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Enhanced Cooperation among Stakeholders in PPP Mega-Infrastructure Projects: A China Study

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Abstract: Despite the consensus that enhanced cooperation among stakeholders is critical to the successful delivery of public-private partnership (PPP) mega-infrastructure projects, there has been a limited utilization of the quantitative approach to explore the cooperation mechanism. Drawing on research and the actual practice of PPP projects in China, a quantitative mathematical model using evolutionary game theory is constructed to explore the internal cooperation mechanism. Numerical simulation is implemented to investigate the impact of the punitive mechanism and allocation mechanism on the enhanced cooperation. The simulation result indicates that reasonable benefit allocation and a strong punitive mechanism are crucial to enhanced cooperation. Action research supported by a case study in Dalian was conducted to verify the scientific practicalities of the simulation method. An enhanced cooperation framework was proposed. The role conversion of the government and the private sectors makes the enhanced cooperation feasible. This evolution model and cooperation framework can facilitate enhanced cooperation in PPP mega-infrastructure projects.

Keywords: mega-infrastructure projects; PPP; stakeholders; enhanced cooperation; evolution model; case study; China

1. Introduction

The emergence of mega-infrastructure projects has become a global phenomenon over the last two decades as a result of rapid urbanization [1]. As the scale of investment increases, infrastructure investment could not be funded completely by the government alone [2]. In the past decade, public-private partnership (PPP) is supported by governments for mega-infrastructure projects due to its advantages, such as relieving public budgetary constraints, increasing the quality of public services, enhancing innovation, and optimizing risk transfer [3]. PPP mega-infrastructure projects often involve various stakeholders of diverse backgrounds who have different levels and types of interests in the project [4]. In particular, the government and private investors have different perceptions of the project management [5]. Lack of the enhanced cooperation between project stakeholders is identified as a key obstacle to the implementation and efficient delivery of projects [6]. Due to the characteristics of large investments and organizational complexity, stakeholder cooperation has been identified as a significant factor in accomplishing successful PPP projects [7]. In view of this, the research on the cooperation among stakeholders becomes crucial.

The cooperation among stakeholders provides the fundamental driving force for the implementation of the PPP mega-infrastructure projects [8]. Over the past few years, a number of studies have been undertaken to explore cooperation among project stakeholders [9]. However, there are still some concerns regarding the cooperation that is associated with the government and private investors [10]. The cooperation between the government and private investors is at the core of stakeholder cooperation and improves the overall performance, which is determined by the essential nature of PPP mega-infrastructure projects [8]. Although the enhanced cooperation has proven to be crucial for the success of PPP projects, quantitative models have not been well researched for analyzing the impact of cooperation conditions on cooperation [11]. Considering that both the government and private investors have their own relatively project interests, they lack an absolute willingness to enhance cooperation with each other. Whether the two stakeholders choose to enhance cooperation or not depends on the change of cooperation conditions [12]. As these cooperation conditions are constantly changing and have multiple attributes, it is difficult to accurately calculate their impact. Stakeholders are not aware of the internal cooperation impact mechanisms, which can lead to wrong decisions [11]. Furthermore, considering the complexity of PPP mega-infrastructure projects, the evolution of possibilities will not be one or several intermittent decision-making processes, but rather a dynamic continuous process that reflects the character of the evolutionary game process [13]. Hence, this study aims to build a quantitative evolution model using the evolutionary game theory to analyze the evolution of the enhanced cooperation possibilities and explore the internal cooperation mechanism. In addition, project practice varies according to specific national conditions, and this study is for the general situation of the PPP infrastructure project. The research objectives of this study are to design a quantitative model using the evolutionary game theory to explore and analyze the cooperation mechanism and the framework of enhanced cooperation. This study can provide theoretical reference and insights for the enhanced cooperation among stakeholders of PPP mega-infrastructure projects, which is of great significance for improving the performance of PPP mega-infrastructure projects in China and other countries around the world.

This article contains eight sections: Section 1: introduction; Section 2: literature review; Section 3: Methodology; Section 4: evolution model of the enhanced cooperation; Section 5: simulations of the enhanced cooperation; Section 6: case study; Section 7: discussion; and Section 8: conclusions. In Sections 1–3, this article discussed the practical background, theoretical basis, and research framework. Section 4 proposed a quantitative mathematical model to explore the research gap in Sections 1 and 2. In Section 5, a simulation analysis is conducted based on Section 4. In Sections 6 and 7, a case study is conducted to verify the simulation result and discuss the enhanced cooperation framework. Then, Section 8 gives the research conclusion and implications based on the previous research.

2. Literature Review

2.1. Definition and Characteristics of PPP Mega-infrastructure Projects

In order to promote economic development, it is essential for the government to build various types of infrastructures to support social and economic growth [3,6,14]. Research into the management of megaprojects has emerged only relatively recently as a distinct area of study [15]. As for the definition, there is no absolute consensus on the definition of megaprojects [16]. In terms of the cost, some experts have stressed that megaprojects should be defined quantitatively [17]. One of the key criteria for defining a megaproject that is widely accepted is the project cost threshold of US$1 billion [18]. Megaprojects in China are usually initiated by the government and approved by the National Development and Reform Commission (NDRC), with a total investment of RMB 5 billion, or approximately US$754 million (NDRC 2004) [19]. Most infrastructure projects have common characteristics such as large-scale investments, long durations of investment recovery, and multidimensional risks [20,21]. This amount is similar to the key criterion of the US$1 billion megaproject threshold. The United States (U.S.) Department of Transportation gives a definition:

namely, a megaproject is a project with at least a US$1 billion budget (DTOIG 2001) [22]. In the European Union (EU) countries, the International Project Management Association (IPMA 2011) designated a cost threshold of 100 million euros as the basis for defining megaprojects across all industries [23]. In addition to large investments, megaprojects are usually characterized by organizational complexity and uncertainty, the mega construction scale, and great environmental sensitivity [24]. The above distinctive characteristics pose great challenges with regard to the management of megaprojects from both theoretical and practical perspectives [25].

Due to the continuous expansion of investment and the other above-mentioned characteristics, the implementation of mega-infrastructure has been reliant on the use of PPP [26]. In the past few years, an increasing number of mega-infrastructure projects in China are implemented through the PPP. PPP is an abbreviation for public-private partnership. The National Council for PPP in the USA (2009) defined the PPP as a contractual agreement between a public agency and a private investor entity, through which the resources of each sector are shared in order to deliver a service or facility for the use of the general public [27]. Combined with the analysis of mega-infrastructure projects, PPP mega-infrastructure projects are the projects implemented through PPP, with the characteristics of large investments, management complexity, etc. PPP mega-infrastructure projects are often initiated by the government [8]. Both the public and private investors bring their complementary assets and skills to PPP mega-infrastructure projects, with different levels of involvement and responsibility [28].

2.2. Cooperation among Stakeholders in PPP Projects

Cooperation among stakeholders is the key success factor to the PPP projects. Cooperation refers to a reciprocal process in which two or more individuals or organizations work together [29]. Cooperative behaviors generally refer to behaviors that help to advance the goals of a cooperative network of individuals or organizations [30]. Factors that affect the cooperative behaviors are also discussed in several areas of the literature [31,32] The stakeholders are interconnected through contracts and implement the PPP infrastructure project together. Stakeholder's cooperation performance is closely correlated to the relationship among stakeholders; clarifying the relationship between the stakeholders and identifying the core stakeholders is essential to successful cooperation [8]. In PPP mega-infrastructure projects, the key stakeholders include the government and franchise project company set up by private investors [33]. Due to the public properties, mega-infrastructure projects are usually nonprofit government investment projects [34]. The government usually plays the role of a controller of non-PPP mega-infrastructure projects; it is fully responsible for the project management and takes on great risks and heavy management tasks [35]. However, in PPP mega-infrastructure projects, since the government does not get involved in project management directly, the government needs to achieve the project goals through its cooperation with private investors [36]. Thus, the role of the government has shifted from controller to partner. Under such circumstances, the cooperation between government and the private investor is critical to the success of PPP mega-infrastructure projects [7]. The research on the cooperation between the government and private investors becomes urgent.

2.3. Application of Game Theory in the Cooperation of Construction Projects

Game theory has been applied to a number of studies to explore the cooperation of construction projects [37,38] Various types of mathematical models have been constructed to analyze and simulate the evolution of cooperation construction projects [29]. Intensive model using game theory was constructed to investigate the promotion of cooperation in the process of construction management [39]. A financial renegotiation model was built using game theory perspective, and its policy implications also have been discussed [40,41]. From the perspective of game theory, the PPP activities are treated as a game between the government and private investors attempting to maximize their payoffs [12]. The evolutionary game approach is also used to determine the opportunistic behaviors in PPP projects and explore the allocation of control rights [42]. The experimental approach based on game theory was

also conducted to research the negotiation change in PPP projects through output specifications [43]. The evolutionary game theory is derived from biological evolutionism, which is also known as the bounded rationality game theory [44]. Considering the complexity of PPP mega-infrastructure projects, the information asymmetry and the limitations of the decision-making capacity of stakeholders, the ability and speed of analyzing, and the strategy adjustment have the characteristics of bounded rationality in evolutionary game theory [45]. Under bounded rationality, a strategy adjustment process will not be one or several intermittent decision-making processes, but rather a dynamic continuous process [33]. The possibility that the stakeholders choose to enhance cooperation evolved with the change of cooperation conditions.

3. Methodology

This study adopted a hybrid research method including literature review, model simulation, case study and systematic analysis. Methodology and research framework containing four steps are mutually corresponding. Step 1, the methodology of literature review provides the theoretical basis and methodological tools for research. Step 2, from S21 to S24, a quantitative model is established to get enhanced cooperation mechanism, which is a theoretical exploitation at the international level, for the analysis of cooperation conditions and the application of game theory are oriented to the general background. The methodology of a case study is conducted in Step 3. In fact, S21 and S22 proposed a theoretical framework of cooperation conditions, while 31 found a case in reality that fits the above theoretical framework. S31 is the restoration of S32 in reality. Through action research and interviews, the case study in China was conducted and practice results are tracked and analyzed, which verified the model simulation. Then, the enhanced cooperation mechanism got in S24 and supervision model proposed in S33 can prove each other. Finally, the systematic analysis methodology was used to explore the enhanced collaboration among stakeholders in PPP mega-infrastructure projects. Although the practical research is based on the case study in China, the theoretical guidance is at the level of international research. The research methodology and research contents provided the significance at the level of international research. The research roadmap is shown in Figure 1.
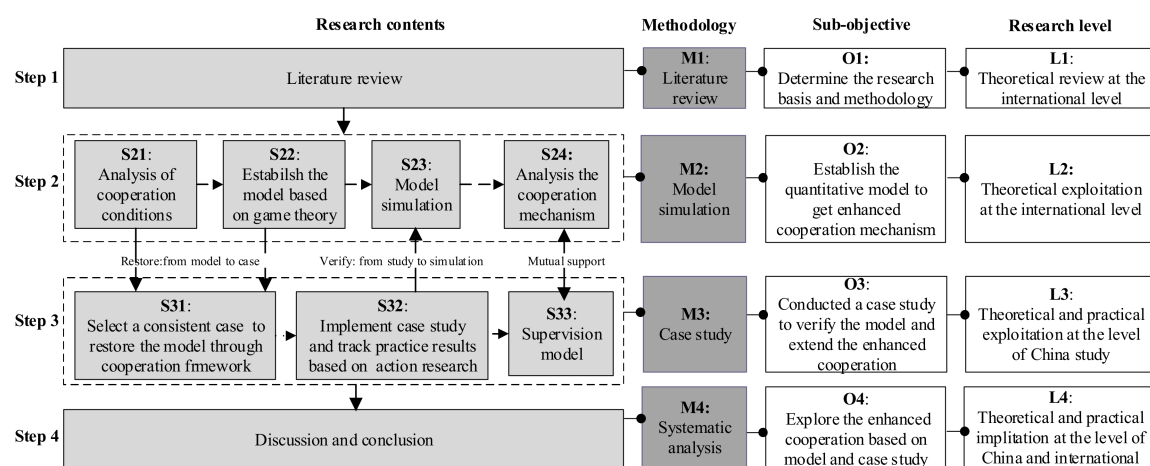

Figure 1. The research roadmap.

4. Evolution Model of the Enhanced Cooperation

4.1. Analysis of the Cooperation Conditions

During the implementation of PPP mega-infrastructure projects in China, the government and private sector usually jointly set up a franchise project company by signing a franchise contract. Through the franchise project company, which is also known as the special purpose vehicle (SPV), the local government (LC) and private investor realized the project financing and started the project [46]. In

management practices, enhanced cooperation between LC and SPV is the key to finishing a successful project delivery. If both the LC and SPV take cooperative actions, there will be synergistic effects. Synergistic effects lead to increased benefits and lower project cost, which is the ultimate goal of the enhanced cooperation [47]. Specific to the enhanced cooperation behavior, LC can increase financial subsidies, provide more supportive policies, and enhance diverse supervision, which can help the SPV to gain much more project benefits. The enhanced cooperation behavior of SPV can mainly manifest in improving the management level, which can also give the government extra benefits (e.g., the risk and cost reduction caused by the smooth implementation of the project) [48]. In general, the extra benefits and induced cost should also be allocated to the two stakeholders proportionately. An unequal allocation of benefits and costs will reduce the willingness to cooperate, which is identified as a key obstacle to the delivery of projects [49]. It should be noted that all of the incremental benefits and reduced costs are for the PPP mega-infrastructure project as a whole. However, stakeholders should pay the costs related to the act of enhancing cooperation, such as policy costs, economic costs, management costs, etc. If one stakeholder chooses to enhance cooperation while the other stakeholder does not, the former stakeholder suffers losses, and the latter receives additional benefits. Under such circumstances, both the LC and SPV may choose to give up the enhanced cooperation, because uncooperative stakeholders are not responsible for their betrayal behavior [50]. The above situation has formed a kind of game relationship between LC and the SPV, which is also a manifestation of the prisoner's dilemma [51]. In order to solve this problem, the punitive mechanisms need to be introduced in order to limit the opportunistic behavior of stakeholders. This research used game theory to study the above problems. Therefore, the basic cooperation conditions of cooperation are the allocation mechanism and the punitive mechanism. The extra emphasis is that all of the cooperative actions need to be conducted under the regulation of the government [52]. Moreover, the specific cooperation behavior is very flexible, and is not limited to the above content [53]. Rigid PPP should be avoided [54]. This study selects the most common cooperation behavior as the research object.

4.2. Model Establishment

4.2.1. Description of Model Basic Information

During the operational period of PPP projects, the LC and the SPV affect each other's cooperative strategy choices, and the interaction can be viewed as a dynamic game process [42]. To investigate the internal mechanism of the enhanced cooperation, a cooperation-evolution model based on the evolutionary game theory, which is abbreviated as the evolution model, was established and solved in this section. To maintain the objectivity and scientific nature of the study, this paper proposes the following basic information.

Both LC and SPV choose their own cooperative strategies independently under bounded rationality, which is the basic assumption of this model and is driven from evolutionary game theory. Over the course of the game, either party can dynamically adjust their strategies. Both LC and SPV have two strategy choices in the PPP project operational period. From the perspective of LC, the first choice is to enhance cooperation, specifically to provide supportive policies and financial subsidies to the SPV; another choice is to behave negatively, for example, by not providing assistance to the SPV. From the perspective of the SPV, the first choice is to improve the management performance; another choice is to behave opportunistically, for example, by not performing improvement and technology upgrades, and thereby lowering the management performance. There are both synergistic effects and spillover effects in this game process. When both LC and SPV choose to enhance cooperation, synergistic effects will be generated and lead to increased project benefits and a lower project cost [55]. When a stakeholder chooses to enhance cooperation while the other does not, spillover effects will be generated. Stakeholders who do not choose to enhance cooperation will receive spillover benefits. Both an allocation mechanism and a punitive mechanism have been established in this game. The extra benefits and induced costs based on synergistic effects can be allocated to the two stakeholders

according to a certain proportion. Combined with the practice of the case study and the punitive mechanism, the stakeholder who chooses not to enhance cooperation should pay a certain amount of default costs to the stakeholder who chooses to enhance cooperation.

In order to establish a mathematical model, assume that the set of strategies that the stakeholders choose from is {to enhance cooperation, not to enhance cooperation}. The possibility that the LC chooses to enhance cooperation is x, while the choice not to enhance is $(1 - x)$. The possibility that the LC chooses to enhance cooperation is y, while choosing not to enhance cooperation is $(1 - y)$. Then, the evolutionary state of possibility that both the two stakeholders choose to enhance cooperation can be represented by points (x, y) in the area of $[0, 1] \times [0, 1]$.

4.2.2. Payoff Matrix of the Enhanced Cooperation

Based on the above model hypothesis, the payoff matrix constructed of the two stakeholder's benefits under a different strategy combination is built. The payoff matrix of the enhanced cooperation is shown in Table 1. According to the model information, there is a four-strategy combination: the corresponding payoff combination can be recorded as Combination 1 (R_{11}^A, R_{11}^B), Combination 2 (R_{12}^A, R_{12}^B), Combination 3 (R_{21}^A, R_{21}^B), or Combination 4 (R_{22}^A, R_{22}^B). Take R_{12}^A as an example; it represents the benefits of the LC under the conditions that the LC chooses to enhance cooperation, while the SPV does not.

Table 1. Payoff matrix of cooperation.

		SPV	
Stakeholders in the Game		**To Enhance Cooperation** (y)	**Not to Enhance Cooperation** $(1 - y)$
LC	To enhance cooperation (x)	(R_{11}^A, R_{11}^B)	(R_{12}^A, R_{12}^B)
	Not to enhance cooperation $(1 - x)$	(R_{21}^A, R_{21}^B)	(R_{22}^A, R_{22}^B)

Combination 1: (R_{22}^A, R_{22}^B) is the payoff combination of the LC and SPV under the conditions that both the LC and SPV choose to enhance cooperation. Under such conditions, they can only get the basic benefits. Their respective basic benefits are defined as R_a and R_b. Thus, $R_{22}^A = R_a$, $R_{22}^B = R_b$.

Combination 2: (R_{12}^A, R_{12}^B) is the payoff combination under the conditions that the LC chooses to enhance cooperation, while the SPV does not. Under such conditions, the increased project benefits belong to the LC, while the SPV can get additional spillover benefits from the LC. Simultaneously, the SPV should pay the default costs due to the opportunistic behavior. So, we set c_0 as the constraint parameters to represent the default costs of the punitive mechanism. The default costs paid by the SPV is c_0. Setting η as the spillover coefficient reflects the extent of spillover effects. We use R and c to represent the benefits and costs of the enhanced cooperation separately. ΔR_a is defined as the increased benefits of the LC in the enhanced cooperation. ΔR_b is defined as the increased benefits of the SPV in the enhanced cooperation. c_a is defined as the enhanced cooperation cost of the LC, such as the cost of increased financial subsidies, supportive policies, and diverse supervision. c_b is defined as the enhanced cooperation cost of the SPV, such as the cost of enhanced management. According to the model hypothesis and parameter definition, $R_{12}^A = R_a + \Delta R_a - c_a + c_0$, $R_{12}^B = R_b + \eta \Delta R_a - c_0$.

Combination 3: (R_{21}^A, R_{21}^B) is the payoff combination under the conditions that the SPV chooses to enhance cooperation, while LC does not. Similarly, $R_{21}^A = R_a + \eta \Delta R_b - c_0$, $R_{21}^B = R_b + \Delta R_b - c_b + c_0$.

Combination 4: (R_{11}^A, R_{11}^B) is the payoff combination under the conditions that both the LC and SPV choose to enhance cooperation. Under these conditions, the total increased benefits and total cost caused by the synergistic effects are allocated based on allocation coefficients. So, we set α as the coefficient of benefits increasing, which represents the extent of benefits increasing. Then, we set β as a coefficient of cost-reducing, which represents the extent of cost-reducing. Finally, we set the symbol μ as the allocation coefficient of the LC's cooperation benefits, which reflects the proportion of innovation

benefits allocated to the LC. Meanwhile, $(1 - \mu)$ reflects the proportion of innovation benefits allocated to the SPV, and we set the symbol λ as the allocation coefficient of cooperation cost, which reflects the proportion of cooperation costs allocated to the LC. Meanwhile, the symbol $(1 - \lambda)$ reflects the proportion of costs allocated to SPV. Total incremental benefits are defined as $\alpha(\Delta R_a + \Delta R_b)$. Total cost is defined as $\beta(c_1 + c_2)$. According to the hypothesis and parameters definition, $R_{11}^A = R_1 + \mu\alpha(\Delta R_a + \Delta R_b) - \beta\lambda(c_a + c_b)$. Similarly, $R_{11}^B = R_2 + (1 - \mu)\alpha(\Delta R_a + \Delta R_b) - \beta(1 - \lambda)(c_a + c_b)$.

4.3. Model Solution

4.3.1. Replicator Dynamic Equation

In evolutionary game theory, replicator dynamics equations are used to describe the rate of evolution [56]. In this study, the replicator dynamics equation (RDE) is introduced into the evolution model to describe the evolution rate of the possibility that the LC chooses to enhance cooperation. The RDE of the strategy that the SPV chooses to enhance cooperation is shown in the following equation:

$$f(x) = \frac{dx}{dt} = x(1 - x)(u_1^a - u_2^a) \tag{1}$$

where u_1^a is the expected gain when the LC chooses to enhance cooperation. The expected gain when the LC does not choose to enhance cooperation is u_2^a. Thus, $u_1^a = yR_{11}^A + (1 - y)R_{12}^A$, $u_2^a = yR_{21}^A + (1 - y)R_{22}^A$. The RDE of the strategy in which the LC chooses to enhance cooperation is shown as follows:

$$f(x) = \frac{dx}{dt} = x(1 - x)[(\mu\beta\Delta R - \beta\lambda c - \eta\Delta R_a + c_a)y + (\Delta R_a - c_a + c_0) \tag{2}$$

Similarly, the RDE of the strategy in which the SPV chooses to enhance cooperation is shown as follows:

$$f(y) = \frac{dy}{dt} = y(1 - y)[(\beta(1 - \mu)\Delta R - \beta(1 - \lambda)c - \eta\Delta R_b + c_b)x + (\Delta R_b - c_b + c_0) \tag{3}$$

4.3.2. Analysis of Equilibrium Points

In evolutionary game theory, the evolutionary stable strategy (ESS) is the ultimate evolution result [57]. ESS has usually existed in the equilibrium points, which represent the potential results of evolution. In this study, equilibrium points represent the possible results of evolution. In order to identify the equilibrium points, the replicator dynamic equations that the stakeholders choose to enhance cooperation should be solved to analyze the stability of the evolution result and identify the evolutionary stable strategy (ESS). Then, the RDEs is set to be zero. When $f(x) = 0$ and $f(y) = 0$, the equilibrium points can be listed as $(0, 0)$, $(0, 1)$, $(1, 0)$, $(1, 1)$, and (x_s, y_s), where

$$y_s = (c_a - \Delta R_a - c_0)/(\mu\alpha\Delta R - \beta\lambda c - \eta\Delta R_b - \Delta R_a + c_a),$$

$$x_s = (c_b - \Delta R_b - c_0)/[(1 - \mu)\alpha\Delta R - \beta(1 - \lambda)c - \eta\Delta R_a - \Delta R_b + c_b]$$

In order to identify the ESS in the equilibrium points, this study uses the Jacobian matrix to analyze the stability of these five equilibrium points [42]. The Jacobian matrix is shown as follows:

$$J = \begin{bmatrix} \frac{\partial f(x)}{\partial x} & \frac{\partial f(x)}{\partial y} \\ \frac{\partial f(y)}{\partial x} & \frac{\partial f(y)}{\partial y} \end{bmatrix} \tag{4}$$

When an equilibrium point makes the determinant of the matrix larger than zero and the trace is less than zero, this point can be judged as an evolutionary stable strategy (ESS) [58]. ESS is essentially the final result of the evolution of the enhanced cooperation possibilities. The results of stability analysis are shown in Table 2.

Table 2. Results of equilibrium points analysis. ESS: evolutionary stable strategy.

Equilibrium Points	Sign of Determinant	Sign of Trace	Stability
O (0, 0)	+	−	ESS
A (1, 0)	+	+	Unstable point
B (1, 1)	+	−	ESS
C (0, 1)	+	+	Unstable point
S (x_s, y_s)	−	0	Saddle point

Table 2 shows that point O and point B are the ESS. It means that whatever the intermediate process, the final evolution result is one of these two points. These two points revealed two results of the evolution of the enhanced cooperation possibilities. Point O means that both LC and SPV do not choose to enhance cooperation. Point B means that both LC and SPV choose to enhance cooperation. It is obvious that Point B is the optimal ESS.

4.4. Evolution Analysis

In order to further analyze the evolution process, Figure 2 is drawn to simulate the evolution trend. Point S (x_s, y_s) represents the possibility that both the LC and SPV choose to enhance cooperation. As a saddle point, there are two evolutionary trends for Point S, corresponding to the two results of Point B and Point O, respectively. Point B means that both parties choose to enhance cooperation, while Point O indicates just the opposite. It is obvious that the location of Point S (x_s, y_s) determines the area value of quadrilateral M, and the area value of quadrilateral M represents the probability that they choose to enhance cooperation. The area value determines the enhanced cooperation probability of the two core stakeholders. So, the key to the research has been transformed into the calculation of area M.
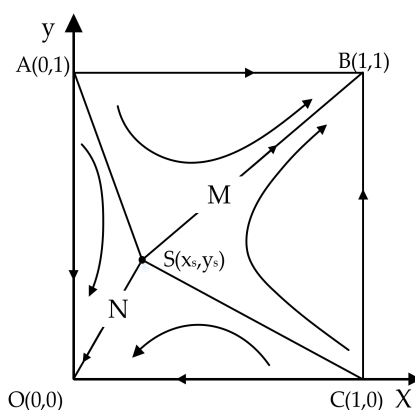
Figure 2. Evolution phase diagram of this model.

The area value of quadrilateral M can be expressed by the following Equation (5):

$$S_M = 1 - (x_s + y_s)/2 \tag{5}$$

Substituting x_s and y_s into the right side of Equation (5), the authors obtain:

$$S_M = 1 - \left[\frac{c_a - \Delta R_a - c_0}{\mu \alpha \Delta R - \beta \lambda c - \eta \Delta R_b - \Delta R_a + c_a} + \frac{c_b - \Delta R_b - c_0}{(1-\mu)\alpha \Delta R - \beta(1-\lambda)c - \eta \Delta R_a - \Delta R_b + c_b} \right]/2 \tag{6}$$

According to Equation (6), the possibility that the stakeholders choose to enhance cooperation can be calculated. Through the evolution model constructed in this study, the possibility of the enhanced cooperation is available for calculation and simulation. Furthermore, we calculate the first-order partial derivative of parameter α and parameter η. It is obvious that $\partial_M/\partial_\alpha > 0$, and $\partial_M/\partial_\eta < 0$. The

first-order partial derivative indicates that the area value of quadrilateral M is positively correlated with the synergistic coefficients and negatively correlated with the spill coefficients. Evolution analysis proved that the enhanced cooperation between the LC and SPV is positively related with synergistic effects and negatively related to spillover effects.

5. Simulations of the Enhanced Cooperation

5.1. Simulation of the Allocation Mechanism

Since the possibility of the enhanced cooperation can be calculated through Equation (6), the impact of cooperation conditions on the enhanced cooperation between the LC and SPV are able to be analyzed. Considering the nonlinear relationship between the allocation coefficient and the area value, this study conducts the numerical simulation to explore the impact of the allocation mechanism on the enhancement of cooperation. According to Equation (6), the values of λ are set to 0.1, 0.3, 0.5, and 0.7, respectively. Unchanged parameters are set as shown in the following Table 3.

Table 3. Parameters on the simulation of μ.

Parameters	ΔR_a	ΔR_b	c_a	c_b	η	α	β	c_0
Setting value	2	1	2	3	0.1	1.4	0.5	0.6

Based on the platform of Matlab2016, the function image of S_M under the above conditions can be expressed as shown in Figure 3.
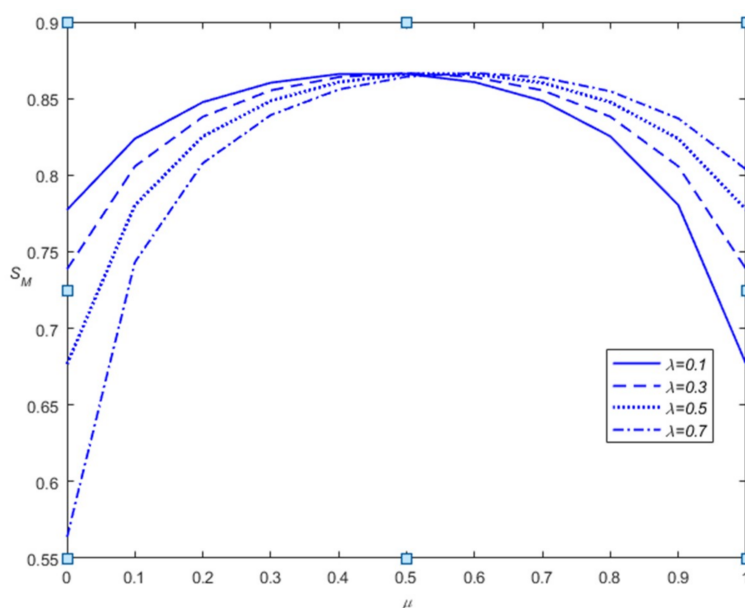

Figure 3. The impacts of μ on S_M under different values of λ.

The horizontal axis indicates the allocation coefficient of increased benefits. The vertical axis indicates the possibility that both the LC and SPV choose to enhance cooperation. The trend of curves in Figure 3 shows that the impact of μ on S_M is not monotonically increasing. There exists an optimal value of μ for S_M to reach its maximum value. The picture shows that this optimal value is around 0.5. The closer μ is to 0 or 1, the smaller the value of S_M. It is obvious that λ is negatively related to S_M before μ reaches its optimal value, while it is positively related to S_M after μ is beyond its optimal value.

The simulation of the allocation coefficient proved that the most reasonable coefficient is close to 0.5, which illustrates that the increased benefits based on the enhanced cooperation should be allocated

as equitably as possible between the LC and SPV. The greater the difference of allocation coefficient between the LC and SPV, the smaller the possibility of the enhanced cooperation. When the allocation coefficient is close to 0 or 1, it shows that one stakeholder owns almost all of the increased benefits, and that cooperation is almost impossible to realize in this case.

5.2. Simulation of the Punitive Mechanism

The simulation of the punitive mechanism is also implemented to explore its impact on the evolution of the enhanced cooperation. The impact of c_0 on the evolution of cooperation possibility is simulated by drawing the phase diagram of RDEs. The parameters remain unchanged, and the four values of c_0 are 0, 0.2, 0.4, and 0.6. Suppose that the initial value of the possibility that the LC chooses to enhance cooperation is 0.3, and that the initial value of the possibility that the SPV chooses to enhance cooperation is 0.4. Thus, $x = 0.3$, $y = 0.4$. The initial possibility is the point (0.3, 0.4). In order to conduct a comparative analysis accurately, the four trajectory curves are displayed in the same phase diagram, as shown in Figure 4.
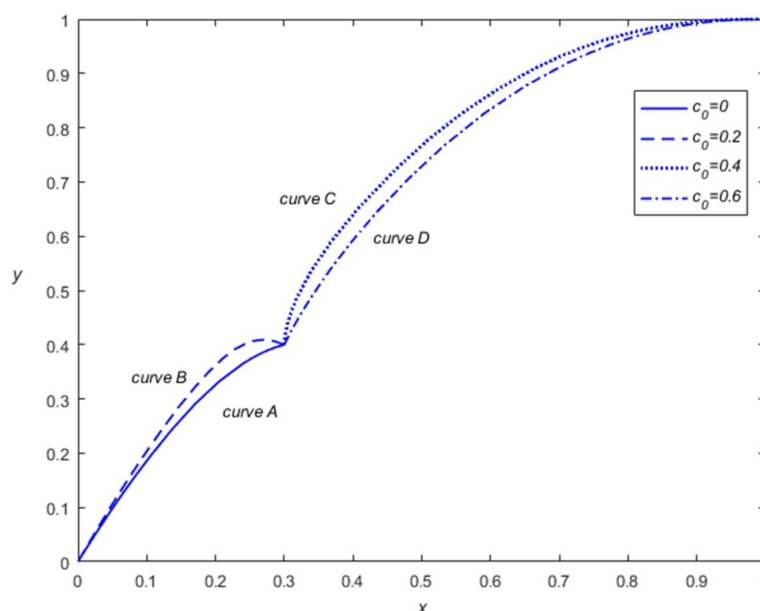

Figure 4. The impacts of c_0 on the trajectory of evolution.

In Figure 4, the horizontal axis represents the possibility that the LC chooses to enhance cooperation, while the vertical axis indicates the possibility that the SPV chooses to enhance cooperation. According to Table 2, this study concluded that two ESS exist. In Figure 4, the point (0.3, 0.4) will evolve to (0, 0) under the circumstances that $c_0 = 0$ or $c_0 = 0.2$. If $c_0 = 0.4$ or $c_0 = 0.6$, then the initial point (0.3, 0.4) will evolve to (1, 1) eventually. The trajectory of the four curves shows that there is a threshold value for c_0 to evolve to the optimal ESS.

The simulation of default costs proved that the punitive mechanism plays an important role in the evolution of the enhanced cooperation possibility. If the default costs are small or even non-default, then the LC and SPV may not choose to enhance cooperation eventually, even if there is a certain possibility of the enhanced cooperation in the initial state. When the default cost exceeds a threshold value, the LC and SPV will eventually choose to enhance cooperation. The simulation result proved that the punitive mechanism is positively related to the enhancement of cooperation between the LC and SPV.

6. Case Study

In the previous part, the factors affecting enhanced cooperation and the evolution mechanism have been simulated. However, simulation results still require project practice to verify. Essentially, the results of virtual simulation studies can be verified by actual action research methods. In a broad sense, action research can be defined as a methodology in which the researcher setting collaborates in the diagnosis of a problem [59], which has been proven as effective for project management. The case study was defined as a research strategy that allows the in-depth view of a specific instance or project [60]. Not all case studies are action research, but most action research is based on case study investigations [61]. There has been widespread use of case study methodology in construction engineering and project management [62]. In order to continue exploring the enhanced cooperation mechanism, a case study of the Dalian Bridge-Island-Tunnel (BIT) project, which is a typical PPP mega-infrastructure project, was conducted to verify the results of the simulation.

The Dalian BIT project is a cross-sea transportation engineering project consisting of a bridge, an artificial island, and an undersea tunnel, with a total investment of 30 billion RMB, or approximately $4.467 billion. In order to obtain practical information, the research team tracked the stakeholder interactions of the project. In the practice of the Dalian BIT project, the Dalian government and the private investor set up a franchise project company together by signing a franchise contract. Through the franchise project company, the government and private investor realized the project financing and started the project. However, in the progress of the project, due to many uncertainties caused by the complexity of the project, there had been a series of conflicts between the government and the private capital parties. After a series of communication, the stakeholders agreed that an enhanced cooperation framework was urgently needed. Moreover, the content related to benefit allocation and punitive mechanism should be included in this defined framework of enhanced cooperation. In order to achieve more flexible cooperation between the government and the project company, the local government set up the government management office (GMO), which was a specialized government representative agency authorized by the local government to support and cooperate with the franchise project company. The enhanced cooperation framework is shown in Figure 5. Through this governance framework, an enhanced cooperation relationship between the two core stakeholders had been build, which ensured the smooth progress of the project. Moreover, a framework that meets the preconditions of previous simulations can bridge the simulation analysis and case studies.

To further validate the critical role of enhanced collaboration in this project and the simulation result, a semi-structured face-to-face interview was conducted. A total of 10 professionals experienced in the PPP mega-infrastructure project were interviewed according to the actual conditions of the BIT project. The 10 experts consisted of three contractors, two designers, two government officials, one supervisor, and two professors. Each round of interviews lasted 30–90 min. After two rounds of interviews, the opinions of the 10 experts tended to be consistent. The 10 experts' opinions confirmed that an enhanced cooperation that contains the reasonable benefit allocation and the strong punitive mechanism is crucial to the smooth progress of the BIT project, since inter-organizational conflicts in this BIT project had decreased. The results of the case study verify the conclusions of the simulation study.
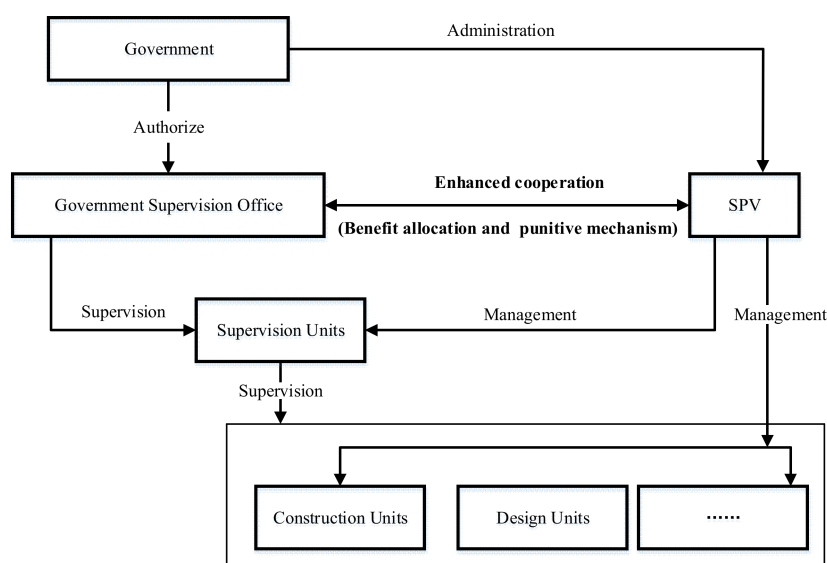
Figure 5. The enhanced cooperation framework.

7. Discussion

By combining simulation research with a case study, we believe that this study actually provides a PPP mega-infrastructure project management model. In accordance with the signing of the franchise contract, the GMO is responsible for providing policy support, financial subsidies, diverse supervision, etc. Apart from the above function, the GMO also has a coordinating function to integrate the resources of the relevant government departments. The SPV works as the actual direct project manager of the BIT project, and is fully responsible for all of the project management task of project implementation, whereas the GMO plays the role of coordinator. The independent implementation of project management by the SPV can give full play to its initiative and professional management advantage. The GMO and SPV are the core stakeholders, which represent the government and private investors, respectively. Enhanced cooperation between the government and the private investors is essentially the cooperation between the GMO and SPV. The GMO can release the local government from heavy professional management and frequent conflicts with the SPV, and transfer the risk effectively. In this way, the reasonable benefit allocation and the strong punitive mechanism come true. This case study not only validates the simulation results, it also suggests that real enhanced cooperation requires the transformation of government roles. The characteristics of government management within the framework of enhanced cooperation can be seen in Table 4. The integration of professional project management provided by the SPV and the government's administrative power determines that the supervision mode is a feasible enhanced cooperation framework. The government can implement supervision by the approach of the franchise contract, government regulations, administration inspection, and social supervision.

Table 4. Contrastive analysis of government management. PPP: public-private partnership.

Key Features	In General Projects [35,63]	In PPP Projects [64,65]	In this Framework
Management roles	Project controller	Project partner	Supervisor
Management tasks	Project management	Administrative management	Supervision
Management pressure	Heavy pressure	Minor pressure	Minor pressure
Risk allocation	Major risk	Minor risk	Minor risk
Control level	Strict control	Loose and insufficient	Moderate control

The concrete application of the quantitative model and case study is very useful but needs to consider some specific conditions. There are both strengths and limits of the proposed model. The

advantage of simulation base on systematic modeling is that it can explore the issues about the mechanism in a clear and straightforward manner. Especially, these mechanisms are difficult or can't be examined with real-world data and actual action. However, the limits are also obvious. The cooperation conditions which is the theoretical basis of the model is derived from the combination of literature review and practical research. Systematic modeling oriented simulation is unlikely to cover all of the cooperation conditions, so the model proposed in this study only contains a more important part. The theoretical system of the model is feasible but still needs improvement. In the process of applying the model, the stakeholder can set up new cooperation conditions according to the actual situation to implement simulation, making the model more portable. In short, the model and the actual case are two aspects of the dichotomy, which are mutually supported and inseparable.

8. Conclusions

Drawing on the previous research of cooperation analysis in PPP projects, this study summarized that the research that analyzes cooperation mechanisms through quantitative approaches is significant. Simulation methodology based on evolutionary game theory can be used to explore the impact of various cooperation conditions on the enhanced cooperation with the characteristics of bounded rationality. An evolution model based on simulation was constructed to quantitatively research the impacts of benefits allocation and the punitive mechanism on the enhancement of cooperation among stakeholders in PPP mega-infrastructure projects. The results show that benefits allocation and the punitive mechanism are positively related to the enhancement of cooperation between the government and private investors. An action research support through a case study in China was conducted to verify the simulation result. The cooperation framework in the case study supported the description of cooperative mechanisms in the simulation studies. Furthermore, a feasible enhanced cooperation framework was proposed based on the combination of the simulation and the case study. The government has to complete the role transition from direct manager to project supervisor and coordinator in the proposed enhanced cooperation framework.

The study provides a methodology based on the combination of a quantitative research model and a case study. The advantage of simulation is that it can test the mathematical model in a clear and straightforward approach. Case studies can be used as a necessary complement and a good extension to model analysis. The evolution model, which was based on a simulation and an enhanced cooperation framework, and was explored in the case study, can provide a significant theoretical reference and practical insight on the implementation of PPP project management.

However, the research contribution must be considered in the light of the study's limitation. From the perspective of the research scope, the cooperation simulation and case study are based on a Chinese case study, which indicates that the simulation result is only part of all of the possibilities in PPP mega-infrastructure projects, and the universality of the enhanced framework remains to be discussed. From the perspective of the research date, the date used in this model is based on numerical simulation; it is impossible to give a measure of the cost of a specific contract. Of course, this is not the focus of this study. In future study, more cooperation conditions should be considered in the process of exploring the cooperation among stakeholders of PPP mega-infrastructures. Furthermore, the actual project data should be applied to the model calculation as much as possible. In any case, the evolution model proposed in this paper is helpful for the research of the enhanced cooperation among stakeholders of PPP mega-infrastructure projects.

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