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Evolutionary Game Analysis on Operation Mode Selection of Big-Science Infrastructures

Zhenyu Huang

College of Humanities and Social Sciences, Harbin Engineering University, Harbin 150001, China; huangzy@hrbeu.edu.cn

Abstract: As big-science infrastructures (BSIs) become the new infrastructure to support the construction of strong science and technology in China, how to choose an operation mode that is more conducive to achieving the construction goals of BSIs has become a current focus issue. The existing literature focuses more on the governance relationship between BSIs and universities or research institutes, while the important role of government has not yet been thoroughly analyzed. This study argues that government plays a fundamental role in the selection of operation modes for BSIs. Therefore, this study builds an evolutionary game model between the government and the contractor based on the perspective of asset specificity by analyzing the practical basis for the strategic choices of the government and the contractor for the operation of BSIs. The model is numerically simulated and analyzed. The research results indicate that the government's decisions on operation strategies, outsourcing strategies, and the combination of the two significantly affect the strategic choices of the contractor, thereby affecting whether the government can obtain the value of asset specificity of BSIs. The government's choice of the "independent operation" strategy or the combination "dependent operation + controlled outsourcing" strategy is more conducive to encouraging the contractor to choose the "cooperation" strategy for producing specific value for BSIs. The main contribution of this study is to clarify that the allocation of the government control right is the key factor in obtaining the value of asset specificity of BSIs.

Keywords: big-science infrastructure; operation mode; asset specificity; evolutionary game analysis; outsourcing strategy; causal loop diagram

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1. Introduction

Big-science infrastructures (BSIs, also known as Major Science and Technology Infrastructure or Large Research Infrastructure) have become the new infrastructure to support the construction of strong science and technology and economic and social development in China [1,2]. Scientific research organizations established on BSIs are often named "Big Science organizations" [3], such as the European Organization for Nuclear Research (CERN), Lawrence Berkeley National Laboratory of the United States, High Energy Accelerator Research Institute of Japan, Beijing Electron-Positron Collider National Laboratory of China, etc. According to the existing literature, there are obvious differences in the management research topics of BSIs in China before and after China's 13th Five-Year Plan period. Before China's 13th Five-Year Plan, the operation mode of BSIs was the main research topic. Among them, the contract outsourcing model of GOCO (government-owned, contractor-operation) in the United States and the management system or organizational structure of BSIs under this model are the hot topics of concern [4,5]. If the BSIs are operated by an existing research institute or university, it is called "dependent-operation mode". If BSIs are operated by a specialized independent organization (such as CERN), it is called "independent-operation mode" [6]. After China's 13th Five-Year Plan, as China proposed and implemented the decision of building comprehensive national science centers in places where BSIs are clustered, research topics began to shift to promoting industrial technology innovation based on BSIs [7–10]. Accordingly, innovation systems such as the Havel Science Park in the UK or Grenoble Science City in France became the topics of concern [11–13].

Although the management research topics after the shift meet China's new requirements for the construction objectives of BSIs, it also leads to the delay of the research on the operation mode of BSIs to a certain extent. In particular, some management problems caused by dependent-operation mode have not been effectively solved. For example, some studies have found that under dependent-operation mode, other scientific research institutions within the same organization will compete for and consume resources invested in the construction and operation of BSIs [14,15]. This problem does not only occur in China. For more than a decade from the 1980s to the 1990s, the US government believed that the dependent-operation mode led to high levels of waste, mismanagement, academic misconduct and deviant goals in national laboratories [16,17]. When we investigated the construction of comprehensive national science centers in Shanghai and Shenzhen in China during the year 2019–2022, we found that the choice of the operation mode of BSIs was still a major concern in China.

Although some literature has analyzed the causes of the governance problems of the dependent-operation model from the perspective of transaction cost theory [18], it is mostly limited to the governance relationship between big-science infrastructure and universities or research institutes, while the important role of "government" has not been deeply analyzed. We believe that the role of government cannot be ignored. Faced with the problem of relying on operation, the United States Department of Energy put an end to the long-term monopoly of large scientific devices by an institution and established an independent operation mode through the implementation of the "management right bidding system" in 1996. For instance, big science organizations such as Brookhaven National Laboratory, Los Alamos National Laboratory, Lawrence Livermore National Laboratory and Argonne National Laboratory belong to the independent operation mode [5,6,18]. The two core research questions of this study are thus derived as follows.

(1) What is the role of government decision in the selection of the operation mode for BSIs?
(2) Which operation mode is more conducive to realizing the special value of BSIs?

Following the transaction cost theory of existing studies, this study will answer the above questions by using evolutionary game analysis. First of all, as pointed out by the existing studies on transaction cost theory, under the constraint of bounded rationality, the appropriate governance structure is often difficult to be adopted at the very beginning. Instead, the governance structure is promoted to evolve along the path of minimizing the transaction cost through continuous learning [19,20]. Secondly, evolutionary game analysis is an effective tool to analyze group decision making, which can reveal the group learning mechanism and the evolutionary path of behavioral decision making from the perspective of bounded rationality [21]. Thus, evolutionary game analysis can provide a more general explanation for the relationship between government decision making and the choice of operation mode for BSIs. Finally, this study will further simulate the dynamic evolution mechanism of the relationship between government decisions and the operation mode of big-science infrastructure, and tries to help the government explore an operation mode conducive to the development of BSIs under the background of promoting industrial technological innovation based on BSIs.

2. Evolutionary Game Strategy Analysis

BSIs are a combination of engineering and science, with high construction difficulty, long construction time, a wide range of technological fields, etc. BSIs not only require a high-level industrial foundation, but also require high construction costs (e.g., a single infrastructure often requires an investment of billions or even tens of billions of RMB yuan) [22]. This makes the government the main investor, and the BSIs are therefore committed to clear strategic missions and scientific objectives [23]. Although the government is a major investor in BSIs, it is often necessary to obtain professional operation services provided by the contractors through outsourcing, and thus achieve the purpose of government investment.

From the perspective of the transaction cost theory, the basic assumptions of human cognition and behavior are bounded rationality and opportunism [24]. As the core research dimension of transaction cost theory, asset specificity refers to the extent to which assets can be reused for different purposes and used by different users without sacrificing production value [25]. According to transaction cost theory, investment with high asset specificity is more suitable to adopt an integrated governance structure, emphasizing a centralized power mechanism [26]. BSIs are assets with high specialty. When the government needs professional services but cannot directly operate BSIs through integrated governance, the integrated governance structure shifts to the allocation of control rights by the government over BSIs. For example, the government can achieve effective governance of BSIs by setting operational goals and punishing contractors for deviating from operational goals [18].

However, the government's allocation of control rights to the BSIs is not cost-free. The opportunistic behavior of contractors cannot be ignored, which makes it an evolutionary game problem whether the government and contractors can establish an effective outsourcing relationship for BSIs. This evolutionary game problem can be expressed as that through multiple games between the government and contractors running BSIs, the high-yield outsourcing strategy will gradually replace the low-yield outsourcing strategy and eventually form an evolutionary equilibrium strategy.

2.1. Government's Optional Combination Strategies

In this study, the government can be either the central government or the local governments [23]. On the one hand, in China's institutional environment, both the central and local governments can serve as representatives of the country [27]. On the other hand, in the early construction of large science installations, the central government was the main investor of BSIs, while since the 13th Five Year Plan, local governments with strong financial strength (such as Shenzhen in Guangdong Province) have become investors in the construction and operation of BSIs [28].

There are two kinds of strategies for the government. On the one hand, reviewing the evolution of the organization mode of BSIs and the existing research literature, it is found that dependent operation and independent operation are the two main operation modes, and also the primary strategy combination of the government. On the other hand, when outsourcing the operation and management tasks of BSIs, the optional strategy of the government is "uncontrolled outsourcing" and "controlled outsourcing", and the generation of these two strategies also has a practical basis.

(1) Operation strategies: Dependent Operation and Independent Operation

Dependent operation first arose in the United States. Because American universities are deeply involved in the formation of national laboratories, and some national laboratories are developed from university laboratories, the U.S. government chose some of the universities (such as the university of Chicago, university of California, Berkeley, and Stanford university, etc.) as the initial contractors [5,18].

Independent operation refers to the establishment of a special operation management agency for BSIs, which has been adopted in many countries. Since the 1980s, some national laboratories under the U.S. Department of Energy have shifted from being operated by universities to being operated by independent management companies. For example, the contract of Brookhaven National Laboratory was changed from the Union of Universities to Brookhaven Science Alliance LLC. in 1998, and the contract for Argonne National Laboratory was changed from the University of Chicago to the University of Chicago Argonne LLC. in 2007 [18]. Germany adopts the mode of "government ownership and government management", with Helmholtz Federation as the specialized organization for the management and operation of BSIs [29]. When Japan initially established big science organization, it also adopted the mode of "dependent operation". However, after the reform of administrative legal persons in 2002, its main public scientific research institutions (such as the National Institute of High Energy Physics of Japan, which owns BSIs such as the pulsed neutron hash device and the synchrotron radiation device) have adopted the mode of "independent operation" with Independent Administrative Institution [30].

For a long time, China has mainly adopted the dependent operation mode, that is, depending on universities or depending on scientific research institutes under the Chinese Academy of Sciences to operate BSIs. Although there has always been related academic field and practice field researchers called for the establishment independent operation mode, under the current administrative system in China the resources possessed by an organization are closely related to the organization's discourse power and promotion of administrative level, which makes it difficult for the organization to have expansion incentives and spontaneously generate reform momentum [18]. With the advancement of the construction of comprehensive national science centers, the government has begun to participate in the operation and management of BSIs. For example, Beijing and Hefei have established the Huairou Science City Management Committee and the Binhu Science City Management Committee, respectively, Shanghai has established the Office for Promoting the Construction of Science and Technology Innovation Centers, Shenzhen has established Guangming District Science City Development and Construction Bureau, etc. [31]. These institutions are directly responsible for the planning, coordination, construction, and operation of BSIs, and the exploration and practice of "independent operation" are thus launched in China.

(2) Outsourcing strategies: controlled outsourcing and uncontrolled outsourcing

From the perspective of the transaction cost theory, in order to avoid the low efficiency of "exclusive possession" and achieve the scientific mission and strategic goals of BSIs, the choice of "controlled outsourcing" strategy is a decision in line with the characteristics of asset specificity of BSIs. However, under the constraints of bounded rationality, the government cannot predict the opportunistic behavior of the contractor in advance, and the selection process of outsourcing strategy becomes a process of experiment and learning. For example, when the United States initially relied on universities to operate BSIs, it adopted "uncontrolled outsourcing", resulting in the long-term "exclusive possession" of big science organizations by their supporting institutions (such as the relationship between the University of California and Los Alamos National Laboratory) [18]. Until the 1980s, because of frequent problems of relying on universities to operate BSIs, the US Department of Energy issued the "management right bidding system" for national laboratories, and the allocation of control after the event promoted the emergence of the independent operation mode [18].

China also has a similar situation. Before China's 13th Five-Year Plan, when a BSI was "settled" in an institution, it was often "exclusively owned" by this institution. The construction of a comprehensive national science center has put the government's control over the allocation of large scientific facilities on the agenda. For example, during our research at Zhangjiang Laboratory in Shanghai in 2019, we found that the previous approach of "who leads the construction makes who responsible for the operation and management" was replaced by "separation of construction and use", i.e., the construction task of a BSI is contracted to a certain university or Chinese Academy of Sciences, and the operation and management tasks after completion are contracted to Shanghai Higher Research Institute. In addition, we also found during the research process that Shenzhen is currently exploring a governance model that can change the contracting objects according to the needs of the assessment results. For example, Shenzhen assesses the operation and management institutions of BSIs based on whether they have made contributions to industrial development. Failure to pass the assessment may result in accountability or even change of management institutions. This is an important manifestation of the current control over the operation of BSIs by the Chinese government.

In summary, based on the analysis of operation and outsourcing strategies, the government mainly has four combination strategies:

- Combination strategy 1: dependent operation and uncontrolled outsourcing;
- Combination strategy 2: dependent operation and controlled outsourcing;
- Combination strategy 3: independent operation and uncontrolled outsourcing;
- Combination strategy 4: independent operation and uncontrolled outsourcing.

2.2. Contractor's Optional Combination Strategies

In this study, the contractor refers to an institution that can undertake the operation tasks of BSIs [23]. This type of institution includes both universities or research institutions that existed before BSIs, and specialized institutions established due to the operational needs of BSIs (see Sections 1 and 2.1). For the contractor, the alternative strategy of the contractor is mainly "cooperation" and "noncooperation".

In the face of the operation task of the BSIs outsourced by the government, the contractor can choose to cooperate with the government, commit to the goal set by the government, and realize the special value of the BSIs. However, under the opportunism, it is not necessarily the optimal decision of the contractor to achieve the task objectives of the big-science infrastructure operation outsourced by the government. The contractor may also choose to realize other objectives, or even produce no value in some extreme cases. In this case, the contractor will choose the "noncooperation" strategy.

The choice of the "noncooperation" strategy has a practical basis. In the situation where the operation and management tasks of BSIs are inevitably outsourced, due to the strong professionalism of scientific research and the high degree of information asymmetry, the contractor has a high degree of discretion and information control ability [32]. In this case, the government's assessment and control of whether the contractor achieves the expected operating objectives can often only rely on the final result, which leads to the possibility that the task objectives will be distorted or flexibly executed [33]. Although the task objectives that have been distorted or flexibly executed (e.g., the contractor does not produce specialized value from BSIs) deviate from the government's set goals, the contractor has its own goal orientation, such as institutional ranking, government funding, resource control, competitiveness improvement, a larger number of published papers, etc. These contents are not necessarily related to the specific asset characteristics and strategic goals carried by BSIs [18]. As pointed out earlier, there have been management issues both domestically and internationally, such as the depletion of BSI resources by contractors, the dispersion of research investment and energy, academic misconduct, difficulty in facility sharing, deviation from operational objectives, etc.

3. Evolutionary Game Model

3.1. Evolutionary Game Model Assumptions and Payoff Matrix

By analyzing the realistic basis for the formation of the optional strategies of the government and the contractor, we make the following assumptions about the game situation of both parties:

Assumption 1. *In the outsourcing of operational tasks for BSIs, the subjects of the evolutionary game are bounded rational. It is a learning process for the government to allocate control rights effectively, and the contractors are opportunistic, which leads to the failure to find an optimal strategy at the initial stage of the game. Instead, they constantly adjust their strategies in the process of the game, focusing on their respective goal of maximizing revenue.*

Assumption 2. *In this game, the government has two types of strategy sets, namely (dependent operation, independent operation) and (uncontrolled outsourcing, controlled outsourcing). The two types of strategies are independent of each other. The strategy set of the contractor is (cooperation, noncooperation). Where, the probability that the government chooses "dependent operation" strategy is x, and the probability that the government chooses "independent operation" strategy is $1 - x$, $x \in [0,1]$. The probability that the government chooses the "uncontrolled outsourcing" strategy is y, and the probability that the government chooses the "controlled outsourcing" strategy* *is* $1 - y$, $y \in [0,1]$. *The probability that the contractor chooses the "cooperation" strategy is* z, *and the probability that the contractor chooses the "noncooperation" strategy is* $1 - z$, $z \in [0,1]$.

Assumption 3. *Different initial strategy combinations adopted by the government and the contractor will produce different initial returns. Meanwhile, from the perspective of transaction cost theory, strategy selection and combination are actually institutional choices, so different institutional costs will be generated.*

Parameters involved in the evolutionary game model are shown in Table 1. The analysis of parameter setting is as follows:

1. The government's choice of operation mode. On the one hand, as long as the government invests in the construction of BSIs, no matter what strategy it chooses, it can always obtain the basic income G, because the construction of BSIs is a kind of fixed asset investment, which can bring a certain pulling effect on the society and economy [34,35]. On the other hand, therefore, (1) when the government chooses the dependent operation strategy, it needs to pay the basic institutional cost P_1 (such as formulating the dependent operation process and selecting the dependent operation contractor, etc.); (2) when the government chooses the independent operation strategy, it needs to pay the institutional cost P_2 of the strategy selection.
2. The government's choice of outsourcing strategy:
   (1) If the government chooses uncontrolled outsourcing, the control cost paid is 0, and the government will pay according to the acceptance result. For the convenience of analysis, it is assumed that the special revenue of BSIs obtained in each acceptance period is R. When the government obtains R, it pays the outsourcing price S_1. But if the government does not obtain R, the outsourcing price paid is 0.
   (2) If the government chooses to control outsourcing, under the dependent operation, it needs to pay the control cost C_1 (such as the process supervision cost, assessment cost, incentive cost, sanctions cost, etc.), and under the independent operation, the control cost C_2 will be paid. The outsourcing price S_2 is paid when the dedicated asset revenue R is obtained, otherwise the outsourcing price 0 is paid. It should be pointed out that different operation modes will inevitably produce different control costs, and different outsourcing strategies will also produce different outsourcing prices. If the control costs are equal to the outsourcing price, the analysis of strategy selection is meaningless.
3. The strategic selection of the contractor. In the dependent operation mode, the contractor is an existing scientific research institution (such as a university, enterprise or research institute) with its own goals to pursue.
   (1) If the contractor chooses cooperation: (a) when the government chooses the uncontrolled outsourcing strategy, it needs to pay the cost E to generate special asset revenue R for BSIs, and then it can pay S_1 for the price under uncontrolled outsourcing. (b) When the government chooses a controlled outsourcing strategy, the contractor can obtain payment S_2 for the price under controlled outsourcing and an incentive payment b from the government.
   (2) If the contractor chooses noncooperation: (a) When the government chooses uncontrolled outsourcing strategy, the contractor pays the cost e to produce the non-special asset revenue s of the BSIs, in which the non-special asset revenue s is appropriated by the contractor. (b) When the government chooses the controlled outsourcing strategy, the government will punish the contractor for failing to comply with the contract. Therefore, the contractor will not only pay the cost e to produce the non-special asset revenues, but also face the loss L caused by the government's punishment.

Table 1. Parameter description of the evolutionary game model.

Game Subjects	Parameters	Meaning
Government	x	The probability of choosing the "dependent operation" strategy
	y	The probability of choosing the "uncontrolled outsourcing" strategy
	P_1	The institutional cost of choosing the "dependent operation" strategy
	P_2	The institutional cost of choosing the "independent operation" strategy
	S_1	Price cost of an uncontrolled outsourcing strategy
	S_2	Price cost of a controlled outsourcing strategy
	C_1	Cost control under operation-dependent
	C_2	Cost control under independent operation
	G	Basic income from investment in building big-science infrastructure
	R	The contractor selects the special proceeds under the cooperation strategy
Contractor	z	The probability of choosing the cooperative strategy
	E	Costs under cooperative strategy
	e	Costs under the "operation-dependent + noncooperation" strategy
	s	The benefits of the "operation-dependent + noncooperation" strategy
	S_1	Government payments for revenue derived from the production of big-science infrastructure under uncontrolled outsourcing
	S_2	Government payments received for dedicated proceeds of production of big-science infrastructure under controlled outsourcing
	b	Incentive payments under the "controlled outsourcing + collaboration" strategy
	L	Penalty payment for non-production of special revenue from big-science infrastructure

In the independent operation mode, the contractor is a specialized organization for the operation and management of BSIs. This kind of contractor exists due to contracting for the operation and management tasks of BSIs, and disappears with the end of the operation and management tasks of BSIs. Therefore, different from the dependent operating contractor, the independent operating contractor has no goal of its own to pursue, it either produces the special value R of BSIs and then obtains the price payment S_1 under uncontrolled outsourcing or obtains the price payment S_2 and reward b under controlled outsourcing, or produces nothing. In other words, if the contractor chooses not to cooperate, then (a) under uncontrolled outsourcing, the contractor pays 0 cost and generates 0 revenue, or (b) under controlled outsourcing, in addition to paying 0 costs and producing 0 benefits, there will also be losses L caused by government punishments.

It is worth further explaining about the contractor's strategic choices that different penalty losses L are not set based on different operating modes in this study. On the one hand, it is conducive to simplifying the analysis; On the other hand, according to our model assumption, even for the same loss, contractors under different operating modes will have different perceptions. If the government cancels the contracting rights of the contractor for the operation and management of BSIs, the contractor under the dependent operation mode can still exist, but the contractor under the independent operation mode will also disappear. For example, the current contractor of Argonne National Laboratory is "UChicago Argonne LLC.". When the United States Department of Energy changes the contractor of Argonne National Laboratory, this will not affect the existence of the University of Chicago, but "UChicago Argonne LLC." will face the risk of cancellation. In addition, we have also made a similar setting for reward b, on the one hand, the corresponding "R" remains unchanged, and on the other hand, because S_1 and S_2 can accommodate payment changes under different outsourcing strategies, b reflects the government's incentive control. For the government, b and L come from the control costs provided by the government, therefore, the value of "$b + L$" is greater than 0 (if equal to 0, the meaning of control cannot be reflected), but less than or equal to C_1 and C_2, respectively.

According to the above assumptions, the payment income matrix of the government and the contractor can be obtained (see Tables 2 and 3).

Table 2. Payoff matrix of the government's choice of dependent operation (x).

Strategy Selection		**Contractor**	
		Cooperation (z)	**Noncooperation ($1-z$)**
Government	Uncontrolled outsourcing (y)	$(G-P_1, R-S_1, S_1-E)$	$(G-P_1, 0, s-e)$
	Controlled outsourcing ($1-y$)	$(G-P_1, R-S_2-C_1, S_2+b-E)$	$(G-P_1, -C_1, s-e-L)$

Table 3. Payoff matrix of government choosing independent operation ($1-x$).

Strategy Selection		**Contractor**	
		Cooperation (z)	**Noncooperation ($1-z$)**
Government	Uncontrolled outsourcing (y)	$(G-P_2, R-S_1, S_1-E)$	$(G-P_2, 0, 0)$
	Controlled outsourcing ($1-y$)	$(G-P_2, R-S_2-C_2, S_2+b-E)$	$(G-P_2, -C_2, -L)$

3.2. The Replication Dynamic Equation of Evolutionary Game Model

When the government chooses the strategy of "dependent operation" and "independent operation", the expected revenue is U_{11} and U_{12}, respectively, and the average expected revenue is U_1. When the government chooses the strategy of "uncontrolled outsourcing" and "controlled outsourcing", the expected revenue is U_{21} and U_{22}, respectively, and the average expected revenue is U_2. When the contractor chooses the "cooperation" and "noncooperation" strategy, the expected return is U_{31} and U_{32}, respectively, and the average expected return is U_3.

According to the payment income matrix in Tables 2 and 3, when the government chooses the "dependent operation" strategy, its expected income is

$$U_{11} = (G-P_1)yz + (G-P_1)(1-y)z + (G-P_1)y(1-z) + (G-P_1)(1-y)(1-z) = G-P_1 \quad (1)$$

When the government chooses the "independent operation" strategy, its expected revenue is

$$U_{12} = (G-P_2)yz + (G-P_2)(1-y)z + (G-P_2)y(1-z) + (G-P_2)(1-y)(1-z) = G-P_2 \quad (2)$$

Therefore, the average revenue of the government under the mixed strategy (dependent operation, independent operation) is

$$U_1 = U_{11}x + U_{12}(1-x) = G - P_1x + P_2x - P_2 \quad (3)$$

Similarly, the average revenue of the government under the mixed strategy (uncontrolled outsourcing, controlled outsourcing) is

$$U_2 = U_{21}y + U_{22}(1-y) = (C_1-C_2)xy - (C_1-C_2)x + C_2y - (S_1-S_2)yz + (R-S_2)z - C_2 \quad (4)$$

The average return of the contractor under the mixed strategy (cooperation and noncooperation) is

$$U_3 = U_{31}z + U_{32}(1-z) = (S_2-E+L+b)z + (S_1-S_2-L-b)yz + Ly - (s-e)xz - (s-e)x - L \quad (5)$$

Combined with Formulas (1)–(3), the replicative dynamic equation of government's operation strategy selection can be obtained as follows:

$$F(x) = \frac{d(x)}{d(t)} = x(U_{11} - U_1) = x(1-x)(P_2 - P_1) \tag{6}$$

Similarly, the replication dynamic equation of government control strategy selection can be obtained as follows:

$$F(y) = \frac{d(y)}{d(t)} = y(U_{21} - U_2) = y(1-y)[C_2 + (C_1 - C_2)x - (S_1 - S_2)z] \tag{7}$$

The dynamic replication equation of the contractor is

$$F(z) = \frac{d(z)}{d(t)} = z(U_{31} - U_3) = z(1-z)[\ (S_2 + b - E + L) - (s-e)x - (S_2 + b - S_1 + L)y] \tag{8}$$

Formulas (6)–(8) constitute an evolutionary game system consisting of government operation mode selection, government outsourcing strategy selection and cooperative strategy selection. Let $F(x) = 0$, $F(y) = 0$ and $F(z) = 0$, by solving Formulas (6)–(8), eight local equilibrium points of evolutionary games can be obtained as follows: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,0,1)$, $E_4(1,0,1)$, $E_5(0,1,0)$, $E_6(1,1,0)$, $E_7(0,1,1)$, and $E_8(1,1,1)$.

3.3. Stability Analysis of Equilibrium Points in Evolutionary Game Model

For the stability problem of an evolutionary game, a stable state must have robustness to small perturbations to be called an evolutionary stability strategy. Here, the eight local equilibrium points must, in addition to being themselves equilibrium, conform to the property that if some player deviates from them by accidental error, the replication dynamic will still bring them back to equilibrium. In other words, according to the evolutionary game theory, when all eigenvalues satisfying the Jacobi matrix are non-positive equilibrium points, the evolutionarily stable strategy (ESS) of the evolutionary game system can be obtained.

According to Friedman's method [36], the evolutionary stability strategy of the differential equation system can be obtained by analyzing the local stability of the Jacobi matrix of the system. By taking partial derivatives of $F(x)$, $F(y)$ and $F(z)$ with respect to x, y and z, the Jacobi matrix can be obtained.

$$\boldsymbol{J} = \begin{vmatrix} \frac{dF(x)}{dx}, & \frac{dF(x)}{dy}, & \frac{dF(x)}{dz} \\ \frac{dF(y)}{dx}, & \frac{dF(y)}{dy}, & \frac{dF(y)}{dz} \\ \frac{dF(z)}{dx}, & \frac{dF(z)}{dy}, & \frac{dF(z)}{dz} \end{vmatrix} = \begin{vmatrix} (1-2x)(P_2-P_1), & 0, & 0 \\ y(1-y)(C_2-C_1), & (1-2y)[C_2+(C_1-C_2)x-(S_1-S_2)z], & y(1-y)(S_2-S_1) \\ z(1-z)(e-s), & z(1-z)(S_1-S_2-L-b), & (1-2z)\begin{bmatrix} (L+b+S_2-E)-(s-e)x \\ -(L+S_2+b-S_1)y \end{bmatrix} \end{vmatrix} \tag{9}$$

Then, we put eight Equant into the Jacobi matrix to calculate their eigenvalues, respectively. The Jacobi matrix J_{E1} of *E1 (0,0,0)* is

$$J_{E1} = \begin{vmatrix} P_2 - P_1, & 0, & 0 \\ 0, & C_2, & 0 \\ 0, & 0, & L + b + S_2 - E \end{vmatrix} \tag{10}$$

The eigenvalues are as follows: $\lambda_1 = P_2 - P_1$, $\lambda_2 = C_2$, $\lambda_3 = L + b + S_2 - E$.

Similarly, the eigenvalues of other equilibrium points can be obtained, respectively. All eigenvalues are shown in Table 4.

Table 4. The eigenvalues of the 8 equilibrium points in the evolutionary game.

Balanced Point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1(0,0,0)$	$P_2 - P_1$	C_2	$S_2 + b - E + L$
$E_2(1,0,0)$	$-(P_2 - P_1)$	$-C_1$	$(S_2 + b - E) - (s - e - L)$
$E_3(0,0,1)$	$P_2 - P_1$	$(C_2 + S_2) - S_1$	$-(S_2 + b - E + L)$
$E_4(1,0,1)$	$-(P_2 - P_1)$	$(C_1 + S_2) - S_1$	$-[(S_2 + b - E) - (s - e - L)]$
$E_5(0,1,0)$	$P_2 - P_1$	$-C_2$	$S_1 - E$
$E_6(1,1,0)$	$-(P_2 - P_1)$	$-C_1$	$(S_1 - E) - (s - e)$
$E_7(0,1,1)$	$P_2 - P_1$	$-[(C_2 + S_2) - S_1]$	$-(S_1 - E)$
$E_8(1,1,1)$	$-(P_2 - P_1)$	$-[(C_1 + S_2) - S_1]$	$-[(S_1 - E) - (s - e)]$

In order to better analyze the sign of the corresponding eigenvalues of different equilibrium points, let $S_1 - E > 0$, $s - e > 0$ and $S_2 + b - E > 0$, that is, as long as the contractor takes the production action (whether the action produces the specialized value or non-special value of BSIs), the action benefits obtained by the contractor itself always exceed the action costs paid by itself. The purpose of this assumption is to focus the analysis on asset specificity. Since the parameters in the model are relatively complex, the evolutionary game stability strategy is discussed in five situations, and the eigenvalue symbols in different cases are shown in Table 5.

Table 5. The local stability of the equilibrium point (Situation 1–5).

Balanced Point	Situation 1 (a)		Situation 1 (b)		Situation 2		Situation 3		Situation 4		Situation 5	
$E_1(0,0,0)$	−,+,+	U	−,+,+	U	+,+,+	S	+,+,+	S	+,+,+	S	+,+,+	S
$E_2(1,0,0)$	+,−,+−	U	+,−,+−	U	−,−,−	ESS	−,−,+	U	−,−,+−	U	−,−,+−	U
$E_3(0,0,1)$	−,−,−	ESS	−,+,−	U	+,+−,−	U	+,+−,−	U	+,+−,−	U	+,+−,−	U
$E_4(1,0,1)$	+,+−,+−	S	+,+−,+−	S	−,−,+	U	−,−,−	ESS	−,+,+−	U	−,+,+−	U
$E_5(0,1,0)$	−,−,+	U	−,−,+	U	+,−,+	U	+,−,+	U	+,−,+	U	+,−,+	U
$E_6(1,1,0)$	+,−,+−	U	+,−,+−	U	−,−,+−	U	−,−,+−	U	−,−,−	ESS	−,−,+	U
$E_7(0,1,1)$	−,+,−	U	−,−,−	ESS	+,+−,−	U	+,+−,−	U	+,+−,−	U	+,+−,−	U
$E_8(1,1,1)$	+,+−,+−	S	+,+−,+−	S	−,+,+−	U	−,+,+−	U	−,−,+	U	−,−,−	ESS

Note: *Situation 1(a)* = $(C_2 + S_2) - S_1 < 0$. *Situation 1(b)* = $(C_2 + S_2) - S_1 > 0$. Evolutionary Stability Strategy = ESS. Unstable Point = U. Saddle Point = S.

Situation 1. When $P_2 - P_1 < 0$, $(C_2 + S_2) - S_1 < 0$ or $(C_2 + S_2) - S_1 > 0$, it means that the cost of the government choosing the "independent operation" strategy is lower than the cost of the "dependent operation" strategy. When $S_1 - E > 0$ and $S_2 + b - E > 0$ are the precondition of this model, whether the government chooses "controlled outsourcing" or "uncontrolled outsourcing", the contractor always chooses "cooperation". In this situation, the equilibrium points $E_3(0,0,1)$ or $E_7(0,1,1)$ fits all eigenvalues as nonpositive, whose corresponding evolution strategy is (independent operation, controlled outsourcing, cooperation) or (independent operation, uncontrolled outsourcing, cooperation).

Situation 2. When $P_2 - P_1 > 0$, $(C_1 + S_2) - S_1 < 0$ and $(S_2 + b - E) - (s - e - L) < 0$, that is, the cost of "dependent operation" chosen by the government is lower than that of "independent operation", the cost of "controlled outsourcing" is lower than that of "uncontrolled outsourcing", and the benefits of "noncooperation" chosen by the contractor are higher than that of "cooperation". In this situation, all the eigenvalues corresponding to equilibrium point $E_2(1,0,0)$ are not positive, and the corresponding evolution strategy is (operations-dependent, controlled outsourcing, noncooperation).

Situation 3. When $P_2 - P_1 > 0$, $(C_1 + S_2) - S_1 < 0$ and $(S_2 + b - E) - (s - e - L) > 0$, that is, the cost of "dependent operation" chosen by the government is lower than that of "independent operation", the cost of "controlled outsourcing" is lower than that of "uncontrolled outsourcing", and the benefits of "cooperation" chosen by the contractor are higher than that of "noncooperation". In this situation, all eigenvalues corresponding to the equilibrium point

$E_4(1,0,1)$ are not positive, and its corresponding evolution strategy is (dependent operation, controlled outsourcing, cooperation).

Situation 4. When $P_2 - P_1 > 0$, $(C_1 + S_2) - S_1 > 0$ and $(S_1 - E) - (s - e) < 0$, that is, the cost of government choosing "dependent operation" is lower than that of "independent operation", the cost of "uncontrolled outsourcing" is lower than that of "controlled outsourcing", and the income of the contractor choosing "cooperation" is lower than that of "noncooperation". In this situation, all the eigenvalues corresponding to the equilibrium point $E_6(1,1,0)$ are not positive, and its corresponding evolution strategy is (dependent operation, uncontrolled outsourcing, noncooperation).

Situation 5. When $P_2 - P_1 > 0$, $(C_1 + S_2) - S_1 > 0$ and $(S_1 - E) - (s - e) > 0$, that is, the cost of government choosing "dependent operation" is lower than that of "independent operation", the cost of "uncontrolled outsourcing" is lower than that of "controlled outsourcing", and the income of the contractor choosing "cooperation" is higher than that of "noncooperation". In this situation, all eigenvalues corresponding to equilibrium point $E_8(1,1,1)$ are not positive, and the corresponding evolution strategy is (dependent operation, controlled outsourcing, cooperation).

From the above five situations, it can be found that, on the one hand, when the government chooses a dependent operation strategy, no matter what outsourcing strategy the government chooses, the contractor will eventually choose to cooperate; on the other hand, when the government chooses the strategy of "dependent operation", for the government, no matter what kind of outsourcing strategy it chooses, in the process of system evolution, it can always find an appropriate "outsourcing price" or "outsourcing price + incentive", so that the contractor can choose the "cooperation" strategy. For the contractor, no matter what outsourcing strategy the government chooses, the contractor will always make a choice by comparing the benefits of "cooperation" and "noncooperation".

The above analysis raises the following two questions:

(1) Whether the government chooses "independent operation" or "dependent operation", the outsourcing strategy does not seem to affect the final strategy choice of the contractor. Does this mean that it is not necessary for the government to consider the outsourcing strategy?
(2) As long as the government can find a suitable outsourcing price, it can encourage the contractor to choose the "cooperation" strategy under "dependent operation". Does this mean that the government need not consider the strategic difference between "independent operation" and "dependent operation"?

Therefore, the intuitive analysis of the above five situations cannot obtain more valuable policy measures. Next, we will simulate the evolution game model by using MATLAB R2020b, and make further analysis of the evolution strategy between the government and the contractor according to the simulation results.

4. Simulation of Evolutionary Game Model

According to the research purpose, the evolutionary game model simulation here is mainly used to analyze the following two aspects:

(1) Given the operation strategy, which strategy of "controlled outsourcing" or "uncontrolled outsourcing" can better promote the strategic evolution direction of the contractor to "cooperation"?
(2) Given the outsourcing strategy, which of the two strategies, "independent operation" or "dependent operation", can better lead to the evolution of the contractor's strategy in the direction of "cooperation"?

In terms of the initial value setting of game system parameters: on the one hand, from the evolutionary game system composed of Formulas (6)–(8), G and R are not the key parameters affecting the evolution of the system, therefore, it is sufficient to make sure that the government's income of investment in the construction of BSIs and strategies is greater than 0. On the other hand, the eigenvalues of Table 4 also show that the government's choice of operation strategy mainly depends on the institutional cost of the initial period, namely the difference between P_1 and P_2. However, restricted by bounded rationality, the government and the contractor in the early stage of evolution do not know what the strategy is better, and the asset specificity characteristics and value of BSIs have not yet emerged. Therefore, it is necessary to consider an initial value setting where there is no equilibrium stable point under any probability, in order to better compare different strategy choices through parameter changes. After conducting experiments in MATLAB R2020b, the initial parameters of the payoff matrix in this study are set as shown in Table 6, and the subsequent parameters are mainly adjusted on the basis the initial parameters of Table 6.

Table 6. The initial value setting for the parameters.

G	R	P_1	P_2	C_1	C_2	S_1	S_2	L	E	b	s	e
40	60	10	10	0	0	30	30	0	30	0	0	0

4.1. The Influence of Outsourcing Strategy on the Evolution of Cooperation Strategy under Dependent Operation

On the basis of Table 6, when the government chooses the dependent operation strategy, the comparison of institutional costs in the initial period is the main reason for the government's selection of operational strategies, so that we let $P_2 = 20$, then $P_2 - P_1 = 10$. When the government chooses the dependent operation strategy, the government needs to consider the asset specificity of BSIs, so that we let $s = 15$ and $e = 10$, then the net income from the use of BSIs by contracting parties for non-special purposes is $s - e = 5$.

When the government chooses an uncontrolled outsourcing strategy, for the contractor to cooperate, the analysis of "Situation 5" requires $(C_1 + S_2) - S_1 > 0$ and $(S_1 - E) - (s - e) > 0$. In this case, let $C_1 = 7$, $S_1 = 36$, $L = C_1 = 7$, $S_1 = 36$, $L = 3$, and $b = 4$.

When the government chooses a controlled outsourcing strategy, for the contractor to cooperate, the analysis of "Case 3" requires that $(C_1 + S_2) - S1 < 0$ and $(S_2 + b - E) - (s - e - L) > 0$. In this case, let $C_1 = 6$, $S_1 = 37$, $L = 3$, and $b = 3$.

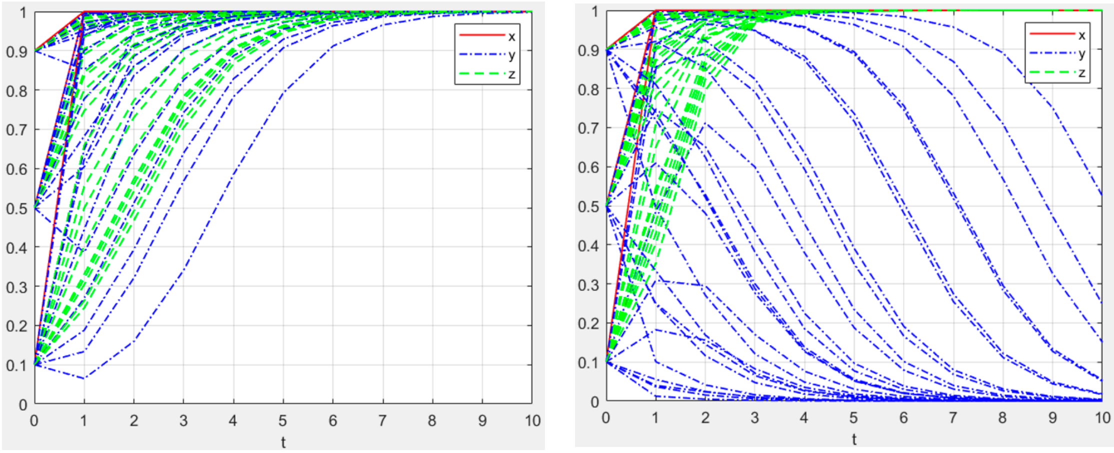
The values of the parameters for both cases are shown in Table 7.

Table 7. Parameter values of two outsourcing strategies under dependent operation.

	G	R	P_1	P_2	C_1	C_2	S_1	S_2	L	E	b	s	e
Uncontrolled outsourcing	40	60	10	20	7	0	36	30	3	30	4	15	10
Controlled outsourcing	40	60	10	20	6	0	37	30	3	30	3	15	10

Based on the parameters in Table 7, we conducted a simulation analysis on the strategy selection between the government and the contracting party under dependent operation strategy (see Figure 1).

By comparing Figure 1a,b, it can be seen that, on the one hand, the government's choice of outsourcing strategies mainly depends on the institutional cost of different strategies. Comparatively, the government is more sensitive to the cost of uncontrolled outsourcing. On the other hand, the government's outsourcing policy selection has a significant impact on the strategy selection of the contractor, and when the institutional cost of uncontrolled outsourcing $((C_1 + S_2) - S_1 = 1)$ is equal to the institutional cost of controlled outsourcing $(S_1 - (C_1 + S_2) = 1)$, the contractor can evolve towards a cooperative strategy faster under controlled outsourcing. Therefore, when the government chooses the "dependent operation" strategy, if the institutional cost of the two outsourcing strategies is the same, choosing the "controlled outsourcing" can more effectively encourage the contractor to choose the "cooperation" strategy.



(**a**) (**b**)

Figure 1. Simulation of two outsourcing strategies under dependent operation. (**a**) Uncontrolled outsourcing; (**b**) controlled outsourcing.

4.2. The Influence of Outsourcing Strategy on the Evolution of Cooperation Strategy under Independent Operation

Based on Table 6, given the government choosing an independent operation strategy, similarly, the comparison of institutional costs in the initial period is the main reason for the government's selection of operational strategies, so that we let $P_1 = 20$, then $P_2 - P_1 = -10$. When the government chooses the independent operation strategy, according to our model assumption that the contractor within the independent operation either produces the asset specificity value of BSIs or produces nothing, we therefore let $s = 0$ and $e = 0$.

When the government chooses an uncontrolled outsourcing strategy, in order to make the contractor choose cooperation, according to the analysis in Situation 1, it requires $(C_2 + S_2) - S_1 > 0$. In this case, we let $C_2 = 7$, $S_1 = 36$, $L = 3$, and $b = 4$.

When the government chooses the controlled outsourcing strategy, in order to make the contractor choose cooperation, according to the analysis in Situation 1, it requires $(C_2 + S_2) - S_1 < 0$. In this case, we let $C_2 = 6$, $S_1 = 36$, $L = 3$, and $b = 3$.

The parameter values of the two cases are shown in Table 8.

Table 8. Parameter values of two outsourcing strategies under independent operation.

	G	**R**	$\mathbf{P_1}$	$\mathbf{P_2}$	$\mathbf{C_1}$	$\mathbf{C_2}$	$\mathbf{S_1}$	$\mathbf{S_2}$	**L**	**E**	**b**	**s**	**e**
Uncontrolled outsourcing	40	60	20	10	0	7	36	30	3	30	4	0	0
Controlled outsourcing	40	60	20	10	0	6	37	30	3	30	3	0	0

Based on the parameters in Table 8, we conducted a simulation analysis on the strategy selection between the government and the contracting party under the dependent operation strategy (see Figure 2).

By comparing Figure 2a,b, it can be found that, on the one hand, likewise, the government's choice of outsourcing strategies depends on the institutional cost of the different strategies; on the other hand, the government's outsourcing strategy choice has an almost equal impact on the strategy choice of the contractor. In other words, when the government chooses the "independent operation" strategy, if the system of the two outsourcing strategies is not much different, no matter what kind of outsourcing strategy it chooses, it can encourage the contractor to choose the "cooperation" strategy. This shows that under the case of the government choosing the "independent operation" strategy, the institutional cost of different outsourcing policies becomes the main factor affecting government decisions.

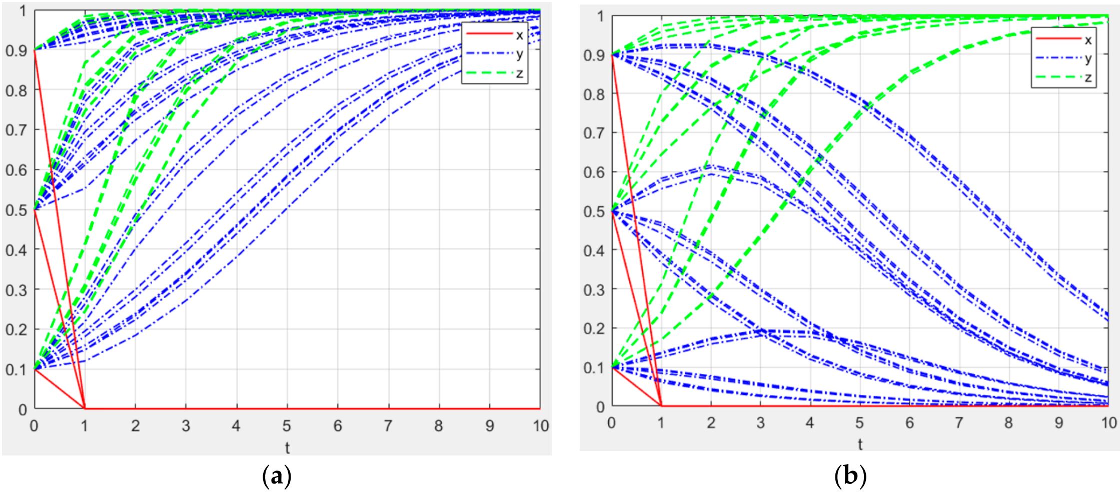


Figure 2. Simulation of two outsourcing strategies under independent operation. (**a**) Uncontrolled outsourcing; (**b**) controlled outsourcing.

4.3. The Influence of Operational Strategy on the Evolution of Cooperative Strategy under Uncontrolled Outsourcing

When the government chooses the uncontrolled outsourcing strategy, Table 9 is obtained by combining the parameters for uncontrolled outsourcing in Table 7 and the parameters for uncontrolled outsourcing in Table 8.

Table 9. Parameter values of two operation strategies under uncontrolled outsourcing.

	G	R	P_1	P_2	C_1	C_2	S_1	S_2	L	E	b	s	e
dependent operation	40	60	10	20	7	0	36	30	3	30	4	15	10
independent operation	40	60	20	10	0	7	36	30	3	30	4	0	0

Based on the parameters in Table 9, we conducted a simulation analysis on the strategy selection between the government and the contracting party under the dependent operation strategy (see Figure 3).

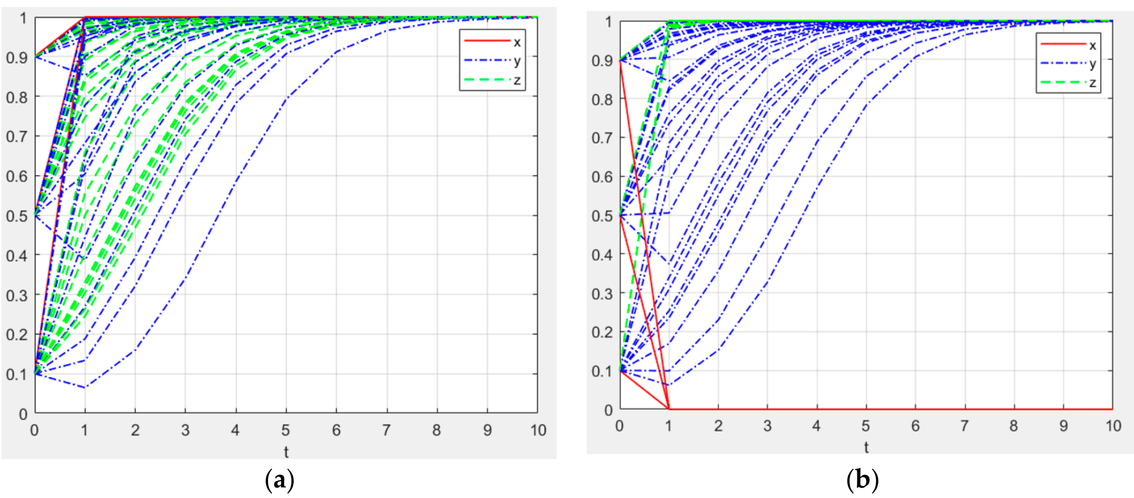


Figure 3. Simulation of two operation strategies under uncontrolled outsourcing. (**a**) Dependent operation; (**b**) independent operation.

Comparing Figure 3a,b, it can be found that under the condition of equal cost of the two uncontrolled outsourcing strategy systems, the operation mode has a significant impact on the contractor's choice of strategy. In this case, the government's choice of independent operation strategy over dependent operation strategy can accelerate the evolution of contractor towards cooperative strategy.

4.4. The Influence of Operation Strategy on the Evolution of Cooperation Strategy under Controlled Outsourcing

When the government chooses the controlled outsourcing strategy, Table 10 is obtained by combining parameters for controlled outsourcing in Table 7 and parameters for controlled outsourcing in Table 8.

Table 10. Parameter values of two operation strategies under controlled outsourcing.

	G	R	P_1	P_2	C_1	C_2	S_1	S_2	L	E	b	s	e
dependent operation	40	60	10	20	6	0	37	30	3	30	4	15	10
independent operation	40	60	20	10	0	6	37	30	3	30	3	0	0

Based on the parameters in Table 10, we conducted a simulation analysis on the strategy selection between the government and the contracting party under the dependent operation strategy (see Figure 4).

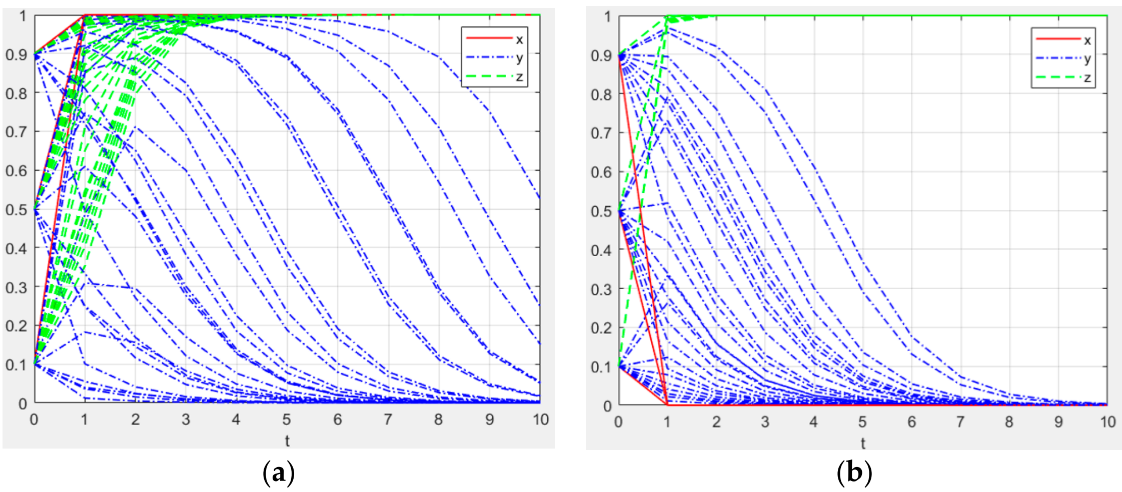


Figure 4. Simulation of two operation strategies under controlled outsourcing. (**a**) dependent operation; (**b**) independent operation.

Comparing Figure 4a,b, it can be found that under the condition of equal cost of the two controlled outsourcing strategy systems, the operation mode also has a significant impact on the contractor's choice of strategy. In this case, similarly, the government's choice of an independent operation strategy over a dependent operation strategy can accelerate the evolution of the contractor towards a cooperative strategy.

5. Discussions

5.1. Key Factors and System Structure of the Evolutionary Game Model for Selecting Operating Modes of BSIs

From the perspective of asset specificity, this study aims to identify which operation mode is more conducive to obtaining specialized asset revenue of BSIs, and thus establish an evolutionary game model consisting of the government and contractor. The simulation results reveal that government-controlled outsourcing and independent operation are two important strategies that encourage the contractor to cooperate. However, the underlying reasons for the effectiveness of these two strategies still need further discussion. This study examines the game relationship between the government and the contractor from a systematic perspective. Combining the results of evolutionary game and simulation analysis, this study developed a causal loop diagram (CLD) to demonstrate the key factors and system structure of this evolutionary game model (see Figure 5).

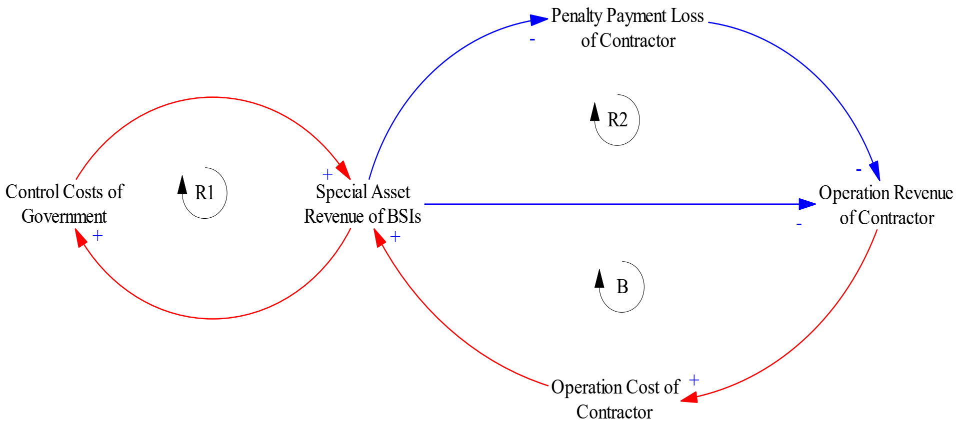


Figure 5. Causal loop diagram for the special asset revenue of BSIs.

CLD is an important tool for describing the feedback structure of complex systems, which uses a closed loop composed of a series of interconnected variables to represent key factors in the system and the causal loop relationships between these factors, thereby reflecting the structure of a complex system [37]. The CLD shown in Figure 5 includes two reinforcing loops (R1 and R2) and one balancing loop (B).

(1) Reinforcing loop R1. R1 represents a positive feedback relationship between government control costs and special asset revenue of BSIs. Increasing the control cost of the government can enhance the special asset revenue of BSIs; the increase in special asset revenue of BSIs makes the government believe that it is necessary to continue to increase the control cost.
(2) Reinforcing loop R2. R2 represents a positive feedback relationship between the special asset revenue of BSIs and the penalty payment loss, production benefits, and production costs of the contractor. For the contractor, increasing the control cost of the government means strengthening the monitoring of the contractor and punishing its breach of contract. The lower the special asset revenue of BSIs produced by the contractor, the greater the penalty payment loss will be, thereby reducing the operation revenue of the contractor. In this case, the contractor needs to increase operation costs to raise the special asset revenue of BSIs and reduce penalty losses.
(3) Balancing loop B. B represents the negative feedback relationship between the special asset revenue of BSIs and the operation revenue and costs of the contractor. In the absence or low control cost of government, the contractor will obtain the non-special asset revenues of BSIs by reducing operation costs, which reduces the special asset revenues of BSIs.

The analysis of the CLD indicates that government control costs are a key factor in obtaining special asset revenues of BSIs, which is the underlying reason why government-controlled outsourcing and independent operation strategies can be effective. Strengthening government control is in line with the reasoning of transaction cost theory, which emphasizes centralized power mechanisms for investment with high asset specificity. In other words, as highly specialized assets, an effective operation system for BSIs needs to be built around the allocation of government control rights as the core.

5.2. The Relationship between the Operation Mode and the Strategic Status and Construction Goal of China's BSIs

Before China's 13th Five-Year Plan, the strategic status of BSIs was rarely clearly stated at the national policy level, and the construction goals varied according to the management organizations of BSIs. For example, in the early research literature of the Chinese Academy of Sciences, the BSIs were positioned as experimental facilities for science research [38].

While the universities became management organizations of BSIs, the BSIs became a new way to build world-class universities [39]. During this period, the central and local governments rarely directly intervened in the operation and management of BSIs, as “dependent operation + uncontrolled outsourcing” had become the main operation mode in China [18]. During China’s 13th Five-Year Plan period, China clearly put forward a plan to build a comprehensive national scientific center around BSIs, aiming at original innovation and key technological breakthroughs in major industries. The 14th Five-Year Plan for Economic and Social Development and Long-Range Objectives through the year 2035 of the People’s Republic of China has clearly incorporated the BSIs and comprehensive national science centers into the national system of building strategic scientific and technological forces. The state has become a direct participant in the operation and management of BSIs, which is manifested as the joint establishment of specialized management institutions by the central government (such as the Shanghai Promotion of Science and Technology Innovation Center Construction Office mentioned earlier) or the independent establishment of specialized management institutions by local governments (such as the Dongguan Songshan Lake High tech Industrial Development Zone Management Committee). In this circumstance, the management problem of “dependent operation + uncontrolled outsourcing” mode and the organization expansion incentive problem have become an important restriction of national action. Thus, the selection of operation mode for BSIs has received attention from the current practical community, and the current policy environment changes provide a foundation for the transformation of operation “dependent operation + uncontrolled outsourcing” mode. Obviously, the trend of China’s operation mode transformation is to rebuild the government’s control over the operation of BSIs.

5.3. Institutional Conditions Conducive to the Government’s Choice of Independent Operation Strategy

The government’s decision on operational strategy selection depends on the institutional cost comparison of different strategies; however, under the constraints of bounded rationality, the strategy selection in the initial period may not be optimal. BSIs first appeared in the United States. Due to the lack of precedent and the fact that the United States established national laboratories based on university laboratories, depending on university to operate national laboratories became the only option for the United States at that time. However, whether the “independent operation” strategy can enter the decision-making process of the government is closely related to its institutional conditions. For example, after the U. S. Department of Energy put forward the “management right bidding system” of the National Laboratory in the 1980s, universities and colleges, universities and enterprises and other different entities have competed for the management right of the National Laboratory by jointly establishing non-profit companies, which shows that the institutional conditions in the United States allow the government to choose the “independent operation” strategy [5,18]. In comparison, during the 12th Five Year Plan period, Chinese academia had proposed to build big science organizations with independent legal person status. However, under the institutional conditions of China at that time, depending on the Chinese Academy of Sciences or universities to build and operate BSIs had become the only choice. However, the institutional conditions of “independent operation” can be created. For example, Japan’s BSIs were initially managed by universities. After the reform of administrative juridical person, Japan had created big-science organizations with independent legal entity status [40]. Therefore, it is necessary for the government to create institutional conditions that are conducive to the “independent operation” mode for BSIs in a planned manner, in order to strengthen government control through the adoption of the “independent operation” mode.

5.4. Policy Implication for China and Limitations in This Study

Under the constraint of path dependence, the policy implication of this study for China is that institutional conditions conducive to the government’s choice of “controlled outsourcing” strategy should be explored in the near future. Creating institutional conditions conducive to the government's choice of "independent operation" strategy may be difficult to achieve in a short period of time, which not only involves institutional reform at multiple levels, but also has path-dependent constraints on the initial evolution conditions. Therefore, "dependent operation" is still the main strategic choice in China. The simulation results show that when the government chooses the strategy of "dependent operation", compared to "uncontrolled outsourcing", "controlled outsourcing" can more effectively encourage contractor to choose the cooperative strategy. However, achieving "controlled outsourcing" is not an easy task, as there have been instances at home and abroad where the government lacks control over the operation of BSIs [5,18]. In 2018, during our participation in the construction of a provincial laboratory with BSIs, we also found that although the contractor would strive for government support for the establishment of the laboratory, it would exclude the government from exercising its participation and veto power during the operation of the laboratory. In order to obtain the political achievements brought by the construction of the laboratory, the local government would make a certain degree of compromise. However, the current policy environment also provides the possibility for the creation of the "control outsourcing" system, which is exemplified by the policy practice of four comprehensive national science centers in Beijing, Shanghai, Hefei and the Greater Bay Are. Therefore, it is necessary to make empirical research and a summary on the existing policy practice, and help the Chinese government to create institutional conditions conducive to the choice of a "controlled outsourcing" strategy in the near future.

There are still some limitations in this study. On the one hand, focusing on the research purpose, this study only conducted a simulation analysis on how different combinations of government strategies can more effectively encourage contractors to choose "cooperative" strategies, but did not explore the impact of other parameters. For example, in the "controlled outsourcing" strategy, how should the government allocate the ratio of punishment and incentives, and how different ratios affect the strategic choices of contractors? These questions still need to be answered. On the other hand, this study only analyzes the system characteristics from the perspective of CLD. In future research, we will enrich existing game models and combine system dynamics modeling and simulation analysis to further explore this system.

6. Conclusions

Starting from the practical basis of strategies adopted by the government and the contractor, and from the perspective of asset specificity, this study has built an evolutionary game model, of which the Jacobi matrix is used to analyze the equilibrium stability point, and simulation is conducted on different combination strategies to explore the problem of operation mode selection for BSIs. The research results have answered the two core questions raised at the beginning of this study:

(1) The government's decisions on operational strategies, outsourcing strategies, and their combination strategies significantly affect the strategic choices of contractors, thereby affecting whether the government can obtain the value of asset specificity of BSIs.
(2) The government's choice of "independent operation" or "dependent operation + controlled outsourcing" strategy for the operation of BSIs will be more conducive to encouraging contractors to choose cooperation strategies.

The main contribution of this study is to clarify that government control is the key factor in obtaining special asset revenue of BSIs.

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Data Availability Statement: The data and program code of MATLAB R2020b used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Ge, Y.; Yang, W. Thoughts on strengthening the construction of large research infrastructures under the background of "new infrastructure construction". *Sci. Manag. Res.* **2021**, *39*, 45–50.
2. Qiao, L.; Han, X.; Liu, Z. Analysis on the path to first-class university based on major science and technology infrastructure construction: Complex products and system (CoPS) dynamic capability evolution perspective. *Sci. Technol. Prog. Policy* **2021**, *38*, 10–19.
3. Li-Ying, J.; Sofka, W.; Tuertscher, P. Managing innovation ecosystems around Big Science Organizations. *Technovation* **2022**, *116*, 102523. [CrossRef]
4. Siegel, D.; Boger, M.L.A.M.; Jennings, P.D.; Xue, L. Technology transfer from national/federal labs and public research institutes: Managerial and policy implications. *Res. Policy* **2023**, *52*, 104646. [CrossRef]
5. Li, H.; Fang, C.; Li, X. Experience and enlightenment of American national laboratory operation management. *Exp. Technol. Manag.* **2023**, *40*, 243–254.
6. Liu, Y.; Zhai, X. Characteristics and enlightenment of basic research in DOE national laboratories. *Stud. Sci. Sci.* **2022**, *40*, 1085–1095.
7. Qiao, L.; Mu, R.; Chen, K. Scientific effects of large research infrastructures in China. *Technol. Forecast. Soc. Change* **2016**, *112*, 102–112.
8. Zhang, Y.; Yan, Q. Analysis of technology innovation paradigm and evolutionary dynamic of big science. *China Soft Sci.* **2023**, *6*, 1–25.
9. Liu, Q.; Zeng, L. Functional characteristic and construction strategies of major national science and technology infrastructure. *Sci. Manag. Res.* **2023**, *41*, 35–44.
10. Wang, Y.; Bai, Y. Developing mega-science facility to lead the innovation globally. *J. Manag. World* **2020**, *36*, 172–188.
11. Li, X.; Zhong, Y.; Liu, J.; Zhao, Z. Construction practice and enlightenment of comprehensive national science center in UK. *Sci. Manag. Res.* **2021**, *39*, 139–145.
12. Fleming, N. How Grenoble has mastered industry-academia science collaborations. *Nature* **2023**. [CrossRef] [PubMed]
13. Huang, Z. Building innovative ecosystem based on large scientific infrastructure: Rainforest model and evolutionary transaction cost. *Sci. Technol. Prog. Policy* **2019**, *36*, 9–16.
14. Li, T.; Wen, K.; Huang, H.; You, D. How to attract, recruit and retain talents? Experience and inspiration from national research institutes worldwide. *Bull. Chin. Acad. Sci.* **2022**, *37*, 1300–1310.
15. Wang, Z.; Chen, W. Breaking down institutional barriers and accelerating the construction of national laboratories based on investigation of Beijing, Hefei, Shanghai and Qingdao. *Sci. Technol. Manag. Res.* **2020**, *13*, 171–177.
16. Bruce, C.D.; Timothy, D.M. *The Rise of Federally Funded Research and Development Centers*; Sandia National Laboratories: Albuquerque, NM, USA, 2000.
17. United States Government Accountability Office. *DOE's Policies and Practices in Competing Research Laboratory Contracts*; Government Accountability Office: Washington, DC, USA, 2003. Available online: http://gao.gov/products/GAO-03-932T (accessed on 4 September 2023).
18. Huang, Z. Research on the governance dilemma and governance reform of big-science infrastructure in China. *Sci. Soc.* **2021**, *11*, 44–60.
19. Ulset, S. The rise and fall of global network alliances. *Ind. Corp. Chang.* **2008**, *17*, 267–300. [CrossRef]
20. Nagano, H. The impact of knowledge diversity: Integrating two economic perspectives through the dynamic capability approach. *Manag. Decis. Econ.* **2020**, *41*, 1057–1070. [CrossRef]
21. Ji, S.; Zhao, D.; Luo, R. Evolutionary game analysis on local governments and manufacturers' behavioral strategies: Impact of phasing out subsidies for new energy vehicles. *Energy* **2019**, *189*, 116064. [CrossRef]
22. Wang, T.; Chen, K.; Lu, T.; Mu, R. The research on the evaluation system of large research infrastructures' comprehensive benefits with an application in the evaluation of FAST. *J. Manag. World* **2020**, *36*, 213–236.
23. Chang, X.; Zhong, D. Study on management system of nation's laboratory and its large research infrastructure. *China Soft Sci.* **2021**, *6*, 13–22.
24. Syed, T.A.; Mehmood, F.; Qaiser, T. Brand-SMI collaboration in influencer marketing campaigns: A transaction cost economics perspective. *Technol. Forecast. Soc. Change* **2023**, *192*, 122580. [CrossRef]
25. Williamson, O.E. Comparative economic organization: The analysis of discrete structural alternatives. *Adm. Sci. Q.* **1991**, *36*, 269–296. [CrossRef]
26. Cevikparmak, S.; Celik, H.; Adana, S.; Uvet, H.; Sauser, V.; Nowicki, D. Scale development and validation of Transaction Cost Economics typology for contracts: A systems thinking approach. *J. Purch. Supply Manag.* **2022**, *28*, 100769. [CrossRef]
27. Cao, Z.; Nie, J.; Zhang, X. Centralization and decentralization of public goods provision in China: The relations with state governance. *Acad. Mon.* **2020**, *52*, 69–83.
28. Chen, B. Strategic evaluation of building Shenzhen into a global science center. *Sci. Res. Manag.* **2017**, *38*, 216–222.
29. Dai, G.; Wang, F.; Liu, Y.; Min, S.; Xue, Y.; Wu, M. Research on the guiding mechanism of scientific research innovation direction of national laboratories. *Sci. Res. Manag.* **2023**, *44*, 11–16.
30. Fujisue, K.; Sakata, I.; Nakano, T. Unit-type research system and institutional complementarity: A consideration of Japan's national lab reforms. *J. Soc. Proj. Manag.* **2017**, *2*, 23–31.

31. Zhang, Y.; Yang, H. The evolution of science cities in the world and its implication to the Guangdong-Hong Kong-Macao Greater Bay Area. *Forum Sci. Technol. China* **2023**, *1*, 161–169.
32. Zhou, L. Organizational boundary of administrative subcontract: An analysis of "the separation of officials and local staff" and stratified mobility. *Chin. J. Sociol.* **2016**, *36*, 34–64. [CrossRef]
33. Chen, J. Control rights theory and governance studies: A research review. *Acad. Bimest.* **2022**, *5*, 53–63.
34. Scaringella, L.; Chanaron, J. Grenoble—GIANT Territorial Innovation Models: Are investments in research infrastructures worthwhile? *Technol. Forecast. Soc. Change* **2016**, *112*, 92–101. [CrossRef]
35. Wu, Y.; Yong, X.; Tao, Y.; Zhou, J.; He, J.; Chen, W.; Yang, Y. Investment monitoring key points identification model of big science research infrastructures—Fuzzy BWM-entropy-PROMETHEE II method. *Socio-Econ. Plan. Sci.* **2023**, *86*, 101461. [CrossRef]
36. Friedman, D. Evolutionary Game in Economics. *Econometrica* **1991**, *59*, 637–666. [CrossRef]
37. Esfandabadi, Z.S.; Ranjbari, M. Exploring carsharing diffusion challenges through systems thinking and causal loop diagrams. *Systems* **2023**, *11*, 93. [CrossRef]
38. Huang, M.; Yang, H. Improvement of management of large scientific facilities in China. *Bull. Chin. Acad. Sci.* **2006**, *21*, 213–218.
39. Wu, C.; Yan, T. Thoughts on construction of university large scientific and technological infrastructures in new era. *Exp. Technol. Manag.* **2021**, *38*, 27–32.
40. Zhu, X.; Wang, S.; Dong, Y. Analysis on the changes of Japanese national research institutions' functions. *World Sci-Tech R D* **2023**, *5*, 1–10. [CrossRef]