ratio, free-riding is a major factor. The penalties for non-cooperation and the initial cost of cooperation stipulated in the initial agreement between the two parties in the game can prevent both parties from not cooperating. However, it will not affect the two sides to adopt a conservative cooperation strategy. (4) We propose the optimal strategy and sub-optimal strategy for the allocation of key resources in collaborative innovation projects for enterprises. When key resources are very tight, it is also feasible for enterprises to adopt a strategy of partially allocating key resources.

The rest of this article is organized as follows: Section 2 reviews the literature on key resource allocation of collaborative innovation projects. Section 3 establishes a cooperative evolutionary game model based on the allocation of key resources in collaborative innovation projects. Section 4 gives results of all the strategic combinations of resource allocation and utilization by the cooperative innovation partner and determines stable solutions. Section 5 discusses strategies for the allocation of key corporate resources in collaborative innovation projects under different circumstances. Section 6 gives conclusions. Section 7 puts forth management implications.

2. Literature Review

2.1. The Connotation of Key Resources

Following the definition of innovation by Stevenson and Jarillo [12], we can understand innovation as follows: the behavioral process of integrating resources to develop opportunities. These opportunities do not exist in the current application scope of resources but may create new value of resources applied in the future. Innovation is a process in which companies discover opportunities and organize resources to establish new projects, thereby creating new market values. Therefore, for innovative projects, possession and acquisition of key resources are necessary conditions for new projects to ultimately realize value creation. Effectively using key resources can help enterprises to improve the innovation ecology [13].

Earlier, scholars divided resources into three types, namely material resources (inventory, equipment), financial resources (funds, loans), and human resources (labor, managers). The resource-based theory emphasizes the heterogeneity and uniqueness of resources. Therefore, these resources evolved into more detailed organizational resources (combination of skills and knowledge), technology (technical know-how), and reputation resources.

Key resources are also called core resources. A view generally recognized by academia is that “heterogeneous” resources can easily form a sustainable competitive advantage for enterprises. Amit and Paul [14] believed that key resources have scarcity, irreplaceability, occupancy, and limited mobility. Markides and Williamson [15] believed that “strategic resources” have characteristics of slow accumulation, are difficult to replace, non-trading, and meeting market requirements. Zhou et al. [16] emphasized the value, scarcity, incomplete imitation, and organizational characteristics of the skills and experience of directors and executives. Jiang and Zhang [17] proposed five characteristics of core resources in the new environment: non-imitable duplication, profitability, competitiveness, controllability, and strategic environment. Levi et al. [18] found that the capacity of enterprises with complementary resources is limited by the most scarce resources.

Core resources are the resources that are most in short supply in an enterprise, and various projects vie for their use. The possibility of owning the resources will directly affect the status of the project in the entire enterprise system. For the resource allocation relationship, the strategic goals and project portfolio goals of the entire organization will be affected. Important resources in an enterprise are limited. If the resources are not allocated in time during the execution of the project, it will have a huge impact on the progress of the project and the quality of delivery. In addition to the production resources used in project management, they are mostly related to people (the allocation of time and energy for project team personnel and people). Intellectual capital is the essential, key, intangible resource [19]. Shah et al. developed a task-expert matching model to allocate scarce expert resources reasonably [20]. It is worth mentioning that there is a special type of resource, that is, the resource related to the characteristics of the corporate executives’ (especially entrepreneurs) social capital, also known as network resources or relationship resources, which play a very important role in the results of collaborative innovation projects. Therefore, it is also a key resource. The reward and control of middle and senior managers also have an impact on resource allocation decisions [21].

2.2. Enterprise Resource Allocation

Resource allocation is an important research issue in the project management [22]. Companies with sufficient resources can ensure the supply of resources and participate deeply in the cooperation [23–25]. The full cooperation of group rationality can effectively save project resources [26]. The additional benefits of active cooperation can make collaborative innovation projects go smoothly [27]. All parties in the cooperation should pay attention to curbing “free-riding” behaviors [28] and avoid opportunistic behaviors from adversely affecting the cooperation, and the expected benefits of cooperation will effectively inhibit the occurrence of opportunistic behaviors [29]. Cooperation naturally involves the allocation of resources. Resource allocation will affect the innovation performance of the project [30,31]. The exchange of key resources between enterprises rather than internal retention can improve performance [32].

The effectiveness of resource allocation is reflected by revenue. The distribution plan of project benefits will affect the benefits of both parties and, in turn, affect the resource cooperation strategy. A reasonable income distribution coefficient plays an important role in improving the level of cooperation, and high-level cooperation improves the net income of the project [33,34]. Etzkowitz and Leydesdorff [35] used the triple-helix theory model to illustrate the interactive form of politics, industry, academia, and research, emphasizing the common benefits of cooperation. Project complexity and team capabilities are the influencing factors of resource allocation [36,37]; they control key resources so that project goals can be completed [38]. The interaction of different platforms affects the allocation of key resources [39]. To reduce the conflicts caused by too many interactions, Baiman [40] studied the optimal resource allocation problem under the premise that agents do not like more resources.

There are many models to solve the problem of resource allocation optimization. For example, integer programming models, genetic algorithms, and other optimization models can be used to solve the resource allocation equilibrium problem, and the obtained allocation plan can optimize the overall effect of the project [41,42]. However, in practice, the applicability of the optimal resource allocation obtained through a one-time solution is low. Some scholars adopt new methods to improve the applicability of the model. Stein et al. [43] designed an online resource allocation model aiming at expected capacity utilization. Fu et al. [44] put forward the asymptotic stabilization method to solve the problem of shared resources. Lyu et al. [45] designed a unified method for resource allocation under strategies of a different attribute. Many allocation algorithms are based on sorting rules. However, when the differences of the subjects to be allocated are difficult to distinguish, the allocation rules of sorting will cause negative effects [46].

2.3. Resource Allocation and Utilization Game

The evolutionary game method is more in line with the limited rationality and incomplete information in reality and can be used to explore the factors that make the system stable. The limitation of resources changes the strategy of the game in the process of evolution [47]. Xing et al. [29] found that the expected benefits will affect the partner’s support for project resources through an evolutionary game model based on negotiation. Song et al. [48] constructed a dynamic game model and pointed out that the use of cost-sharing methods is more effective in increasing innovation revenue.

There is a game in the allocation of project resources. The continuity of resource supply will affect the implementation speed of the project, thereby changing the project income, so there will be a game. Lin et al. [49] explored the cooperative game scheme of resource transfer problem and pointed out that because of the limited initial resources, the redistribution of resources will bring additional benefits. They further found that the contributions of cooperative managers can promote the benefits of cooperation. Insufficient resource allocation will increase the possibility of project delays, and penalties and rewards are usually linked to the duration of the project, so all parties will have a game on the negotiation of resource provision efficiency [50]. Lin et al. [51] considered the cooperative

game problem of resource allocation among contractors and put forward management insights, pointing out that the key resources of the project will flow to the project on the critical path and transfer to the efficient partner.

Resource-constrained multi-project scheduling needs to consider many factors. The cooperative game negotiation mechanism can effectively promote the coordinated allocation of resources, considering the influence of information asymmetry and the self-interest of decision makers, and reduce the total cost of the project [52]. Cost is the main factor affecting the cooperation-oriented resource allocation [53]. Qi et al. [54] constructed a tripartite game model for resource sharing among collaborative innovation entities, analyzed the benefits of all parties under different sharing and regulatory strategies, and proposed that mechanisms should be innovated to reduce the risk and cost of resource sharing. Wu et al. [33] established a cooperation incentive model through game theory, indicating that the synergy produced by cooperation will increase the intensity of one party's resource transfer to the other party's investment, which can increase the efforts of both parties and project benefits. The effort of all parties is also related to conflict resolution capabilities. Using a reasonable mechanism to optimize the allocation of resources can balance the gains and losses caused by the game between the parties in the project conflict and reduce the negative impact of the conflict on the project [55].

In summary, the allocation and utilization of key resources in collaborative innovation projects have a significant impact on the achievement of project goals and the quality of project results.

3. Methods

For the sake of their own project goals and economic interests, each entity of the collaborative innovation project will inevitably use various means to obtain more key resources because enterprises and A&R have certain differences in their technical level and management level and ability to withstand market risks. There are also differences in the game's ability to obtain resources. In the face of changes in internal and external environments, one party will compete with other subjects for the right to use the limited key resources in the project. This paper adopts the evolutionary game method of repeated games between two groups to study the cooperative game process between enterprises and A&R parties based on three types of resource allocation strategies.

3.1. Assumptions

To simplify the problem and draw on the analysis ideas of Chen et al. [56], this article analyzes the assumption that the following conditions are met:

Assumption 1. *For simplicity, assume that the enterprise is responsible for resource allocation, and the A&R is responsible for resource utilization. There is a game between the enterprise and the A&R. The innovation subject can adopt three strategies, respectively.*

For the enterprise, there are deep cooperation strategies (active cooperation strategies), that is, sufficient allocation of key resources; simple cooperation strategy (conservative cooperation strategy), that is, the basic allocation of key resources; and non-cooperation policy (negative policy), in which key resources are not configured or not configured.

For the A&R, there are deep cooperation strategies (active cooperation strategies), that is, making full use of key resources; simple cooperation strategy (conservative cooperation strategy), that is, the general use of resources although some resources may be idle; and non-cooperative strategy (negative strategy), that is, the resource is not used, leaving the resource idle.

In-depth cooperation: For enterprises, in-depth cooperation is to fully allocate resources to projects and, for A&R parties, make full use of resources. Participants communicate frequently and effectively can play a synergistic effect and can bring more value-added knowledge. Because collaborative innovation involves the integration of resources, the higher the degree of integration, the greater the value-added knowledge it can bring.

The “simple cooperation” strategy refers to conservative cooperation. For the enterprise, part of the key resources are allocated to the project, and for the A&R side, part of the resources are used. The level of communication and information sharing is average, which can only bring less value-added knowledge.

In the process of cooperation between the two parties, one party may abandon the cooperation due to development strategy adjustment, research and development (R&D) risk uncertainty, trust crisis, and other reasons. For the enterprise, it does not allocate key resources timely, and for the A&R party, it refuses to use the key resources configured by the enterprise. The “non-cooperation” strategy, in which both parties use their resources for development, can only bring less value-added knowledge. The strategy of “non-cooperation” cannot add value to knowledge.

In this way, in the collaborative innovation project group, there is a strategy game of cooperation between the enterprise side and the A&R side. The set of the enterprise strategies is (full allocation of resources (i.e., deep cooperation), simple cooperation allocation of resources (i.e., simple cooperation), and no allocation of resources (i.e., no cooperation)). The set of the strategy of the A&R side is (make full use of key resources (i.e., deep cooperation), simply use key resources (i.e., general use, simple cooperation), and rarely use key resources (i.e., no cooperation)).

In the evolutionary game process, both parties will learn and imitate and continue to adjust and choose their strategies according to the other’s strategies.

Assumption 2. (The initial parameter assumptions): When both parties adopt a simple cooperation strategy, that is, when the enterprise simply allocates resources to the project, the A&R side also simply uses these key resources (that is, the effort to use resources meets the requirements). Suppose that within a certain period of the project, the amount of key corporate resources that are simply configured by the enterprise and generally used by the A&R side is its use cost c , and the benefit to the project, which is I (also called the net benefit of cooperative innovation, or additional benefit). Under normal circumstances, $I > c$. Otherwise, it is an invalid configuration. The field is the net income of the project.

Let α be the distribution ratio of $I - c$ by the academic research side, then $(1 - \alpha)$ is the distribution ratio of the enterprise. These proportional coefficients (percentages) are obtained by negotiation between the two parties. If the A&R side has a high negotiating position and strong bargaining power, it requires a higher ratio of the project income distribution (such as 30–80%). Otherwise, the enterprise side with strong bargaining power will require a lower proportion of the project’s net income distribution.

Suppose that the amount of key enterprise resources used by the A&R is R under simple configuration of the enterprise. The increment of the allocation of resources ΔR brings the increment of benefit ΔI and the net incremental benefit $\Delta I - \Delta c$ at the extra cost Δc . For simplicity, it may be assumed that $\phi = \frac{\Delta I}{\Delta R}$ is a proportionality coefficient, which indicates the degree of benefit brought by the use of the incremental key resources. Thus, ΔI can be written as $I\phi$, that is, $\Delta I = I\phi$. ϕ can also be understood as the degree of increase (or decrease) in the use of key resources by the A&R party, and it can also be understood as a reasonable value (relative to the general configuration) for making full use of incremental resources, which is a constant. $\phi > 0$ means that it brings positive benefits, and $\phi = 0$ implies no increase in resources.

Assuming that $\delta = \frac{\Delta c}{\Delta R}$ is a proportionality coefficient, which represents the degree of cost brought about by using the incremental key resources, so Δc can be written as $c\delta$, that is, $\Delta c = c\delta$, which is a constant. $\delta > 0$ means a positive cost, and $\delta = 0$ represents no increase in resources. Thus, the net incremental income of the project is $\Delta I - \Delta c = I\phi - c\delta$. Then, the income obtained by the A&R and the enterprise can be expressed as

$$s = \alpha I(1 + \phi) - c(1 + \delta) \tag{1}$$

and

$$q = (1 - \alpha)I(1 + \phi) - c(1 + \delta), \tag{2}$$

respectively.

3.2. Payout Matrix for Both Sides of the Game

Case 1: When both parties adopt simple cooperation strategies, $\delta = \phi = 0$. Denote the incomes obtained by the A&R party and by the enterprise by e and d , respectively. Then, from (1) and (2), we have

$$e = \alpha(I - c), \quad d = (1 - \alpha)(I - c), \quad \text{where } I > c,$$

which means that the key resource with cost c should create more benefits for the project than its cost.

Case 2: Both the A&R party and the enterprise adopt in-depth cooperation strategies (the allocation of resources is sufficient, and efforts are made to utilize resources). In this case, $\delta > 0$ and $\phi > 0$ (proportion of the increase in profit and cost). At this time, the project net income is $p_{net} = \Delta I - \Delta c = I\phi - c\delta$.

We denote the incomes obtained by the A&R party and by the enterprise by a and b , respectively. Then, from (1) and (2), we have

$$\begin{aligned} a &= \alpha[I(1 + \phi) - c(1 + \delta)] = e + \alpha(I\phi - c\delta) = e + \alpha p_{net}, \\ b &= (1 - \alpha)[I(1 + \phi) - c(1 + \delta)] = d + (1 - \alpha)(I\phi - c\delta) = d + (1 - \alpha)p_{net} \end{aligned}$$

Here, αp_{net} is the net benefit to the academic and research side for the incremental use of resources. The assumption $I\phi > c\delta$ means that the benefits of incremental resources should be greater than the cost of their use. In the same way, $(1 - \alpha)p_{net}$ is the net income brought by the incremental resource use to the enterprise.

In the above two cases, $a > e$ means that the in-depth cooperation between the two parties (the A&R party makes full use of resources) will bring more benefits to the A&R party than simple cooperation, while $b > d$ means that the benefits brought to the company by the in-depth cooperation between the two parties (the company fully allocates resources) are greater than the benefits brought by the simple cooperation.

Case 3: When both the A&R side and the enterprise adopt a non-cooperative strategy due to the complexity of the technology, the enterprise side does not have strong enough scientific research capabilities for independent development, and the innovation income is $w_2 = 0$ at this time. For the A&R party, if they do not have market capabilities, they can only obtain limited benefits if they are developed. At this time, the innovation benefits are $w_1 = 0$.

Case 4: Here, the A&R side adopts an in-depth cooperation strategy, and the enterprise adopts a simple cooperation strategy. At this time, although the A&R side is still working hard to use resources, the supply of resources is not sufficient (only the basic requirements are met), and the benefits at this time will be less than the benefits a when the resources are sufficient. Suppose that the reduced income is h_1 so that the income obtained by the A&R party is

$$s = a - h_1 = e + \alpha(I\phi - c\delta) - h_1.$$

For the enterprise, the income at this time is greater than d (the income of the enterprise when both parties in the game adopt a simple cooperation strategy), so the enterprise takes the free ride of the A&R side. The income of the enterprise is $d + h_1$.

Case 5: Here, the A&R side adopts an in-depth cooperation strategy, and the enterprise adopts a non-cooperative strategy. The enterprise does not allocate (or allocates very little) key resources to the project. However, the allocation of resources is far from meeting the requirements (lack of resource supply), so the A&R side will not get innovation benefits from the project but instead has to pay the cost of wasting resources c_{1q} . Therefore, the income obtained for the A & R is $-c_{1q}$, while the enterprise cannot obtain innovation income, and the loss (for example, the penalty for default) is m_q . Therefore, the income obtained by the enterprise is $-m_q$.

Case 6: Here, when the A&R side adopts a simple cooperation strategy, the enterprise adopts an in-depth cooperation strategy. Under this situation, although the company allocates sufficient resources, the A&R party generally works hard and simply uses the resources, causing some resources to be idle. This brings losses to the enterprise h_2 . Therefore, the income of the enterprise at this time is $b - h_2 = d + (1 - \alpha)(I\phi - c\delta) - h_2$. The A&R side adopts a simple cooperation strategy, but sufficient resources will still bring additional benefits h_2 . In this way, the A&R party will take the free ride of the enterprise and obtain $e + h_2$.

Case 7: The A&R side adopts a simple cooperation strategy, and the enterprise adopts a non-cooperative strategy in this scenario. At this time, although the A&R party simply uses resources, the enterprise has insufficient resources to allocate resources and cannot generate innovation benefits. In this way, the A&R party will not obtain innovation benefits from the project but has to pay the cost of resource waste c_{1q} , which brings losses to the A&R party c_{2q} (it can also be understood as the cost of using this part of the resource). At this time, the income of the college side is $-c_{2q}$. The enterprise also cannot obtain the innovation income and has to pay the default fine m_q , so the enterprise obtains the income of $-m_q$.

Because the two strategies of Cases 5 and 7 require the A&R party to use resources differently, and the losses caused by resource supply are different as well, it can be further assumed that $c_{1q} > c_{2q} > 0$.

Case 8: Here, the A&R side adopts a non-cooperative strategy, and the enterprise adopts an active cooperation strategy (full supply of resources). In this case, the A&R party does not use resources, wastes the allocated resources, and causes losses to the enterprise $c_{1s} > 0$. It should pay a certain liquidated penalty m_s , and the cost of allocating resources at this time is $-c_{1s}$.

Case 9: In this case, the A&R side adopts a non-cooperative strategy, and the enterprise adopts a simple cooperation strategy (supply some resources). At this time, the A&R party does not work hard to use the resources, wasting part of the allocated resources, and the resource loss caused to the enterprise is $c_{2s} > 0$ (the cost of the company at this time allocating resources), and the A&R party should pay a certain default penalty m_s .

In summary, the income payout matrix of the cooperative game of innovative entities is established as given in Table 1.

Table 1. Income payout matrix, where the short-hand notations Coll., coop, and KR stand for collaborative and cooperation, key resources, respectively.

		Enterprise (Allocating KRs)		
Strategy		Full Coop (x_1)	Simple Coop (x_2)	Non-Coop ($1 - x_1 - x_2$)
A&R (using KRs)	Full coop (y_1)	$e + \alpha p_{net}, d + (1 - \alpha)p_{net}$	$e + \alpha p_{net} - h_1, d + h_1$	$-c_{1q}, -m_q$
	Simple coop (y_1)	$e + h_2, d + (1 - \alpha)p_{net} - h_2$	e, d	$-c_{2q}, -m_q$
	Non-coop ($1 - y_1 - y_2$)	$-m_s, -c_{1s}$	$-m_s, -c_{2s}$	0, 0

3.3. Game Analysis of Cooperative Evolution of Innovation Group and Equilibrium Points

Assume that in the project group, the proportions of enterprise choosing collaborative cooperation, simple cooperation, and non-cooperation are x_1, x_2 , and $1 - x_1 - x_2$, respectively. The proportions of A&R party choosing collaborative cooperation, simple cooperation, and non-cooperation are y_1, y_2 , and $1 - y_1 - y_2$, respectively.

(1) The expected benefit when an enterprise chooses to make full use of key resources for in-depth cooperation is

$$U_{q1} = y_1 b + y_2 (b - h_2) + (1 - y_1 - y_2)(-c_{1s}) = y_1 (b + c_{1s}) + y_2 (b - h_2 + c_{1s}) - c_{1s}.$$

(2) The expected benefit of simple cooperation when an enterprise chooses to utilize some key resources is

$$U_{q2} = y_1(d + h_1) + y_2d + (1 - y_1 - y_2)(-c_{2s}) = y_1(d + h_1 + c_{2s}) + y_2(d + c_{2s}) - c_{2s}$$

(3) The expected benefits when an enterprise chooses a non-cooperative strategy (not using key resources) is

$$U_{q3} = y_1(-m_q) + y_2(-m_q) + (1 - y_1 - y_2)(0) = -(y_1 + y_2)m_q.$$

Therefore, the average expected innovation income of the enterprise is

$$\begin{aligned} \bar{U}_q &= x_1U_{q1} + x_2U_{q2} + (1 - x_1 - x_2)U_{q3} = x_1(U_{q1} - U_{q3}) + x_2(U_{q2} - U_{q3}) + U_{q3} \\ &= x_1[y_1(b + c_{1s} + m_q) + y_2(b - h_2 + c_{1s} + m_q) - c_{1s}] \\ &\quad + x_2[y_1(d + h_1 + c_{2s} + m_q) + y_2(d + c_{2s} + m_q) - c_{2s}] - (y_1 + y_2)m_q. \end{aligned}$$

The replicating dynamic equations for the enterprise to adopt collaborative innovation and simple cooperation are

$$\begin{aligned} \frac{dx_1}{dt} &= x_1(U_{q1} - \bar{U}_q) = x_1[(1 - x_1)(U_{q1} - U_{q3}) - x_2(U_{q2} - U_{q3}) \\ &= x_1\{[y_1(b + c_{1s} + m_q) + y_2(b - h_2 + c_{1s} + m_q) - c_{1s}](1 - x_1) \\ &\quad - x_2[y_1(d + h_1 + c_{2s} + m_q) + y_2(d + c_{2s} + m_q) - c_{2s}]\} \end{aligned}$$

and

$$\begin{aligned} \frac{dx_2}{dt} &= x_2(U_{q2} - \bar{U}_q) = x_2[(1 - x_2)(U_{q2} - U_{q3}) - x_1(U_{q1} - U_{q3})] \\ &= x_2\{[y_1(d + h_1 + c_{2s} + m_q) + y_2(d + c_{2s} + m_q) - c_{2s}](1 - x_2) \\ &\quad - x_1[y_1(b + c_{1s} + m_q) + y_2(b - h_2 + c_{1s} + m_q) - c_{1s}]\}, \end{aligned}$$

respectively.

The expected innovation gains when an A&R side chooses a collaborative innovation strategy, a simple cooperation strategy, and a non-cooperative strategy are

$$\begin{aligned} U_{p1} &= x_1a + x_2(a - h_1) + (1 - x_1 - x_2)(-c_{1q}) = x_1(a + c_{1q}) + x_2(a - h_1 + c_{1q}) - c_{1q}, \\ U_{p2} &= x_1(e + h_2) + x_2e + (1 - x_1 - x_2)(-c_{2q}) = x_1(e + h_2 + c_{2q}) + x_2(e + c_{2q}) - c_{2q}, \end{aligned}$$

and

$$U_{p3} = x_1(-m_s) + x_2(-m_s) + (1 - x_1 - x_2)0 = -(x_1 + x_2)m_s,$$

respectively.

Therefore, the average expected innovation income of the A&R party is

$$\begin{aligned} \bar{U}_p &= y_1U_{p1} + y_2U_{p2} + (1 - y_1 - y_2)U_{p3} = y_1(U_{p1} - U_{p3}) + y_2(U_{p2} - U_{p3}) + U_{p3} \\ &= y_1[x_1(a + c_{1q} + m_s) + x_2(a - h_1 + c_{1q} + m_s) - c_{1q}] \\ &\quad + y_2[x_1(e + h_2 + c_{2q} + m_s) + x_2(e + c_{2q} + m_s) - c_{2q}] - (x_1 + x_2)m_s. \end{aligned}$$

The replicating dynamic equations for the study and research side to adopt a collaborative innovation strategy and a simple cooperation strategy are

$$\begin{aligned} \frac{dy_1}{dt} &= y_1(U_{p1} - \bar{U}_p) = y_1[(U_{p1} - U_{p3})(1 - y_1) - y_2(U_{p2} - U_{p3})] \\ &= y_1\{[x_1(a + c_{1q} + m_s) + x_2(a - h_1 + c_{1q} + m_s) - c_{1q}](1 - y_1) \\ &\quad - y_2[x_1(e + h_2 + c_{2q} + m_s) + x_2(e + c_{2q} + m_s) - c_{2q}]\} \end{aligned}$$

and

$$\begin{aligned} \frac{dy_2}{dt} &= y_2(U_{p2} - \bar{U}_p) = y_2[(U_{p2} - U_{p3})(1 - y_2) - y_1(U_{p1} - U_{p3})] \\ &= y_2\{[x_1(e + h_2 + c_{2q} + m_s) + x_2(e + c_{2q} + m_s) - c_{2q}](1 - y_2) \\ &\quad - y_1[x_1(a + c_{1q} + m_s) + x_2(a - h_1 + c_{1q} + m_s) - c_{1q}]\}, \end{aligned}$$

respectively.

For brevity, denote

$$\begin{cases} f_1 = f_1(x_1, x_2, y_1, y_2) = \frac{dx_1}{dt}, f_2 = f_2(x_1, x_2, y_1, y_2) = \frac{dx_2}{dt}, \\ f_3 = f_3(x_1, x_2, y_1, y_2) = \frac{dy_1}{dt}, f_4 = f_4(x_1, x_2, y_1, y_2) = \frac{dy_2}{dt}, \\ a_{11} = b + c_{1s} + m_q, a_{12} = b - h_2 + c_{1s} + m_q, \\ a_{21} = d + h_1 + c_{2s} + m_q, a_{22} = d + c_{2s} + m_q, \\ a_{31} = a + c_{1q} + m_s, a_{32} = a - h_1 + c_{1q} + m_s, \\ a_{41} = e + h_2 + c_{2q} + m_s, a_{42} = e + c_{2q} + m_s, \end{cases} \quad (3)$$

Possible equilibrium solutions (x_1, x_2, y_1, y_2) for both sides can be found by solving the following differential equation system:

$$\frac{dx_1}{dt} = \frac{dx_2}{dt} = \frac{dy_1}{dt} = \frac{dy_2}{dt} = 0.$$

That is,

$$\begin{cases} \frac{dx_1}{dt} = f_1 = x_1 \{ [a_{11}y_1 + a_{12}y_2 - c_{1s}](1 - x_1) - x_2[a_{21}y_1 + a_{22}y_2 - c_{2s}] \} = 0, \\ \frac{dx_2}{dt} = f_2 = x_2 \{ [a_{21}y_1 + a_{22}y_2 - c_{2s}](1 - x_2) - x_1[a_{11}y_1 + a_{12}y_2 - c_{1s}] \} = 0, \\ \frac{dy_1}{dt} = f_3 = y_1 \{ [a_{31}x_1 + a_{32}x_2 - c_{1q}](1 - y_1) - y_2[a_{41}x_1 + a_{42}x_2 - c_{2q}] \} = 0, \\ \frac{dy_2}{dt} = f_4 = y_2 \{ [a_{41}x_1 + a_{42}x_2 - c_{2q}](1 - y_2) - y_1[a_{31}x_1 + a_{32}x_2 - c_{1q}] \} = 0. \end{cases} \quad (4)$$

Since $x_1, x_2, x_1 + x_2, y_1, y_2, y_1 + y_2 \in [0, 1]$, from (4), it is easy to obtain special solutions with at least one of x_1, x_2, y_1, y_2 to be 1, and the rest are 0 as follows:

$$(x_1, x_2, y_1, y_2) \in \{E_1 = (0, 0, 0, 0), E_2 = (0, 0, 0, 1), E_3 = (0, 0, 1, 0), E_4 = (0, 1, 0, 0), E_5 = (1, 0, 0, 0), E_6 = (1, 0, 1, 0), E_7 = (1, 0, 0, 1), E_8 = (0, 1, 0, 1), E_9 = (0, 1, 1, 0)\}.$$

Other special solutions are different from the above, with one or two of the coordinates of (x_1, x_2, y_1, y_2) to be zero, and can be found as follows (some solution expressions were found by using Maplesoft):

$E_{10} = (0, x_2, 0, y_2)$ with $x_2 \cdot y_2 \neq 0$: Both x_2 and y_2 satisfy

$$\begin{cases} (a_{22}y_2 - c_{2s})(1 - x_2) = 0, \\ (a_{42}x_2 - c_{2q})(1 - y_2) = 0. \end{cases}$$

Thus,

$$x_2 = \frac{c_{2q}}{a_{42}} = \frac{c_{2q}}{e + c_{2q} + m_s}, y_2 = \frac{c_{2s}}{a_{22}} = \frac{c_{2s}}{d + c_{2s} + m_q}. \quad (5)$$

Accordingly,

$$E_{10} = \left(0, \frac{c_{2q}}{e + c_{2q} + m_s}, 0, \frac{c_{2s}}{d + c_{2s} + m_q} \right).$$

$E_{11} = (0, x_2, y_1, 0)$ with $x_2 \cdot y_1 \neq 0$: Both x_2 and y_1 satisfy

$$\begin{cases} (a_{21}y_1 - c_{2s})(1 - x_2) = 0, \\ (a_{32}x_2 - c_{1q})(1 - y_1) = 0. \end{cases}$$

Thus,

$$x_2 = \frac{c_{1q}}{a_{32}} = \frac{c_{1q}}{a - h_1 + c_{1q} + m_s}, y_1 = \frac{c_{2s}}{a_{21}} = \frac{c_{2s}}{d + h_1 + c_{2s} + m_q}. \quad (6)$$

Consequently,

$$E_{11} = \left(0, \frac{c_{1q}}{a - h_1 + c_{1q} + m_s}, \frac{c_{2s}}{d + h_1 + c_{2s} + m_q}, 0 \right) \tag{7}$$

is a feasible equilibrium point, provided $a - h_1 + m_s \geq 0$.

$E_{12} = (x_1, 0, y_1, 0)$ with $x_1 \cdot y_1 \neq 0$: Both x_1 and y_1 satisfy

$$\begin{cases} (a_{11}y_1 - c_{1s})(1 - x_1) = 0, \\ (a_{31}x_1 - c_{1q})(1 - y_1) = 0. \end{cases}$$

Thus,

$$x_1 = \frac{c_{1q}}{a_{31}} = \frac{c_{1q}}{a + c_{1q} + m_s}, y_1 = \frac{c_{1s}}{a_{11}} = \frac{c_{1s}}{b + c_{1s} + m_q}. \tag{8}$$

Therefore,

$$E_{12} = \left(\frac{c_{1q}}{a + c_{1q} + m_s}, 0, \frac{c_{1s}}{b + c_{1s} + m_q}, 0 \right) \tag{9}$$

is a feasible equilibrium point.

$E_{13} = (x_1, 0, 0, y_2)$ with $x_1 \cdot y_2 \neq 0$: Both x_1 and y_2 satisfy

$$\begin{cases} (a_{12}y_2 - c_{1s})(1 - x_1) = 0, \\ (a_{41}x_1 - c_{2q})(1 - y_2) = 0. \end{cases}$$

Thus,

$$x_1 = \frac{c_{2q}}{a_{41}} = \frac{c_{2q}}{e + h_2 + c_{2q} + m_s}, y_2 = \frac{c_{1s}}{a_{12}} = \frac{c_{1s}}{b - h_2 + c_{1s} + m_q}. \tag{10}$$

Consequently,

$$E_{13} = \left(\frac{c_{2q}}{e + h_2 + c_{2q} + m_s}, 0, 0, \frac{c_{1s}}{b - h_2 + c_{1s} + m_q} \right) \tag{11}$$

is a feasible equilibrium point provided $b - h_2 + m_q \geq 0$.

$E'_{14} = (0, x_2, y_1, y_2)$ with $x_2 \cdot y_1 \cdot y_2 \neq 0$: x_2, y_1 , and y_2 satisfy

$$\begin{cases} (a_{21}y_1 + a_{22}y_2 - c_{2s})(1 - x_2) = 0, \\ (a_{32}x_2 - c_{1q})(1 - y_1) - y_2(a_{42}x_2 - c_{2q}) = 0, \\ (a_{42}x_2 - c_{2q})(1 - y_2) - y_1(a_{32}x_2 - c_{1q}) = 0. \end{cases}$$

Thus,

$$\begin{cases} x_2 = \frac{c_{1q} - c_{2q}}{a_{32} - a_{42}} = \frac{c_{1q} - c_{2q}}{a + c_{1q} - c_{2q} - e - h_1}, \\ y_1 = -\frac{a_{22} - c_{2s}}{a_{21} - a_{22}} = -\frac{d + m_q}{h_1}, \\ y_2 = \frac{a_{21} - c_{2s}}{a_{21} - a_{22}} = \frac{d + m_q}{h_1}. \end{cases}$$

However, since $x_2, y_1, y_2, y_1 + y_2 \in [0, 1]$, but $y_1 = -\frac{d + m_q}{h_1} < 0$. Therefore, there is no such feasible equilibrium point in the form of $(0, x_2, y_1, y_2)$ with $x_2 \cdot y_1 \cdot y_2 \neq 0$.

$E_{14} = (x_1, 0, y_1, y_2)$ with $x_1 \cdot y_1 \cdot y_2 \neq 0$: x_1, y_1 and y_2 satisfy

$$\begin{cases} (a_{11}y_1 + a_{12}y_2 - c_{1s})(1 - x_1) = 0, \\ (a_{31}x_1 - c_{1q})(1 - y_1) - y_2(a_{41}x_1 - c_{2q}) = 0, \\ (a_{41}x_1 - c_{2q})(1 - y_2) - y_1(a_{31}x_1 - c_{1q}) = 0. \end{cases}$$

Thus,

$$\begin{cases} x_1 = \frac{c_{1q}-c_{2q}}{a_{31}-a_{41}} = \frac{c_{1q}-c_{2q}}{a+c_{1q}-c_{2q}-e-h_2}, \\ y_1 = -\frac{a_{12}-c_{1s}}{a_{11}-a_{12}} = -\frac{b-h_2+m_q}{h_2} = 1 - \frac{b+m_q}{h_2}, \\ y_2 = \frac{a_{11}-c_{1s}}{a_{11}-a_{12}} = \frac{b+m_q}{h_2}. \end{cases} \tag{12}$$

Notice that $y_1 + y_2 = 1$. Accordingly, if $x_1, y_1, y_2 \in [0, 1]$, then

$$E_{14} = \left(\frac{c_{1q}-c_{2q}}{a+c_{1q}-c_{2q}-e-h_2}, 0, 1 - \frac{b+m_q}{h_2}, \frac{b+m_q}{h_2} \right) \tag{13}$$

is a feasible equilibrium point.

$E'_{15} = (x_1, x_2, 0, y_2)$ with $x_1 \cdot x_2 \cdot y_2 \neq 0$: x_1, x_2 and y_2 satisfy

$$\begin{cases} (a_{12}y_2 - c_{1s})(1 - x_1) - x_2(a_{22}y_2 - c_{2s}) = 0, \\ (a_{22}y_2 - c_{2s})(1 - x_2) - x_1(a_{12}y_2 - c_{1s}) = 0, \\ (a_{41}x_1 + a_{42}x_2 - c_{2q})(1 - y_2) = 0. \end{cases}$$

Thus,

$$\begin{cases} x_1 = \frac{a_{42}-c_{2q}}{a_{41}-a_{42}} = -\frac{e+m_s}{h_2} < 0 \\ x_2 = \frac{a_{41}-c_{2q}}{a_{41}-a_{42}} = \frac{e+h_2+m_s}{h_2} \\ y_2 = \frac{c_{1s}-c_{2s}}{a_{12}-a_{22}} = \frac{c_{1s}-c_{2s}}{b+c_{1s}-c_{2s}-d-h_2} \end{cases}$$

Again, since $x_1 < 0$, there is no such a feasible equilibrium point in the form of $(x_1, x_2, 0, y_2)$ with $x_1 \cdot x_2 \cdot y_2 \neq 0$.

$E_{15} = (x_1, x_2, y_1, 0)$ with $x_1 \cdot x_2 \cdot y_1 \neq 0$: x_1, x_2 and y_1 satisfy

$$\begin{cases} (a_{11}y_1 - c_{1s})(1 - x_1) - x_2(a_{21}y_1 - c_{2s}) = 0, \\ (a_{21}y_1 - c_{2s})(1 - x_2) - x_1(a_{11}y_1 - c_{1s}) = 0, \\ (a_{31}x_1 + a_{32}x_2 - c_{1q})(1 - y_1) = 0, \end{cases}$$

Thus,

$$\begin{cases} x_1 = -\frac{a_{32}-c_{1q}}{a_{31}-a_{32}} = -\frac{a-h_1+m_s}{h_1} = 1 - \frac{a+m_s}{h_1}, \\ x_2 = \frac{a_{31}-c_{1q}}{a_{31}-a_{32}} = \frac{a+m_s}{h_1}, \\ y_1 = \frac{c_{1s}-c_{2s}}{a_{11}-a_{21}} = \frac{c_{1s}-c_{2s}}{b+c_{1s}-c_{2s}-d-h_1}. \end{cases} \tag{14}$$

Notice that $x_1 + x_2 = 1$. So, if $x_1, x_2, y_1 \in [0, 1]$, then

$$E_{15} = \left(1 - \frac{a+m_s}{h_1}, \frac{a+m_s}{h_1}, \frac{c_{1s}-c_{2s}}{b+c_{1s}-c_{2s}-d-h_1}, 0 \right) \tag{15}$$

is a feasible equilibrium point.

In the case of $E_{16} = (x_1, x_2, y_1, y_2)$, where $x_1, x_2, y_1, y_2 \in (0, 1)$, that is, all of them are nonzero, they may be found (formally or symbolically) by solving the following nonlinear equation system:

$$\begin{cases} (a_{11}y_1 + a_{12}y_2 - c_{1s})(1 - x_1) - x_2(a_{21}y_1 + a_{22}y_2 - c_{2s}) = 0, \\ (a_{21}y_1 + a_{22}y_2 - c_{2s})(1 - x_2) - x_1(a_{11}y_1 + a_{12}y_2 - c_{1s}) = 0, \\ (a_{31}x_1 + a_{32}x_2 - c_{1q})(1 - y_1) - y_2(a_{41}x_1 + a_{42}x_2 - c_{2q}) = 0, \\ (a_{41}x_1 + a_{42}x_2 - c_{2q})(1 - y_2) - y_1(a_{31}x_1 + a_{32}x_2 - c_{1q}) = 0. \end{cases} \tag{16}$$

The coordinates or components of the solution $(x_1, x_2, y_1, y_2) \in (0, 1)^4$ are formally or symbolically given by

$$\begin{cases} x_1 = -\frac{a_{32}c_{2q}-a_{42}c_{1q}}{a_{31}a_{42}-a_{32}a_{41}} = -\frac{(a-h_1+m_s)c_{2q}-(e+m_s)c_{1q}}{h_1h_2+h_1(e+c_{2q}+m_s)-h_2(a+c_{1q}+m_s)} \\ x_2 = \frac{a_{31}c_{2q}-a_{41}c_{1q}}{a_{31}a_{42}-a_{32}a_{41}} = \frac{(a+m_s)c_{2q}-(e+h_1+m_s)c_{1q}}{h_1h_2+h_1(e+c_{2q}+m_s)-h_2(a+c_{1q}+m_s)} \\ y_1 = -\frac{a_{12}c_{2s}-a_{22}c_{1s}}{a_{11}a_{22}-a_{12}a_{21}} = -\frac{(b-h_2+m_q)c_{2s}-(d+m_q)c_{1s}}{h_1h_2+h_2(d+c_{2s}+m_q)-h_1(b+c_{1s}+m_q)} \\ y_2 = \frac{a_{11}c_{2s}-a_{21}c_{1s}}{a_{11}a_{22}-a_{12}a_{21}} = \frac{(b+m_q)c_{2s}-(d+h_1+m_q)c_{1s}}{h_1h_2+h_2(d+c_{2s}+m_q)-h_1(b+c_{1s}+m_q)} \end{cases} \tag{17}$$

or

$$\begin{cases} x_1 = -\frac{a_{32}-a_{42}-c_{1q}+c_{2q}}{a_{31}-a_{32}-a_{41}+a_{42}} = -\frac{a-h_1-e}{h_1-h_2} \\ x_2 = \frac{a_{31}-a_{41}-c_{1q}+c_{2q}}{a_{31}-a_{32}-a_{41}+a_{42}} = \frac{a-e-h_2}{h_1-h_2} \\ y_1 = -\frac{a_{12}-a_{22}-c_{1s}+c_{2s}}{a_{11}-a_{12}-a_{21}+a_{22}} = -\frac{b-d-h_2}{h_2-h_1} \\ y_2 = \frac{a_{11}-a_{21}-c_{1s}+c_{2s}}{a_{11}-a_{12}-a_{21}+a_{22}} = \frac{b-d-h_1}{h_2-h_1} \end{cases} \tag{18}$$

provided the denominators in the above are nonzero and

$$x_1, x_2, y_1, y_2, x_1 + x_2, y_1 + y_2 \in (0, 1).$$

4. Results

With the aid of the above model and method, we can obtain local asymptotic stability of equilibrium points by the following analysis.

According to the dynamic system theory, the stability problem of the solution of any linear system can be reduced to the stability problem of the zero solution of the corresponding linear homogeneous system. For a linear homogeneous constant coefficient system

$$\dot{x}(t) = Ax(t), x(t) \in R^n, t \in R, \tag{19}$$

where A is an $n \times n$ constant matrix, and the necessary and sufficient conditions such that a zero solution to (19) is local asymptotic stable (LAS, for short) are that the real parts of all the eigenvalues of A are negative [44]. A LAS equilibrium point $x(t)$ is called a stable equilibrium point or a stable solution if it is a solution to the equation

$$Ax(t) = 0, \text{ and } Ax(t), x(t) \text{ is LAS}$$

To analyze the stability at an equilibrium point $E(x_1, x_2, y_1, y_2)$, this study considers the Jacobian matrix at (x_1, x_2, y_1, y_2) . It is given by

$$J = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial y_1} & \frac{\partial f_1}{\partial y_2} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial y_1} & \frac{\partial f_2}{\partial y_2} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial y_1} & \frac{\partial f_3}{\partial y_2} \\ \frac{\partial f_4}{\partial x_1} & \frac{\partial f_4}{\partial x_2} & \frac{\partial f_4}{\partial y_1} & \frac{\partial f_4}{\partial y_2} \end{bmatrix} = \begin{bmatrix} \left[\begin{matrix} (a_{11}y_1 + a_{12}y_2 - c_{1s})(1-2x_1) \\ -x_2(a_{21}y_1 + a_{22}y_2 - c_{2s}) \\ -x_2(a_{11}y_1 + a_{12}y_2 - c_{1s}) \end{matrix} \right] & \begin{bmatrix} -x_1(a_{21}y_1 + a_{22}y_2 - c_{2s}) \\ (a_{21}y_1 + a_{22}y_2 - c_{2s})(1-2x_2) \\ -x_1(a_{11}y_1 + a_{12}y_2 - c_{1s}) \end{bmatrix} & \begin{bmatrix} a_{11}(x_1 - x_1^2) - a_{21}x_1x_2 \\ a_{21}(x_2 - x_2^2) - a_{11}x_1x_2 \\ (a_{31}x_1 + a_{32}x_2 - c_{1q})(1-2y_1) \\ -y_2(a_{41}x_1 + a_{42}x_2 - c_{2q}) \end{bmatrix} & \begin{bmatrix} a_{12}(x_1 - x_1^2) - a_{22}x_1x_2 \\ a_{22}(x_2 - x_2^2) - a_{12}x_1x_2 \\ -y_1(a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ (a_{41}x_1 + a_{42}x_2 - c_{2q})(1-2y_2) \\ -y_1(a_{31}x_1 + a_{32}x_2 - c_{1q}) \end{bmatrix} \end{bmatrix} \tag{20}$$

At $E_1 = (0, 0, 0, 0)$, i.e., $x_1 = x_2 = y_1 = y_2 = 0$, then from (20), the Jacobian becomes

$$J_1 = \begin{bmatrix} -c_{1s} & 0 & 0 & 0 \\ 0 & -c_{2s} & 0 & 0 \\ 0 & 0 & -c_{1q} & 0 \\ 0 & 0 & 0 & -c_{2q} \end{bmatrix} \tag{21}$$

The eigenvalues of J_1 are $-c_{1s}, -c_{2s}, -c_{1q}$, and $-c_{2q}$. They are all negative from (3) and by assumption. Therefore, in this case, the equilibrium $E_1 = (0, 0, 0, 0)$ is LAS.

At $E_2 = (0, 0, 0, 1)$, i.e., $x_1 = x_2 = y_1 = 0, y_2 = 1$, then from (20), the Jacobian becomes

$$J_2 = \begin{bmatrix} a_{12} & 0 & 0 & 0 \\ 0 & a_{22} - c_{2s} & 0 & 0 \\ 0 & 0 & -c_{1q} + c_{2q} & 0 \\ 0 & 0 & c_{1q} & c_{2q} \end{bmatrix}. \tag{22}$$

The eigenvalues of J_2 are

$$\lambda_1 = a_{12}, \lambda_2 = a_{22} - c_{2s} = d + m_q, \lambda_3 = c_{2q} - c_{1q}, \lambda_4 = c_{2q}.$$

Since $\lambda_2 = d + m_q > 0$ and $\lambda_4 = c_{2q} > 0$,

$E_2 = (0, 0, 0, 1)$ is therefore not LAS.

At $E_3 = (0, 0, 1, 0)$, i.e., $x_1 = x_2 = y_2 = 0, y_1 = 1$, then from (19), the Jacobian becomes

$$J_3 = \begin{bmatrix} a_{11} & 0 & 0 & 0 \\ 0 & a_{21} & 0 & 0 \\ 0 & 0 & c_{1q} & 0 \\ 0 & 0 & 0 & c_{1q} + c_{2q} \end{bmatrix}. \tag{23}$$

The eigenvalues of J_3 are

$$\lambda_1 = a_{11}, \lambda_2 = a_{12}, \lambda_3 = c_{1q}, \lambda_4 = c_{1q} + c_{2q}.$$

Since $\lambda_1 = a_{11} = b + c_{1s} + m_q > 0, \lambda_3 = c_{1q} > 0$ and $\lambda_4 = c_{1q} + c_{2q} > 0$,

$E_3 = (0, 0, 1, 0)$ is therefore not LAS.

At $E_4 = (0, 1, 0, 0)$, i.e., $x_1 = y_1 = y_2 = 0, x_2 = 1$, then from (19), the Jacobian becomes

$$J_4 = \begin{bmatrix} c_{2s} - c_{1s} & 0 & 0 & 0 \\ c_{1s} & c_{2s} & 0 & 0 \\ 0 & 0 & a_{32} - c_{1q} & 0 \\ 0 & 0 & 0 & a_{42} - c_{2q} \end{bmatrix}. \tag{24}$$

The eigenvalues of J_4 are

$$\lambda_1 = c_{2s} - c_{1s}, \lambda_2 = c_{2s}, \lambda_3 = a_{32} - c_{1q} = a - h_1 + m_s, \lambda_4 = a_{42} - c_{2q} = e + m_s.$$

Since $\lambda_2 = c_{2s} > 0$ and $\lambda_4 = e + m_s > 0, E_4 = (0, 1, 0, 0)$ is therefore not LAS.

At $E_5 = (1, 0, 0, 0)$, i.e., $x_2 = y_1 = y_2 = 0, x_1 = 1$, then from (20), the Jacobian becomes

$$J_5 = \begin{bmatrix} c_{1s} & c_{2s} & 0 & 0 \\ 0 & c_{1s} - c_{2s} & 0 & 0 \\ 0 & 0 & a_{31} - c_{1q} & 0 \\ 0 & 0 & 0 & a_{41} - c_{2q} \end{bmatrix}. \tag{25}$$

The eigenvalues of J_5 are

$$\lambda_1 = c_{1s}, \lambda_2 = c_{1s} - c_{2s}, \lambda_3 = a_{31} - c_{1q} = a + m_s, \lambda_4 = a_{41} - c_{2q} = e + h_2 + m_s.$$

Since $\lambda_1 = c_{1s} > 0$, $\lambda_3 = a + m_s > 0$, and $\lambda_4 = e + h_2 + m_s > 0$, $E_5 = (1, 0, 0, 0)$ is therefore not LAS.

From the above discussion, we observed that the stabilities of $E_1 \sim E_5$ do not depend on the values of the parameters.

At $E_6 = (1, 0, 1, 0)$, i.e., $x_2 = y_2 = 0$, $x_1 = y_1 = 1$, then from (19), the Jacobian becomes

$$J_6 = \begin{bmatrix} c_{1s} - a_{11} & c_{2s} - a_{21} & 0 & 0 \\ 0 & a_{21} - c_{2s} + c_{1s} - a_{11} & 0 & 0 \\ 0 & 0 & c_{1q} - a_{31} & c_{2q} - a_{41} \\ 0 & 0 & 0 & a_{41} - c_{2q} + c_{1q} - a_{31} \end{bmatrix}. \tag{26}$$

The eigenvalues of J_6 are

$$\begin{cases} \lambda_1 = c_{1s} - a_{11} = -(b + m_q), \\ \lambda_2 = a_{21} - c_{2s} + c_{1s} - a_{11} = d + h_1 + m_q - (b + m_q) = d + h_1 - b, \\ \lambda_3 = c_{1q} - a_{31} = -(a + m_s), \\ \lambda_4 = a_{41} - c_{2q} + c_{1q} - a_{31} = e + h_2 + m_s - (a + m_s) = e + h_2 - a. \end{cases}, \tag{27}$$

Since $\lambda_1 = -(b + m_q) < 0$ and $\lambda_3 = -(a + m_s) < 0$, $E_6 = (1, 0, 1, 0)$ is therefore LAS if and only if

$$\lambda_2 = d + h_1 - b < 0 \text{ and } \lambda_4 = e + h_2 - a < 0. \tag{28}$$

At $E_7 = (1, 0, 0, 1)$, i.e., $x_2 = y_1 = 0$, $x_1 = y_2 = 1$, then from (20), the Jacobian becomes

$$J_7 = \begin{bmatrix} c_{1s} - a_{12} & c_{2s} - a_{22} & 0 & 0 \\ 0 & a_{22} - c_{2s} + c_{1s} - a_{12} & 0 & 0 \\ 0 & 0 & a_{31} - c_{1q} + c_{2q} - a_{41} & 0 \\ 0 & 0 & c_{1q} - a_{31} & -a_{41} + c_{2q} \end{bmatrix}. \tag{29}$$

The eigenvalues of J_7 are

$$\begin{cases} \lambda_1 = c_{2q} - a_{41} = -(e + h_2 + m_s), \\ \lambda_2 = a_{31} - c_{1q} + c_{2q} - a_{41} = a + m_s - (e + h_2 + m_s) = a - e - h_2, \\ \lambda_3 = c_{1s} - a_{12} = h_2 - b - m_q, \\ \lambda_4 = a_{22} - c_{2s} + c_{1s} - a_{12} = d + m_q - (b - h_2 + m_q) = d + h_2 - b. \end{cases}, \tag{30}$$

Since $\lambda_1 = -(e + h_2 + m_q) < 0$, $E_7 = (1, 0, 0, 1)$ is therefore LAS if and only if

$$\lambda_2 = a - e - h_2 < 0, \lambda_3 = h_2 - b - m_q < 0 \text{ and } \lambda_4 = d + h_2 - b < 0. \tag{31}$$

At $E_8 = (0, 1, 0, 1)$, i.e., $x_1 = y_1 = 0$, $x_2 = y_2 = 1$, then from (19), the Jacobian becomes

$$J_8 = \begin{bmatrix} a_{12} - c_{1s} + c_{2s} - a_{22} & 0 & 0 & 0 \\ c_{1s} - a_{12} & -a_{22} + c_{2s} & 0 & 0 \\ 0 & 0 & a_{32} - c_{1q} + c_{2q} - a_{42} & 0 \\ 0 & 0 & c_{1q} - a_{32} & -a_{42} + c_{2q} \end{bmatrix}. \tag{32}$$

The eigenvalues of J_8 are

$$\begin{cases} \lambda_1 = a_{12} - c_{1s} + c_{2s} - a_{22} = b - h_2 + m_q - (d + m_q) = b - h_2 - d, \\ \lambda_2 = -a_{22} + c_{2s} = -(d + m_q), \\ \lambda_3 = a_{32} - c_{1q} + c_{2q} - a_{42} = a - h_1 + m_s - (e + m_s) = a - h_1 - e, \\ \lambda_4 = -a_{42} + c_{2q} = -(e + m_s). \end{cases}, \tag{33}$$

Since $\lambda_2 = -(d + m_q) < 0$ and $\lambda_4 = -(e + m_s) < 0$, $E_8 = (0, 1, 0, 1)$ is therefore LAS if and only if

$$\lambda_1 = b - h_2 - d < 0 \text{ and } \lambda_3 = a - h_1 - e < 0. \tag{34}$$

At $E_9 = (0, 1, 1, 0)$, i.e., $x_1 = y_2 = 0, x_2 = y_1 = 1$, then from (19), the Jacobian becomes

$$J_9 = \begin{bmatrix} a_{11} - c_{1s} + c_{2s} - a_{21} & 0 & 0 & 0 \\ c_{1s} - a_{11} & -a_{21} + c_{2s} & 0 & 0 \\ 0 & 0 & -a_{32} + c_{1q} & c_{2q} - a_{42} \\ 0 & 0 & 0 & a_{42} - c_{2q} + c_{1q} - a_{32} \end{bmatrix}. \tag{35}$$

The eigenvalues of J_9 are

$$\begin{cases} \lambda_1 = -a_{32} + c_{1q} = h_1 - a - m_s, \\ \lambda_2 = c_{1q} - a_{32} + a_{42} - c_{2q} = e + m_s - (a - h_1 + m_s) = e + h_1 - a, \\ \lambda_3 = -a_{21} + c_{2s} = -(d + h_1 + m_q), \\ \lambda_4 = a_{11} - c_{1s} + c_{2s} - a_{21} = b + m_q - (d + h_1 + m_q) = b - d - h_1. \end{cases}, \tag{36}$$

Since $\lambda_3 = -(d + h_1 + m_q) < 0$, $E_9 = (0, 1, 1, 0)$ is therefore LAS if and only if

$$\lambda_1 = h_1 - a - m_s < 0, \lambda_2 = e + h_1 - a < 0 \text{ and } \lambda_4 = b - d - h_1 < 0. \tag{37}$$

In order to save space for the main text, the discussion for the local asymptotic stabilities of equilibrium points $E_{10} \sim E_{16}$ is moved to the Appendix A.

5. Discussion

According to the above analysis, it can be seen that for the equilibrium point $E_1 = (0, 0, 0, 0)$, that is, both parties do not cooperate, the total income of both parties is also 0. This is certainly not a good strategy. From the discussion in Section 4, we know that the stability for each of $E_1 \sim E_5$ and $E_{10} \sim E_{13}$ does not depend on the values of the parameters. That is, E_1 is LAS, but $E_2 \sim E_5$ and $E_{10} \sim E_{13}$ are not LAS regardless of the values of the parameters. Under certain conditions, the equilibrium points $E_6 \sim E_9$ are all LAS.

More detailed discussions about these are given below.

The stabilities of the equilibrium points $E_{14} \sim E_{16}$ are more complicated. It is too complex to discuss their stabilities due to the complex expressions for the corresponding eigenvalues in the cases of E_{14} and E_{15} or no explicit expressions for the eigenvalues in the case of E_{16} . However, for given specific values of parameters, it is easy to determine the existence of the equilibrium points in the form of $E_{14} \sim E_{16}$ and the stability of each of these equilibrium points by finding the eigenvalues of the corresponding Jacobian matrix since these matrices are 4×4 only.

Case 1: The equilibrium point $E_6 = (1, 0, 1, 0)$ means that both parties adopt in-depth cooperation and innovation strategies. The total income of the project created in this case is greater than that from other stable points, and the value created is the greatest. The incomes of both sides are also greater than those from other stable points. The prerequisites for E_6 to be stable are given in (28), that is,

$$a > e + h_2, b > d + h_1,$$

which are equivalent to

$$\alpha(I\phi - c\delta) > h_2, (1 - \alpha)(I\phi - c\delta) > h_1.$$

Here, $(I\phi - c\delta)$ is a constant, so to make the conditions in (49) true, we must either increase the value of α or reduce the benefits of free-riding behavior, h_1 and h_2 .

Therefore, for enterprises, under the condition of ensuring the full allocation of key resources, the allocation ratio α should be set as high as possible so that the benefit of A&R can be made so that the benefits of both parties are greater than the benefits of their respective “free-riding” behaviors. Because under normal circumstances, the enterprise is

in a dominant position in cooperation, the enterprise can also try to reduce the income level h_2 of the “free rider” behavior of the A&R side to reduce the opportunism of the A&R side.

Case 2: The equilibrium point $E_7 = (1, 0, 0, 1)$ refers to a period of game learning between the enterprise and the A&R sides. Among the two types of entities, the enterprise finally adopts the strategy of in-depth cooperation in resource allocation, while the A&R side adopts a strategy of simple cooperation and utilization of resources. The prerequisites for E_7 to be stable are given in (31):

$$a < e + h_1, b > d + h_2, \text{ and } h_2 < b + m_q.$$

These conditions are equivalent to

$$\alpha(I\phi - c\delta) < h_1, (1 - \alpha)(I\phi - c\delta) > h_2.$$

The result of the game is to make the total income of the project reach $I - c + (1 - \alpha)(I\phi - c\delta)$, which is smaller than the income of full cooperation for both sides but greater than the income of simple cooperation between the two sides.

To ensure that the income of the enterprise $(1 - \alpha)(I(1 + \phi) - c(1 + \delta)) - h_2$ is not reduced too much, with the help of the enterprise’s dominant position in the cooperation, the enterprise can try to reduce the A&R side. The income h_2 of the “free rider” behavior is to reduce the opportunism in the cooperation the A&R. In this way, the project income of the enterprise will be close to the income of the in-depth cooperation between the two parties.

Case 3: The equilibrium point $E_8 = (0, 1, 0, 1)$ refers to the evolutionary stability strategy of the enterprise and the A&R side after a period of game learning. Both the enterprise side and the A&R side adopt a simple utilization strategy. The prerequisites are given in (34), i.e.,

$$b < d + h_2 \text{ and } a > e + h_1.$$

These conditions lead to

$$(1 - \alpha)(I\phi - c\delta) < h_2 \text{ and } \alpha(I\phi - c\delta) < h_1.$$

Under these conditions, both the total income of the project and the value created are the smallest. The incomes of the enterprise and the A&R sides are also less than the incomes of other stable points.

Case 4: The equilibrium point $E_9 = (0, 1, 1, 0)$ is reached after a period of game learning between the two parties, at which point the enterprise finally adopts a simple cooperation strategy, while the A&R side adopts a strategy of in-depth cooperation and utilization of resources. The prerequisites are given in (37):

$$b < d + h_1, a > e + h_1, \text{ and } a + m_s > h_1.$$

The implications of these conditions are discussed below.

$$b < d + h_1 \Rightarrow (1 - \alpha)(I\phi - c\delta) < h_1 \text{ (to the enterprise side)}$$

and

$$a > e + h_1 \Rightarrow \alpha(I\phi - c\delta) > h_1 \text{ (to the A&R side)}$$

As for $a + m_s > h_1$, this is satisfactory. Under these conditions, the project’s income reaches in $I - c + \alpha(I\phi - c\delta)$, which is smaller than the income of full cooperation but greater than the income of simple cooperation between the two parties.

In this case, because the enterprise “free-riding” income, h_1 , is less than the incremental input of resources to the A&R side of the net income but greater than the net income to the enterprise; therefore, the allocation ratio α can be set reasonably such that

$$(1 - \alpha)(I\phi - c\delta) < h_1.$$

It is concluded that $\alpha > \frac{1}{2}$. That is, the distribution ratio tends to be in the direction of the A&R side.

6. Management Implications

Therefore, to realize the social benefits and self-interests of both the enterprise and the A&R parties, the enterprise can take the following measures to avoid the “prisoner’s dilemma” and non-cooperation of the two parties, which play an important role in improving the project cooperation and innovation income and the enterprise’s innovation level.

From the results of this article, this study has the following management enlightenments:

Implications 1: Both parties adopt the in-depth cooperation innovation strategy (i.e., the combination strategy of fully allocating resources and making full use of resources) to create a total project revenue greater than other stable points and create the greatest value to society. The income of the enterprise and the income of the A&R sides is also greater than other stable points. It shows that the key resource allocation and utilization performance is the highest at this time. This combination strategy works best. If both parties in the game adopt a conservative cooperation strategy, that is, simple allocation of resources and simple utilization of resources, the key resource allocation and utilization performance is the lowest at this time. The effects of the other two combination strategies are determined by the ratio of the net income of the two parties to the project.

Implication 2: Among the factors that affect resource allocation and utilization performance, in addition to the allocation ratio, free-riding is a major factor. The penalties for non-cooperation and the initial cost of cooperation stipulated in the initial agreement between the two parties in the game can prevent both parties from not cooperating. However, it will not affect the two sides to adopt a conservative cooperation strategy.

Implication 3: For enterprises, when key resources are very tight, it is also feasible to adopt a strategy of partially allocating key resources. However, at this time, the enterprise has to allocate more than half of the project’s revenue to the other party. By implementing these strategies, the interests of both parties can be protected and the smooth implementation of collaborative innovation projects can be promoted.

7. Conclusions

In this article, we have studied the evolutionary game analysis of CIPs based on the allocation and utilization of key resources of the enterprise, where nine scenarios and eighteen strategic combinations of resources allocation have been explored; the explicit expressions of sixteen equilibrium points of the evolutionary game have been derived; detailed analyses of the stabilities of these equilibrium points have been given; and conditions to achieve best benefits for both parties have been discussed.

Among the four cases discussed in Section 5, the first case produces the highest project returns, and the third case has the lowest. Comparing the project income generated by the case with the project income generated by the fourth case, which one is higher depends on which of $(1 - \alpha)(I\phi - c\delta)$ and $\alpha(I\phi - c\delta)$ is larger. Furthermore, it is determined by the size of $(1 - \alpha)$ and α .

For enterprises, except for Case 1 with the highest profit, the second-highest profit is in Case 3 or 4. This depends on whether the benefit of free-riding for a company is greater than the benefit of incremental allocation of key resources. For the A&R side, except for Case 1 with the highest return, the second-highest returns are in Cases 3 and 4. This

depends on whether the benefit of free-riding for the A&R side is greater than the benefit of incremental resource utilization.

Recall that the parameters m_q, c_q are the losses suffered by the enterprise and the A&R when the enterprise adopts the non-cooperation strategy alone, while the parameters m_s, c_s refer to the losses suffered by the enterprise and the A&R when they adopt the non-cooperation strategy alone. These parameters do not appear in the conditional expressions of the stable solutions, indicating that the determination of these stable solutions is not affected by these parameters. This shows that in the agreement, the amount specified by the parameter will not affect the stable strategy (deep cooperation, simple cooperation) finally adopted by the enterprise and the A&R parties. If these parameters are not zero, then they will prevent the players from playing the non-cooperative strategy since at this point, both sides are obtaining 0 or negative.

The four possible stability of equilibrium solutions (stable solutions, in short) and the corresponding benefits/incomes to both sides as well as the total benefits of the project are summarized in Table 2.

Table 2. Stable solutions E6~E9 and the corresponding benefits.

Stable Solutions	Enterprise Income	A&R Income	Total Income for the Project
$E_6 = (1, 0, 1, 0)$	$(1 - \alpha)(I(1 + \phi) - c(1 + \delta))$	$\alpha(I(1 + \phi) - c(1 + \delta))$	$I - c + I\phi - c\delta$
$E_7 = (1, 0, 0, 1)$	$(1 - \alpha)(I(1 + \phi) - c(1 + \delta)) - h_2$	$\alpha(I - c) + h_2$	$I - c + (1 - \alpha)(I\phi - c\delta)$
$E_8 = (0, 1, 0, 1)$	$(1 - \alpha)(I - c)$	$\alpha(I - c)$	$I - c$
$E_9 = (0, 1, 1, 0)$	$(1 - \alpha)(I - c) + h_1$	$\alpha(I(1 + \phi) - c(1 + \delta)) - h_1$	$I - c + \alpha(I\phi - c\delta)$

It can be seen from the analysis in Section 5 that, except for Case 1, neither the enterprise nor the A&R has realized the utilization of the project and the maximization of their interests. This shows that there is a “prisoner’s dilemma” phenomenon in the cooperation of innovative entities.

The article [57] studies a broad class of games in which the optimal mechanism of the subject is static without any meaningful dynamics. The optimal dynamic mechanism, if one exists, simply repeats an optimal mechanism for a single round of problems in each round. The point of this article is that dynamic mechanics are better than static mechanics. For the key resource allocation and utilization problem studied in this paper, every game is a static game, but the repeated game is a dynamic one. It is obvious that both sides of the innovation subject adopt a more rational game behavior (to reach the equilibrium solution) after many game lessons. This also shows that the game dynamic mechanism of key resource allocation and utilization in our paper is better than the static mechanism. This conclusion is consistent with the view given in the article [57].

Restricted by space and available data, this paper does not discuss practical applications of the results obtained in the study. This will be one of the future research topics. Furthermore, in future research, more scenarios and variables can be considered, and the overall asymptotic stability can be further studied to enhance the realistic persuasiveness and validity of the conclusions of the paper.

Although the evolutionary game studied in our paper explores dynamic equilibrium, the matrix of each game is regarded as static. Future research can also consider the change of matrix returns in each game.

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Appendix A

Discussion of local asymptotic stabilities of equilibrium points $E_{10} \sim E_{16}$:

At $E_{10} = (0, x_2, 0, y_2)$ with $x_2 \cdot y_2 \neq 0$, where x_2 and y_2 are given by (5), the Jacobian becomes

$$J_{10} = \begin{bmatrix} a_{12}y_2 - c_{1s} - x_2(a_{22}y_2 - c_{2s}) & 0 & 0 & 0 \\ -x_2(a_{12}y_2 - c_{1s}) & 0 & a_{21}(x_2 - x_2^2) & a_{22}(x_2 - x_2^2) \\ 0 & 0 & (a_{32}x_2 - c_{1q}) & 0 \\ a_{41}(y_2 - y_2^2) & a_{42}(y_2 - y_2^2) & -y_2(a_{32}x_2 - c_{1q}) & 0 \end{bmatrix}. \tag{A1}$$

Denote J_{10} as

$$J_{10} = \begin{bmatrix} c_{11} & 0 & 0 & 0 \\ c_{21} & 0 & c_{23} & c_{24} \\ 0 & 0 & c_{33} & 0 \\ c_{41} & c_{42} & c_{43} & 0 \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries of J_{10} given in (A1). Then, the eigenvalues of J_{10} are given by

$$\lambda_1 = c_{33}, \lambda_4 = c_{11}, \lambda_2 = \sqrt{c_{24}c_{42}}, \lambda_3 = -\frac{1}{2}\sqrt{c_{24}c_{42}}. \tag{A2}$$

Thus, if

$$c_{24}c_{42} \neq 0,$$

then one of the real parts of λ_2 or λ_3 will be positive. Consequently, if

$$c_{24}c_{42} \neq 0,$$

then E_{10} is not LAS. Since

$$\begin{aligned} c_{24} &= a_{22}(x_2 - x_2^2) = (d + c_{2s} + m_q)(x_2 - x_2^2), \\ c_{42} &= a_{42}(y_2 - y_2^2) = (e + c_{2q} + m_s)(y_2 - y_2^2), \\ 0 &< x_2, y_2 < 1, d + c_{2s} + m_q > 0, e + c_{2q} + m_s > 0, \end{aligned}$$

then,

$$c_{24}c_{42} = (d + c_{2s} + m_q)(x_2 - x_2^2)(e + c_{2q} + m_s)(y_2 - y_2^2) > 0. \Rightarrow \lambda_2 = \sqrt{c_{24}c_{42}} > 0.$$

Therefore, E_{10} is not LAS.

At $E_{11} = (0, x_2, y_1, 0)$ with $x_2 \cdot y_1 \neq 0$, where x_2 and y_1 are given by (6), then from (19), the Jacobian becomes

$$J_{11} = \begin{bmatrix} a_{11}y_1 - c_{1s} & 0 & 0 & 0 \\ -x_2(a_{11}y_1 - c_{1s}) & 0 & a_{21}(x_2 - x_2^2) & a_{22}(x_2 - x_2^2) \\ a_{31}(y_1 - y_1^2) & a_{32}(y_1 - y_1^2) & 0 & -y_1(a_{42}x_2 - c_{2q}) \\ 0 & 0 & 0 & a_{42}x_2 - c_{2q} \end{bmatrix}. \tag{A3}$$

Denote J_{11} as

$$J_{11} = \begin{bmatrix} c_{11} & 0 & 0 & 0 \\ c_{21} & 0 & c_{23} & c_{24} \\ c_{31} & c_{32} & 0 & c_{34} \\ 0 & 0 & 0 & c_{44} \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries of J_{11} given in (A3). Then, the eigenvalues of J_{11} are given by

$$\lambda_1 = c_{44}, \lambda_4 = c_{11}, \lambda_2 = \sqrt{c_{23}c_{32}}, \lambda_3 = -\sqrt{c_{23}c_{32}}. \tag{A4}$$

Thus, if

$$c_{23}c_{32} \neq 0,$$

then one of the real parts of λ_2 or λ_3 will be positive. Therefore, if

$$c_{23}c_{32} \neq 0,$$

then E_{11} is not LAS. Since

$$\begin{aligned} c_{23} &= a_{21}(x_2 - x_2^2) = (d + h_1 + c_{2s} + m_q)(x_2 - x_2^2), \\ c_{32} &= a_{32}(y_1 - y_1^2) = (a - h_1 + c_{1q} + m_s)(y_1 - y_1^2), \\ 0 &< x_2, y_1 < 1, d + h_1 + c_{2s} + m_q > 0, \end{aligned}$$

then,

$$\begin{aligned} c_{23}c_{32} &= (d + h_1 + c_{2s} + m_q)(x_2 - x_2^2)(a - h_1 + c_{1q} + m_s)(y_1 - y_1^2) > 0. \\ \Leftrightarrow a - h_1 + c_{1q} + m_s > 0 &\Leftrightarrow a + c_{1q} + m_s > h_1. \end{aligned}$$

Since it is assumed that

$$x_2 = \frac{c_{1q}}{a - h_1 + c_{1q} + m_s} \in (0, 1].$$

then,

$$a - h_1 + c_{1q} + m_s > 0. \Rightarrow c_{23}c_{32} > 0. \Rightarrow \lambda_2 = \sqrt{c_{23}c_{32}} > 0.$$

Therefore, E_{11} is not LAS.

At $E_{12} = (x_1, 0, y_1, 0)$ with $x_1 \cdot y_1 \neq 0$, where x_1 and y_1 are given by (8), then from (19), the Jacobian becomes

$$J_{12} = \begin{bmatrix} 0 & -x_1(a_{21}y_1 - c_{2s}) & a_{11}(x_1 - x_1^2) & a_{12}(x_1 - x_1^2) \\ 0 & (a_{21}y_1 - c_{2s}) & 0 & 0 \\ a_{31}(y_1 - y_1^2) & a_{32}(y_1 - y_1^2) & 0 & -y_1(a_{41}x_1 - c_{2q}) \\ 0 & 0 & 0 & (a_{41}x_1 - c_{2q}) \end{bmatrix}. \tag{A5}$$

Denote J_{12} as

$$J_{12} = \begin{bmatrix} 0 & c_{12} & c_{13} & c_{14} \\ 0 & c_{22} & 0 & 0 \\ c_{31} & c_{32} & 0 & c_{34} \\ 0 & 0 & 0 & c_{44} \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries of J_{12} given in (A5). Then, the eigenvalues of J_{12} are given by

$$\lambda_1 = c_{44}, \lambda_2 = c_{22}, \lambda_3 = \sqrt{c_{13}c_{31}}, \lambda_4 = -\sqrt{c_{13}c_{31}}. \tag{A6}$$

Thus, if

$$c_{13}c_{31} \neq 0,$$

then one of the real parts of λ_3 or λ_4 will be positive. Therefore, if

$$c_{13}c_{31} \neq 0,$$

then E_{12} is not LAS. Since

$$\begin{aligned} c_{13} &= a_{11}(x_1 - x_1^2) = (b + c_{1s} + m_q)(x_1 - x_1^2), \\ c_{31} &= a_{31}(y_1 - y_1^2) = (a + c_{1q} + m_s)(y_1 - y_1^2), \\ 0 &< x_2, y_1 < 1, b + c_{1s} + m_q > 0, \&a + c_{1q} + m_s > 0, \end{aligned}$$

then,

$$c_{13}c_{31} = (b + c_{1s} + m_q)(x_1 - x_1^2)(a + c_{1q} + m_s)(y_1 - y_1^2) > 0. \Rightarrow \lambda_3 = \sqrt{c_{13}c_{31}} > 0.$$

Therefore, E_{12} is not LAS.

At $E_{13} = (x_1, 0, 0, y_2)$ with $x_1 \cdot y_2 \neq 0$, where x_1 and y_2 are given by (10), then from (19), the Jacobian becomes

$$J_{13} = \begin{bmatrix} 0 & -x_1(a_{22}y_2 - c_{2s}) & a_{11}(x_1 - x_1^2) & a_{12}(x_1 - x_1^2) \\ 0 & (a_{22}y_2 - c_{2s}) & 0 & 0 \\ 0 & 0 & (a_{31}x_1 - c_{1q}) & 0 \\ a_{41}(y_2 - y_2^2) & a_{42}(y_2 - y_2^2) & -y_2(a_{31}x_1 - c_{1q}) & 0 \end{bmatrix}. \tag{A7}$$

Denote J_{13} as

$$J_{13} = \begin{bmatrix} 0 & c_{12} & c_{13} & c_{14} \\ 0 & c_{22} & 0 & 0 \\ 0 & 0 & c_{33} & 0 \\ c_{41} & c_{42} & c_{43} & 0 \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries of J_{13} given in (A6). Then, the eigenvalues of J_{13} are given by

$$\lambda_1 = c_{33}, \lambda_2 = c_{22}, \lambda_3 = \sqrt{c_{14}c_{41}}, \lambda_4 = -\sqrt{c_{14}c_{41}}. \tag{A8}$$

Thus, if

$$c_{14}c_{41} \neq 0,$$

then one of the real parts of λ_2 or λ_3 will be positive. Hence, if

$$c_{14}c_{41} \neq 0,$$

then E_{13} is not LAS. Since

$$\begin{aligned} c_{14} &= a_{12}(x_1 - x_1^2) = (b - h_2 + c_{1s} + m_q)(x_1 - x_1^2), \\ c_{41} &= a_{41}(y_2 - y_2^2) = (e + h_2 + c_{2q} + m_s)(y_2 - y_2^2), \\ 0 &< x_2, y_1 < 1, e + h_2 + c_{2q} + m_s > 0, e + c_{2q} + m_s > 0, \end{aligned}$$

so,

$$\begin{aligned} c_{24}c_{42} &= (d + h_1 + c_{2s} + m_q)(x_2 - x_2^2)(a - h_1 + c_{1q} + m_s)(y_1 - y_1^2) > 0. \\ \Leftrightarrow b - h_2 + c_{1s} + m_q &> 0 \Leftrightarrow b + c_{1s} + m_s > h_2. \end{aligned}$$

Since it is assumed that

$$y_2 = \frac{c_{1s}}{b - h_2 + c_{1s} + m_q} \in (0, 1].$$

Accordingly,

$$b - h_2 + c_{1s} + m_q > 0. \Rightarrow c_{14}c_{41} > 0. \Rightarrow \lambda_3 = \sqrt{c_{14}c_{41}} > 0.$$

Therefore, E_{13} is not LAS.

At $E_{14} = (x_1, 0, y_1, y_2)$ with $x_1 \cdot y_1 \cdot y_2 \neq 0$, where x_1, y_1 and y_2 are given by (12), then from (20), the Jacobian becomes

$$\begin{aligned}
 J_{14} &= \begin{bmatrix} (a_{11}y_1 + a_{12}y_2 - c_{1s})(1 - 2x_1) & -x_1(a_{21}y_1 + a_{22}y_2 - c_{2s}) & a_{11}(x_1 - x_1^2) & a_{12}(x_1 - x_1^2) \\ 0 & \begin{bmatrix} a_{21}y_1 + a_{22}y_2 - c_{2s} \\ -x_1(a_{11}y_1 + a_{12}y_2 - c_{1s}) \end{bmatrix} & 0 & 0 \\ a_{31}(y_1 - y_1^2) - a_{41}y_1y_2 & a_{32}(y_1 - y_1^2) - a_{42}y_1y_2 & \begin{bmatrix} (a_{31}x_1 - c_{1q})(1 - 2y_1) \\ -y_2(a_{41}x_1 - c_{2q}) \end{bmatrix} & -y_1(a_{41}x_1 - c_{2q}) \\ a_{41}(y_2 - y_2^2) - a_{31}y_1y_2 & a_{42}(y_2 - y_2^2) - a_{32}y_1y_2 & -y_2(a_{31}x_1 - c_{1q}) & \begin{bmatrix} (a_{41}x_1 - c_{2q})(1 - 2y_2) \\ -y_1(a_{31}x_1 - c_{1q}) \end{bmatrix} \end{bmatrix} \\
 &= \begin{bmatrix} (a_{11}y_1 + a_{12}y_2 - c_{1s})(-x_1) & -x_1(a_{21}y_1 + a_{22}y_2 - c_{2s}) & a_{11}(x_1 - x_1^2) & a_{12}(x_1 - x_1^2) \\ 0 & \begin{bmatrix} a_{21}y_1 + a_{22}y_2 - c_{2s} \\ -x_1(a_{11}y_1 + a_{12}y_2 - c_{1s}) \end{bmatrix} & 0 & 0 \\ a_{31}(y_1 - y_1^2) - a_{41}y_1y_2 & a_{32}(y_1 - y_1^2) - a_{42}y_1y_2 & (a_{31}x_1 - c_{1q})(-y_1) & -y_1(a_{41}x_1 - c_{2q}) \\ a_{41}(y_2 - y_2^2) - a_{31}y_1y_2 & a_{42}(y_2 - y_2^2) - a_{32}y_1y_2 & -y_2(a_{31}x_1 - c_{1q}) & (a_{41}x_1 - c_{2q})(-y_2) \end{bmatrix}.
 \end{aligned} \tag{A9}$$

Denote J_{14} as

$$J_{14} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ 0 & c_{22} & 0 & 0 \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries J_{14} given in (A9).

At $E_{15} = (x_1, x_2, y_1, 0)$ with $x_1 \cdot x_2 \cdot y_1 \neq 0$, where x_1, x_2 and y_1 are given by (14), then from (20), the Jacobian becomes

$$\begin{aligned}
 J_{15} &= \begin{bmatrix} \begin{bmatrix} (a_{11}y_1 - c_{1s})(1 - 2x_1) \\ -x_2(a_{21}y_1 - c_{2s}) \end{bmatrix} & -x_1(a_{21}y_1 - c_{2s}) & a_{11}(x_1 - x_1^2) - a_{21}x_1x_2 & a_{12}(x_1 - x_1^2) - a_{22}x_1x_2 \\ -x_2(a_{11}y_1 - c_{1s}) & \begin{bmatrix} (a_{21}y_1 - c_{2s})(1 - 2x_2) \\ -x_1(a_{11}y_1 - c_{1s}) \end{bmatrix} & a_{21}(x_2 - x_2^2) - a_{11}x_1x_2 & a_{22}(x_2 - x_2^2) - a_{12}x_1x_2 \\ a_{31}(y_1 - y_1^2) & a_{32}(y_1 - y_1^2) & \begin{bmatrix} (a_{31}x_1 + a_{32}x_2 - c_{1q})(1 - 2y_1) \\ 0 \end{bmatrix} & \begin{bmatrix} -y_1(a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ (a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ -y_1(a_{31}x_1 + a_{32}x_2 - c_{1q}) \end{bmatrix} \end{bmatrix} \\
 &= \begin{bmatrix} (a_{11}y_1 - c_{1s})(-x_1) & -x_1(a_{21}y_1 - c_{2s}) & a_{11}(x_1 - x_1^2) - a_{21}x_1x_2 & a_{12}(x_1 - x_1^2) - a_{22}x_1x_2 \\ -x_2(a_{11}y_1 - c_{1s}) & (a_{21}y_1 - c_{2s})(-x_2) & a_{21}(x_2 - x_2^2) - a_{11}x_1x_2 & a_{22}(x_2 - x_2^2) - a_{12}x_1x_2 \\ a_{31}(y_1 - y_1^2) & a_{32}(y_1 - y_1^2) & (a_{31}x_1 + a_{32}x_2 - c_{1q})(-y_1) & -y_1(a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ 0 & 0 & 0 & \begin{bmatrix} (a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ -y_1(a_{31}x_1 + a_{32}x_2 - c_{1q}) \end{bmatrix} \end{bmatrix}.
 \end{aligned} \tag{A10}$$

Denote J_{15} as

$$J_{15} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ 0 & 0 & 0 & c_{44} \end{bmatrix},$$

where the entries c'_{ij} s are equal to the corresponding entries J_{15} given in (A9). Although there are formal expressions for the eigenvalues of both J_{14} and J_{15} , these expressions are too complicated and too long to be given here (a few pages in each case). Thus, it is difficult to discuss whether E_{14} and E_{15} are LAS or not in a general setting for the parameters. However, the stability can be found for given parameters.

At $E_{16} = (x_1, x_2, y_1, y_2)$ where $x_1, x_2, y_1, y_2 \in (0, 1)$ and are given by (17) or (18). Then from (20), its Jacobian J_{16} is given by (20).

$$J_{16} = \begin{bmatrix} (a_{11}y_1 + a_{12}y_2 - c_{1s})(-x_1) & -x_1(a_{21}y_1 + a_{22}y_2 - c_{2s}) & a_{11}(x_1 - x_1^2) - a_{21}x_1x_2 & a_{12}(x_1 - x_1^2) - a_{22}x_1x_2 \\ -x_2(a_{11}y_1 + a_{12}y_2 - c_{1s}) & (a_{21}y_1 + a_{22}y_2 - c_{2s})(-x_2) & a_{21}(x_2 - x_2^2) - a_{11}x_1x_2 & a_{22}(x_2 - x_2^2) - a_{12}x_1x_2 \\ a_{31}(y_1 - y_1^2) - a_{41}y_1y_2 & a_{32}(y_1 - y_1^2) - a_{42}y_1y_2 & (a_{31}x_1 + a_{32}x_2 - c_{1q})(-y_1) & -y_1(a_{41}x_1 + a_{42}x_2 - c_{2q}) \\ a_{41}(y_2 - y_2^2) - a_{31}y_1y_2 & a_{42}(y_2 - y_2^2) - a_{32}y_1y_2 & -y_2(a_{31}x_1 + a_{32}x_2 - c_{1q}) & (a_{41}x_1 + a_{42}x_2 - c_{2q})(-y_2) \end{bmatrix} \tag{A11}$$

There are no explicit formal expressions for the eigenvalues of J_{16} in this case. Thus, once more, it is difficult to discuss whether E_{16} is LAS or not in a general setting for the parameters. However, since J_{16} is a 4×4 real matrix, its eigenvalues can be found for given numerical values of its entries although some eigenvalues may be complex numbers. Therefore, the stability of E_{16} can be determined for given parameters.

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