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Research on Cooperative Evolutionary Game of Design and Construction Consortium of Green Building Project under Design Change

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Abstract: In recent years, with the country's vigorous promotion of green buildings and the increasingly complex and large-scale engineering projects, the design-construction consortium model can better meet the needs of the organization and implementation of large-scale green projects and become a realistic choice for enterprises in project implementation. Therefore, the formation of a good and stable cooperative relationship between consortium members is increasingly important in improving project revenue and quality. The issue of maintaining the stability of consortium relationships is an urgent problem to be solved at this stage. As such, a three-party evolutionary game model, based on evolutionary game theory, comprising the developer unit, design unit, and construction unit, is constructed here. Then, strategies for ensuring evolutionary stability under different design modalities are discussed. Finally, the influence of relevant parameters under changing design conditions on the stability of the design and construction consortium of green building projects is analyzed through numerical simulation. The research results show the following: (1) If the additional revenue distribution coefficient within the consortium members is closer to 0.5, the influence on the stability of the design and construction consortium will be smaller; in contrast, if the influence on the design and construction consortium is increased, the cooperative relationship within the consortium will be more unstable. (2) The presence of additional revenue $\Delta\pi_1$ can increase the stability of the design and construction consortium. An increase in the additional revenue $\Delta\pi_1$ will inhibit the instability of the consortium on the one hand and strengthen the stability of the consortium on the other but will also lead to the occurrence of opportunistic behavior. (3) The construction unit's payment of a subsidy to the cooperative members can help promote the stability of the design and construction consortium to a certain extent and can also weaken the effects of other factors on the stability of the consortium, but there is a threshold value for the amount of said subsidy. (4) On the one hand, the cooperation members actively cooperate with each other to maximize the cooperation benefits of the design and construction consortium, while on the other hand, the construction unit actively promotes the implementation of the green building project, strictly monitors the implementation of the green design and green construction approach by the design and construction units in the early and implementation stages of the project, prevents the design changes caused by the final product failing to meet the green building standard, and actively solves design change problems in a manner that benefits the sustainable development of the green building, so that the cooperative relationship among the members of the consortium can develop steadily, which is beneficial to the green and ecological development of architectural design and construction.

Keywords: green building; design and construction consortium; design changes; evolutionary game

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1. Introduction

Eco-city and green building are global development strategies and promoting the development of green building is the trend of building development in the new period. With the continuous development of construction projects, the project is becoming more and more complex, large-scale, and green, which determines that it has higher requirements for design and construction, which requires not only coordinated management within each enterprise [1] but also the cooperation between enterprises, so the application of the design-construction consortium model in the future construction industry is an inevitable trend. The design-construction consortium model can bring more benefits to large-scale green building projects, and it is superior to the traditional model in terms of cost, schedule, and quality [2–4]. Some studies have also pointed out that this team cooperation mode is also helpful to avoid contract disputes in the construction process [5]. Therefore, the cooperative relationship between the design and construction consortium is an important factor affecting the success or failure of large-scale green building projects.

However, compared with the traditional model, the design and construction consortium model needs the information transmission of the project and the coordination of the stakeholders. In the process of project implementation, the interests of individual members may conflict with those of other partners or even the whole project. In order to safeguard their own interests, the consortium partners may be reluctant to share the project information involving their related interests, or even hide information that is unfavorable to them from the partners in order to maximize their own interests. In the end, it will not only lead to poor implementation of the project in terms of time, cost, and quality but also benefit the consortium [6]. Some scholars have also confirmed this point, and the lag of information transmission and uncoordinated cooperation in the design and construction process of the design and construction consortium will affect the quality of the project [7]. Some studies also believe that the excessive intervention and decision-making mistakes of the owners are also important factors affecting the design and construction consortium [8]. In addition, the stability of the cooperative relationship within the consortium will also affect the number of design changes and the cost of changes [9,10]. In other words, when the cooperation within the consortium is unstable, it is easy to cause design changes. However, there is little research on the influence of design change on consortium relations.

During the implementation of large-scale green projects, design changes are inevitable. Design changes have an important impact on project schedule management, quality management, and investment control, and also have an important impact on the coordination among participants [11]. From extensive research, it can be seen that design change is one of the main factors of cost overrun, and in some cases, it may lead to cost overrun accounting for 5% to 40% of project cost [12,13]. In addition, design change is also an important influencing factor in project delay [14]. Therefore, this is a very important and serious problem. Good design change management is of great significance for improving the construction quality of building projects, enhancing the green degree of building products, and promoting the sustainable development of buildings and the environment.

At present, the research on design change management and cooperation in the design and construction consortium is relatively mature, but most of the research on influencing factors is limited to static analysis. In reality, the influence of a certain factor on the main body is a dynamic process. In addition, many stakeholders are involved in the implementation of large-scale green building projects, and they have different preferences when making decisions, but other stakeholders cannot predict them accurately. Therefore, based on evolutionary game theory, this paper analyzes the cooperative relationship of the design and construction consortium under design change. Evolutionary game theory can not only fully reflect the interaction between participants and describe the specific process of strategy selection, but also combine the research thinking of traditional game theory with the dynamic evolution process and put forward that the game subjects can refer to, imitate, and learn from other people's strategy selection ideas in the game process to make the best judgment, and finally tend to a stable and balanced state. Therefore, it is of certain reference value to use evolutionary game theory to analyze the stability of design and construction consortium under design change.

Therefore, in order to solve the problem of a complex dynamic game and multi-party participation in the cooperation process of the design and construction consortium in large-scale green projects, this paper will analyze the evolutionary game relationship of consortium cooperation stability under design change, build an evolutionary game model composed of a constructer, designer, and developer, combine the computer simulation means of Matlab with the dynamic evolution idea, and describe the influence of equilibrium point stability and related parameters on the strategic evolution of participants and the stability of the design and construction consortium through numerical simulation. This paper aims to reveal the complex dynamics of the game process of consortium cooperation in large-scale green building projects and put forward constructive suggestions for promoting the establishment of harmonious and stable consortium cooperation and the sustainable development of green buildings.

The rest of the paper is structured as follows. The second part summarizes the existing literature, and the third part introduces the game relationship among the constructer, designer, and developer and introduces the construction of the model. The fourth part analyzes the stability of the equilibrium point. In the fifth part, Matlab (2019b) is used to simulate the evolution of the model. The sixth part contains the conclusions and recommendations.

2. Literature Review

This paper reviews the relevant literature in terms of three aspects: The design and construction consortium, design changes in construction projects, and the application of the evolutionary game in the green building, as shown in Table 1.

Table 1. Research related to the design and construction consortium, design changes in construction projects, and the application of evolutionary game in green buildings.

Research Topics	Dimensions	Source Papers
Design and construction consortium	Selection of consortium members and formation of cooperation	[1,15]
	Advantages of consortium model in cost, time and quality	[5,16,17]
	Identification and evaluation of factors affecting consortium cooperation	[18,19]
Design changes in construction projects	Causes of design changes	[20–22]
	Impact of design changes	[23–25]
	In terms of research methods	[26–28]
The application of evolutionary game in green buildings	Save energy and cut emissions	[29]
	Green construction	[30]
	Government dynamic reward and punishment policy	[31–33]
	Construction waste recycling	[34,35]

2.1. Design and Construction Consortium

The development of the consortium mode has become an inevitable trend in the world. As an international intensive form, the international engineering construction consortium has gained popularity in international engineering contracting projects. In the 1980s and 1990s, two cooperative project management modes emerged in developed countries, such as the United States and Britain, namely, Partnering proposed by Charles Cava and Alliancing proposed by BP. The American Building Industry Association (CII1995) pointed out that Partnering can achieve cultural sharing among organizations and establish a relationship of understanding, trust, and common goals among members of organizations. This is undoubtedly the ultimate goal of the consortium. In the formation of the consortium, Wang Xuetong [1] put forward a development model of integrated and collaborative management of design and construction, which made all organizations and departments more integrated and collaborative. In terms of research methods, Park H [15] uses social network analysis (SNA) to study the formation of consortium members' selection and cooperation. In the application of consortium mode, Nasrun M [5] thinks that team cooperation is helpful to avoid delay in the construction process, and Okunlola Ojo S [16] compares the traditional contracting and design-build procurement modes, and the research shows that the design-build mode is superior to the traditional mode in cost, time, and quality standards. Other scholars have suggested that the consortium model can give full play to the advantages of various stakeholders and expand the design depth, which is conducive to the success of construction projects [17]. In addition, Khalef R [18] identifies the influencing factors of the consortium through the analysis of social networks and association rules, and Dogan S Z [19] uses the social network analysis on the e-mail communication network between participants to quantitatively measure the coordination of the consortium cooperation. The research shows that the coordination score is highly correlated with the centrality index.

2.2. Design Changes in Construction Projects

Construction projects are easily influenced by various factors in the implementation process, on the one hand, due to the characteristics of large-scale, complex, and green construction projects themselves, and on the other hand, due to external factors such as the competent decision-making of stakeholders or environmental changes [26]. When a building project is affected to some extent, engineering changes usually occur. Research shows that the standard to measure the success of a construction project is primarily to finish it within time, cost budget, and quality restraints [36], and it is undeniable that design changes will have an impact on these three indicators more or less [37]. Some scholars directly show that frequent design changes are one of the reasons leading to project failure [38]. Therefore, many scholars have carried out extensive research on the management of design change. In terms of the causes of design change, Gharaibeh et al. [20] investigated the factors leading to design change according to the opinions of 252 professionals in Jordan's construction industry and found that the owner's requirements, design errors and omissions, and value engineering are the most important main influencing factors. Yap and Skitmore [14] showed that design changes will cause 5–20% time and cost overruns for construction projects in Malaysia. A lack of coordination among various professional consultants, changes in requirements/specifications, increases/omissions of scope, errors/differences in design documents, and unpredictable ground conditions are the five most important reasons. Yap et al. [21] investigated 39 reasons leading to design changes. The research shows that eight factors, such as the project team's ability, quality and technology, site restrictions and safety considerations, legislation and regulations, active rework, project communication, end-user requirements, and risk management, are the basic reasons leading to design changes. On this basis, Shahab Shoar [22] detailed 23 key reasons and analyzed the relationship among them. The research showed that factors such as "unfamiliar with new construction methods", "design errors", "value engineering", "uncertainty of scope", "change orders", and "neglected constructability in design stage" are easily influenced by other factors, among which is "customer's attitude and experience". In terms of the impact of design changes, Aslam et al. [23] studied the impact of design changes on the project cost, and the research showed that design changes were one of the main factors leading to cost overruns, which might even account for 19% of the project cost. Matusala Bassa [24], through an analysis of questionnaire results, showed that the biggest impact of design changes is the delay in completion schedule, the increase in project cost, the waste of materials during rework, the decline in productivity, and overtime to meet the project deadline. Rahman [25] also confirmed that design changes in Malaysia are the main reason for project schedule and cost overruns. Saad et al. [27] put forward a system dynamics model to capture the factors that may lead to engineering and medical-related design changes in healthcare projects and investigated the impact of these design changes on project performance. Afsharghotli and Yitmen [28] used the artificial neural network (ANN) model to evaluate the quantitative measurement of the time and cost performance of petrochemical projects caused by the interactive design change. AAGA Yana [26] used partial least squares (PLS) to analyze the factors that affect the design change and divided the factors that affect the design change into internal factors and external factors.

2.3. The Application of Evolutionary Game in the Green Building

Evolutionary game theory comes from the theory of biological evolution. In 1973, Smith and Price [39] put forward the strategy of evolutionary stability. Since then, evolutionary game theory has been widely used in the construction industry. Scholars have also studied green buildings from various perspectives. Cohen et al. [29] used game theory to explain the obstacles to energy saving and emission reduction in Israel's construction industry and proved that government subsidies can help eliminate these obstacles. Geng X [30] established an evolutionary game model among developers, contractors, and the government from the perspective of consumers' different green preferences, studied the optimal strategy of the green construction system in different situations, and put forward effective suggestions for each subject. Li X [31], based on the evolutionary game theory, analyzed the influence of a local government subsidy policy on the application strategy of the construction unit. The research showed that in the long run, government subsidies cannot improve the willingness of the construction unit to promote green buildings, so controlling the amount of subsidies and strengthening publicity is conducive to encouraging the construction unit to participate in the transformation and upgrading of the construction industry. Based on evolutionary game theory, Chen Y [32] comparatively analyzed the internal mechanism of behavior evolution of government and construction enterprises under four policies: Static reward and static punishment, static reward and dynamic punishment, dynamic reward and static punishment, and dynamic reward and dynamic punishment. The research results provide theoretical support for the formulation of government policies, and the government should dynamically adjust the intensity of rewards and punishments and determine the upper limit of rewards and punishments. Meng Q [33], based on evolutionary game theory, studied the role of the government incentive mechanism in promoting green building construction. The research shows that dynamic reward and static punishment are the best strategies to promote green building construction. Chen J [34] studied the management of building demolition waste based on evolutionary game theory. The research showed that supervision intensity, supervision cost, punishment, garbage disposal cost, and illegal dumping income are the main factors affecting the decision-making behavior of contractors and government departments. In addition, encouraging the public to participate in supervision can effectively promote the recycling of waste. Su Y [35] studied the strategic changes of local governments, contractors, and recycling factories in the construction waste recycling market based on evolutionary game theory, and analyzed the behaviors, demands, and synergies of stakeholders in the construction waste market, providing management suggestions for policy makers. Evolutionary game theory can aptly study the problem of green buildings, which is the basis of this research model.

To summarize, although domestic and foreign research has achieved certain results related to design and construction consortia, design changes during construction projects, and the application of an evolutionary game in the construction industry, certain limitations still arise, which manifest as follows: (1) Research on the cooperative relationship amongst consortia is mostly limited to the static analysis of influencing factors, while research on the dynamic mechanisms of factors influencing the cooperative relationship of consortia is still rare. (2) On the one hand, although many scholars have recognized the impact of design change management on the smooth implementation of construction projects, most of the research focuses on the causes of design changes and their countermeasures, but the existing research results do not generally consider that design changes are unpredictable, meaning that the relevant enterprises cannot implement the necessary countermeasures in a timely manner. On the other hand, little of the literature has studied design changes during green building projects. (3) Previous studies have shown that the application of evolutionary games to the construction industry is applicable to a certain degree. Evolutionary games can help reveal the long-term dynamic game process, but few have applied evolutionary games to solve the problems related to the stability of the design and construction consortium's cooperative relationship. Therefore, the research focus of this paper is on how to maintain a cooperative relationship within the design and construction consortium so as to manage the impact of design changes during the implementation of large-scale green building projects. This paper addresses the stability of a consortium's cooperative relationship and the influence of relevant factors by constructing a three-party evolutionary game model comprising a construction unit, a design unit, and a construction unit. In relation to improving design change management, this paper aims to provide theoretical support and practical guidance for establishing a harmonious and stable cooperative relationship within a consortium, and further promote the sustainable development of green buildings.

3. Model

The abovementioned design and construction consortium refers to the consortium formed by designers and constructors, in which the lead party bids for the general contracting project. After winning the bid, relying on their respective strengths, they separately complete the design and construction tasks, and both answer to the developer. In this way, the members of the consortium share resources and risks, i.e., maintain individual independence while serving the project together in a stable partnership. After the project is completed, internal liquidation is undertaken, and the organization is dissolved [40].

This paper primarily studies three important groups: The constructors, designers, and developers. In the process of consortium cooperation under the design change of large-scale green projects, the strategic choices of these three groups are both different and changing. In real society, the constructer, designer, and developer are all bounded by rationality, and the information of the three parties in the same construction project is incomplete and unequal. Therefore, each group observes the change in each other's strategies, constantly trying and imitating to improve their own strategies, so that the evolution of all group strategies will eventually become dry and stable. The research logic conforms to the bounded rational conditions, mutation, and selection ideas of evolutionary games. Therefore, evolutionary game theory is suitable for studying the strategy choice of the constructer, designer, and developer.

Under the conditions of bounded rationality and cooperation between the two parties, the developer will initiate a design change, after which the designer and constructer will start to comprehensively consider the costs and benefits and formulate two different strategies, namely "cooperation" and "non-cooperation". In a long-term evolutionary game, an uncooperative designer or constructer may not cooperate, or may withdraw, due to the prioritization of their individual interests, the potential risks related to joint contracting, or the uneven distribution of benefits derived from project implementation. However, when higher or additional revenue is generated via the optimization of cooperation between the two parties, and the revenue obtained comes to be greater than that yielded by separate contracts, the designer and constructer will select "cooperation". When the designer actively cooperates, green, environmentally friendly, and safe products can be made as a result of their professional abilities. When a designer chooses not to cooperate, the efforts made by both parties under the previously pertaining cooperative relationship will be rendered void, and the achievements will be greatly reduced. A designer who makes strategic changes in the middle and later stages of the project will also cause huge losses to be suffered during project implementation. On the other hand, when a constructor pursues cooperation, the product can be made to reach the green quality standard, and its safety will be improved. At the same time, they can help to strictly control the costs associated with the construction process and ensure the maximization of overall interests. However, a constructer who abandons cooperation and withdraws halfway through the project will cause serious losses to be suffered by the developer, resulting in delays in construction. If the design and construction consortium becomes extremely unstable, not only will great economic losses be suffered by the developer but design change behaviors will be triggered [41]. If a consortium member commits a breach of contract when the developer initiates a design change, the developer may seek a new partner to complete future work. If this occurs, the potential benefits brought by the new member will compensate the developer for the losses already incurred, but the developer can also choose whether to initiate further design changes based on the principle of maximizing their own interests.

In a green building project, the foundation of the design and construction consortium is the maximization of personal interests, and design changes can be beneficial to the stable and sustainable development of internal relations. Therefore, this paper focuses on the stability of a design and construction consortium following design changes proposed by a developer.

3.1. Hypotheses and Descriptions

The parameter settings in this paper are shown in Table 2.

Table 2. Main body parameters.

Main Body	Parameters	Explanatory Notes
constructer	π_1	Normal revenue of enterprise with non-cooperation of the constructer
	$\Delta\pi_1$	Additional project benefits derived from cooperation between designer and constructer
	a	Additional income distribution coefficient of the constructer
	D_1	When the developer initiates a design change, the loss of reputation suffered by the constructer within the industry as a result of choosing the "non-cooperation" strategy
	E_1	The additional income obtained by the constructer when the designer cooperates after the default mode on the basis of the original average normal income
	F	Liquidated damages to be paid by the constructer when choosing the non-cooperation strategy
designer	π_2	Normal revenue of an enterprise with the non-cooperation of the designer
	$\Delta\pi_1$	Additional project benefits derived from cooperation between the designer and constructer
	$1 - a$	Additional income distribution coefficient of the designer
	D_2	The loss of reputation suffered by the designer within the industry as a result of choosing the "non-cooperation" strategy when the developer initiates a design change
	E_2	The additional income obtained by the designer when the constructer cooperates after the default mode on the basis of the original average normal income
	F	Liquidated damages to be paid by the designer when choosing the non-cooperation strategy
developer	$\Delta\pi_2$	Additional benefits generated by the developer due to design changes
	B	Loss of normal project income received by the developer when the non-cooperation strategy is adopted by the designer or constructer
	b	Distribution coefficient of developer's profits and losses due to the constructer's non-cooperation
	$1 - b$	Distribution coefficient of the developer's profits and losses due to the designer's non-cooperation
	C	Additional costs incurred by the developer due to design changes
	F_1	When the constructer cooperates, the developer subsidizes them for making design changes
	F_2	When the designer cooperates, the developer subsidizes them for making design changes
	G_1	When the constructer breaches the contract, the potential benefits that the developer will receive after making design changes by seeking a new enterprise
	G_2	When the designer breaches the contract, the potential benefits that the developer will gain after making design changes by seeking a new enterprise

In order to further clarify the game relationship between the research subjects, we have made the following assumptions:

Hypothesis 1 (H1). *Whether or not the designer and the constructer cooperate with the design changes proposed by the developer is denoted as {cooperation, non-cooperation}. Under the "cooperation" strategy, both parties make design changes according to the requirements of the construction unit. Under the "non-cooperation" strategy, one party or both parties break the contract during project implementation and withdraws from the consortium, thus terminating the cooperation relationship. The strategy set of the developer is {initiated design change, not initiated design change}.*

Hypothesis 2 (H2). *When the members of the design and construction consortium all choose the "cooperation" strategy, the increases in revenue received by the constructer and the designer when they cooperate is $\Delta\pi_1$, and the distribution coefficient of* $\Delta\pi_1$ within the design and construction consortium is a.

Hypothesis 3 (H3). *When one or both parties of the design and construction consortium choose the "non-cooperation" strategy, the average normal incomes of the constructer and the designer are* π_1 and π_2*, respectively. When one party chooses to cooperate and the other chooses the non-cooperation strategy, resulting in reputational losses,* D_1 and D_2*, are felt, but additional income (*E_1 and E_2*) is obtained by the defaulting party on the basis of the original average normal income. If "asymmetric information" regarding one party's enterprise is obtained after a breach of contract, the breaching party shall pay liquidated damages L to the other in accordance with the contract and treaty, but if both parties choose the "non-cooperation" strategy, the liquidated damages will be offset against each other and ignored.*

Hypothesis 4 (H4). *When the developer chooses to initiate a change, additional revenue* $\Delta\pi_2$ *will be derived from the optimization of output resulting from cooperation with the green design change, but the additional cost C will be incurred by the design change, and the subsidies* S_1 *and* S_2 *must be paid to the cooperative members. When a member chooses not to cooperate, the construction unit will look for a new cooperative enterprise due to the design change. The potential revenue is* G_1 *and* G_2*.*

Hypothesis 5 (H5). *When the developer chooses not to initiate a change, its basic revenue is* π_3*. Regardless of whether the developer initiates a design change or not, when there are uncooperative members in the design and construction consortium, the developer will bear the corresponding loss B, wherein the profit and loss distribution coefficient among all members is b.*

3.2. Construction of the Model

Assuming bounded rationality, the probability of the constructer choosing the cooperative strategy is x, and the probability of them choosing the non-cooperative strategy is $1 - x$. The probability that the designer chooses the cooperation strategy is y, and the probability that they choose not to cooperate is $1 - y$. The probability that the developer chooses to initiate a design change is z, and the probability that they choose not to initiate a design change is $1 - z$. Based on these assumptions, the revenue matrix is shown in Table 3. In each cell, the first column is the revenue contributed by the constructor, the second is that contributed by the designer, and the third is that contributed by the developer.

Table 3. Matrix of benefits for game subjects.

	Active Supervision (z)		Negative Supervision ($1 - z$)	
	Cooperation (y)	Non-Cooperation ($1 - y$)	Cooperation (y)	Non-Cooperation ($1 - y$)
Cooperation (x)	$\pi_1 + a\Delta\pi_1 + S_1$ $\pi_3 - C + \Delta\pi_2 - S_1 - S_2$ $\pi_2 + (1-a)\pi_1 + S_2$	$\pi_1 + L + S_1$ $\pi_3 - C + \Delta\pi_2 + G_2 - (1-b)B - S_1$ $\pi_2 - D_2 + E_2 - L$	$\pi_1 + a\Delta\pi_1$ π_3 $\pi_2 + (1-a)\pi_1$	$\pi_1 + L$ $\pi_3 - (1-b)B$ $\pi_2 + E_2 - L$
Non-Cooperation ($1 - x$)	$\pi_1 - D_1 + E_1 - L$ $\pi_3 - C + \Delta\pi_2 + G_1 - bB - S_2$ $\pi_2 + L + S_2$	$\pi_1 - D_1$ $\pi_3 - C + \Delta\pi_2 + G_1 + G_2 - B$ $\pi_2 - D_2$	$\pi_1 + E_1 - L$ $\pi_3 - bB$ $\pi_2 + L$	π_1 $\pi_3 - B$ π_2

4. Evolutionary Game Model Analysis

4.1. Calculation of Stable Points

The revenue when the constructor chooses to cooperate is denoted as U_{11}, that when it chooses not to cooperate is denoted as U_{12}, the average revenue of the strategic choice is $\bar{U}_1$, and the replication dynamic equation is given by $F(x)$. The results are as follows:

$$U_{11} = zS_1 + y(a\Delta\pi_1 + L) + \pi_1 + L \tag{1}$$

$$\mathrm{U}_{12} = y(E_1 - L) - zD_1 + \pi_1 \quad (2)$$

$$\bar{U_1} = x\mathrm{U}_{11} + (1-x)\mathrm{U}_{12} = xy[\pi_1 - E_1] + xz(D_1 + S_1) + xL + y(E_1 - L) - zD_1 + \pi_1 \quad (3)$$

According to the Malthusain principle, the dynamic equation regarding the constructor can be written as follows:

$$\mathrm{F}(x) = \frac{dx}{dt} = x(1-x)(\mathrm{U}_{11} - \mathrm{U}_{12}) = x(1-x)[y(a\Delta\pi_1 - E_1) + z(D_1 + S_1) + L] \quad (4)$$

When $y = \frac{z(D_1+S_1)+L}{-(a\Delta\pi_1 - E_1)}$ and $F(x) = 0$, regardless of the value of x, both of the constructor's potential strategies are ESS [39,42]. When $y > \frac{z(D_1+S_1)+L}{-(a\Delta\pi_1 - E_1)}$, let $F(x) = 0$, and then x= 0 and x= 1 can be obtained. $F(0) > 0$, and $F(1) < 0$, x= 1 is the stability point. That is, the constructor chooses the cooperative strategy as the equilibrium point. When $y < \frac{z(D_1+S_1)+L}{-(a\Delta\pi_1 - E_1)}$, let $F(x) = 0$, and then x= 0 and x= 1 can be obtained; $F(0) < 0$, and $F(1) > 0$, x= 0 is the stability point. That is, the constructor chooses the non-cooperative strategy as the equilibrium point.

The revenue when the designer chooses to cooperate is denoted as U_{21}, that when it chooses not to cooperate is denoted as U_{22}, the average revenue of the strategic choice is $\bar{U_2}$, and the replication dynamic equation is given by $G(y)$.

$$\mathrm{U}_{21} = x[(1-a)\pi_1 - L] + zS_2 + \pi_2 + L \quad (5)$$

$$\mathrm{U}_{22} = x(E_2 - L) - zD_2 + \pi_2 \quad (6)$$

$$\bar{U_2} = y\mathrm{U}_{21} + (1-y)\mathrm{U}_{22} = xy[(1-a)\Delta\pi_1 - E_2] + yz(S_2 + D_2) + yL + x(E_2 - L) - zD_2 + \pi_2 \quad (7)$$

$$\mathrm{G(y)} = \frac{dy}{dt} = y(1-y)(\mathrm{U}_{21} - \mathrm{U}_{22}) = y(1-y)[x[(1-a)\Delta\pi_1 - E_2] + z(S_2 + D_2) + L] \quad (8)$$

When $x = \frac{z(S_2+D_2)+L}{-[(1-a)\Delta\pi_1 - E_2]}$, regardless of the value of y, both of the designer's strategies are ESS. When $x > \frac{z(S_2+D_2)+L}{-[(1-a)\Delta\pi_1 - E_2]}$, let $G(\mathrm{y}) = 0$, and then y= 0 and y= 1 can be obtained; $G(0) > 0$, and $G(1) < 0$, y= 1 is the stability point. That is, the designer chooses cooperation as the equilibrium point. When $x < \frac{z(S_2+D_2)+L}{-[(1-a)\Delta\pi_1 - E_2]}$, let $G(\mathrm{y}) = 0$, and then y= 0 and y= 1 will be obtained; $G(0) < 0$, and $G(1) > 0$, y= 0 is the stability point. That is, the designer chooses non-cooperation as the equilibrium point.

The revenue when the developer chooses to initiate the design change strategy is recorded as U_{31}, the revenue when he chooses not to initiate the design change strategy is recorded as U_{32}, the average revenue of the strategy selection is $\bar{U_3}$, and the replication dynamic equation is $H(z)$. The results are as follows:

$$\mathrm{U}_{31} = x(\mathrm{b}B - S_1 - G_1) + y[(1-\mathrm{b})B - S_2 - G_2] + \pi_3 - C + \Delta\pi_2 + G_1 + G_2 - B \quad (9)$$

$$\mathrm{U}_{32} = xbB + y(1-\mathrm{b})\mathrm{B} + \pi_3 - B \quad (10)$$

$$\bar{U_3} = \mathrm{z}\mathrm{U}_{31} + (1-z)\mathrm{U}_{32} = xz(-S_1 - G_1) + yz(-S_2 - G_2) + z(-C + \Delta\pi_2 + G_1 + G_2) + xbB + y(1-\mathrm{b})\mathrm{B} + \pi_3 - B \quad (11)$$

$$\mathrm{H(z)} = \frac{dz}{dt} = z(1-z)(\mathrm{U}_{31} - \mathrm{U}_{32}) = z(1-z)[x(-S_1 - G_1) + y[-S_2 - G_2] + \Delta\pi_2 + G_1 + G_2 - C] \quad (12)$$

When $x = \frac{y[-S_2-G_2]+\Delta\pi_2+G_1+G_2-C}{S_1+G_1}$, regardless of the value of z, both of the developer's potential strategies are ESS. When $x > \frac{y[-S_2-G_2]+\Delta\pi_2+G_1+G_2-C}{S_1+G_1}$, let $H(z) = 0$, and then z= 0 and z= 1 can be obtained; $H(0) > 0$, and $H(1) < 0, z$= 1 is the stability point. That is, the developer initiating the design change is taken as the equilibrium point. When $x < \frac{y[-S_2-G_2]+\Delta\pi_2+G_1+G_2-C}{S_1+G_1}$, let $H(z) = 0$, and then z= 0 and z= 1 will be obtained; $H(0)$ <0, and $H(1) > 0, z$= 0 is the stability point. That is, the developer not initiating design changes is the equilibrium point.

4.2. Evolutionary Equilibrium Stability Analysis

According to the method of analysis proposed by Friedman, the stability of the equilibrium point of the game can be determined by the local stability of the Jacobian matrix. The partial derivatives of x, y, and z within the replicated dynamic equation are obtained individually, and in this way, the Jacobian matrix J of the system is obtained.

$$J = \begin{bmatrix} \frac{\partial F(x)}{x} & \frac{\partial F(x)}{y} & \frac{\partial F(x)}{z} \\ \frac{\partial G(y)}{x} & \frac{\partial G(y)}{y} & \frac{\partial G(y)}{z} \\ \frac{\partial H(z)}{x} & \frac{\partial H(z)}{y} & \frac{\partial H(z)}{z} \end{bmatrix} \quad (13)$$

Based on the Jacobian matrix [43], we let $F(\mathrm{x}) = 0$, $G(y) = 0$, and $H(z) = 0$, and in this way, eight pure strategy equilibrium solutions can be obtained: A1 = (0, 0, 0), A2 = (1, 0, 0), A3 = (0, 1, 0), A4 = (0, 0, 1), A5 = (1, 0, 1), A6 = (0, 1, 1), A7 = (1, 1, 0), and A8 = (1, 1, 1). According to Lyapunov's stability criterion, when the eigenvalue of the Jacobian matrix is non-positive, the equilibrium point will be evolutionarily stable.

$$J = \begin{bmatrix} \lambda_1 & & \\ & \lambda_2 & \\ & & \lambda_3 \end{bmatrix}. \quad (14)$$

where $\lambda_1 = (1-2x)[y(a\Delta\pi_1 - E_1) + z(D_1 + S_1) + L]$, $\lambda_2 = (1-2\mathrm{y})[x[(1-a)\Delta\pi_1 - E_2] + z(S_2 + D_2) + L]$, and $\lambda_3 = (1-2z)[x(-S_1 - G_1) + y[-S_2 - G_2] + \Delta\pi_2 + G_1 + G_2 - C]$.

In relation to the equilibrium point, the possible eigenvalues are shown in Table 4.

Table 4. Equilibria points and their characteristic values.

	λ_1	λ_2	λ_3
(0, 0, 0)	L	L	$\Delta\pi_2 + G_1 + G_2 - C$
(1, 0, 0)	$D_1 + S_1 + L$	$S_2 + D_2 + L$	$-\Delta\pi_2 - G_1 - G_2 + C$
(0, 1, 0)	$a\Delta\pi_1 - E_1 + L$	$-L$	$-S_2 + \Delta\pi_2 + G_1 - C$
(0, 0, 1)	$-L$	$(1-a)\Delta\pi_1 - E_2 + L$	$-S_1 + \Delta\pi_2 + G_2 - C$
(1, 0, 1)	$a\Delta\pi_1 - E_1 + D_1 + S_1 + L$	$-S_2 - D_2 - L$	$S_2 - \Delta\pi_2 - G_1 + C$
(0, 1, 1)	$-D_1 - S_1 - L$	$(1-a)\Delta\pi_1 - E_2 + S_2 + D_2 + L$	$S_1 - \Delta\pi_2 - G_2 + C$
(1, 1, 0)	$-a\Delta\pi_1 + E_1 - L$	$-(1-a)\Delta\pi_1 + E_2 - L$	$-S_1 - S_2 + \Delta\pi_2 - C$
(1, 1, 1)	$-a\Delta\pi_1 + E_1 - D_1 - S_1 - L$	$-(1-a)\Delta\pi_1 + E_2 - S_2 - D_2 - L$	$S_1 + S_2 - \Delta\pi_2 + C$

Following the assumptions of parameter size in the model, $\Delta\pi_2 + G_1 + G_2 - C > 0$. Therefore, (0, 0, 0) and (0, 0, 1) are not asymptotically stable points.

In this game system, the more stable the design–construction consortium is, the less likely it is that design changes will occur, and the more unstable it is, the more likely they become. On the one hand, when the project fails to meet green building standards due to the speculative behavior of the members of the consortium or their failure to build according to the contract, and the required standards can only be met after a change, if it is possible for the standards to be met, the developer will not initiate design changes. However, when the design and construction consortium chooses the "non-cooperation" strategy, the developer tends to favor "initiating design change", meaning we can select

(1, 1, 0) as the optimal asymptotic stability point; that is, (cooperation, cooperation, not initiating design change). On the other hand, due to design changes initiated as a result of an unreasonable design or the irregular construction approaches of members in the consortium, the project will be more capable of meeting the green building standards, thus increasing the developer's income. Further, if one of the consortium members does not adopt the "cooperation" strategy, the developer may seek new members who will cooperate and can carry out the design changes, at which point we can select (1, 1, 1) as the asymptotic stability point.

(1) Stability analysis of the evolutionary game following the first design change.

When the first design change initiated by the developer is greater,$-S_2 + \Delta\pi_2 + G_1 - C_3 < 0$, $-S_1 + \Delta\pi_2 + G_2 - C_3 < 0$ holds, which indicates that for the developer, but not for the members of the design and construction consortium, all other strategies will help make the project green. Here, (1, 0, 0), (0, 1, 0), and (1, 1, 0) are asymptotically stable points, and (1, 1, 0) is the optimal stable point.

① When a $a\Delta\pi_1 - E_1 + L < 0$ and $(1-a)\Delta\pi_1 - E_2 + L < 0$ holds—that is, when the added value of the design and construction consortium's members due to cooperation is low—(1, 0, 0) or (0, 1, 0) will be the stable point of system evolution. When this occurs, both sides may show opportunistic behavior, potentially resulting in one party cooperating and the other party not cooperating. When this happens, the final result of the evolution of the system is determined by the position of the saddle point and the initial point of the system. As shown in the evolutionary phase diagram (Figure 1), if the chosen initial strategy falls within the region of A, the system will eventually converge to (1, 0, 0); that is, the constructer chooses a cooperative strategy, and the designer chooses a green, non-cooperative strategy. If the initial strategy choice falls within the area of B, the system converges to (0, 1, 0); that is, the constructer chooses an uncooperative strategy, and the designer chooses a cooperative strategy.

$$S_A = \frac{1}{2}\left(\frac{-L}{a\Delta\pi_1 - E_1} + \frac{(1-a)\Delta\pi_1 - E_2 + L}{(1-a)\Delta\pi_1 - E_2}\right) \quad (15)$$

According to Equation (15), the size of area S_A is determined by five factors, namely, $a, \Delta\pi_1, E_1, E_1,$ and L. The influence of one such factor, such as $\Delta\pi_1$ or L, on the area of area A is uncertain. The other three parameters will show a monotonically increasing or decreasing relationship with the area of A. The specific effects of these three parameters on the choices of the developer and constructor are shown in the table.

As shown in Table 5, the sizes of parameters a, E_1 and E_2 will affect the saddle point and the area of A. With increases in parameters a and E_2, the saddle point will move to the upper left, and the area of A will increase. At this point, when the probability of the system converging to (1, 0, 0) is greater, the saddle point will move to the upper left, and the area of A will increase with the reduction in parameter E_1. On the other hand, when the probability of the system converging to (0, 1, 0) is greater, the designer will be more willing to implement a cooperative strategy, and the constructor will be more willing to implement a non-cooperative strategy.

② When $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L < 0$, the system's equilibrium point will be stable at (1, 0, 0). This indicates that the income distribution coefficient a has increased. For the constructor, the income created by choosing the "cooperation" strategy will be greater than that generated as a result of the "private information" obtained by choosing "non-cooperation", so regardless of which strategy the designer chooses, the constructor's optimal strategy will be "cooperation". For the designer, the benefits yielded by "private information" will be much higher than those from choosing "cooperation" and will be sufficient to make up for the loss of liquidated damages. Therefore, the designer will choose an "uncooperative" strategy.

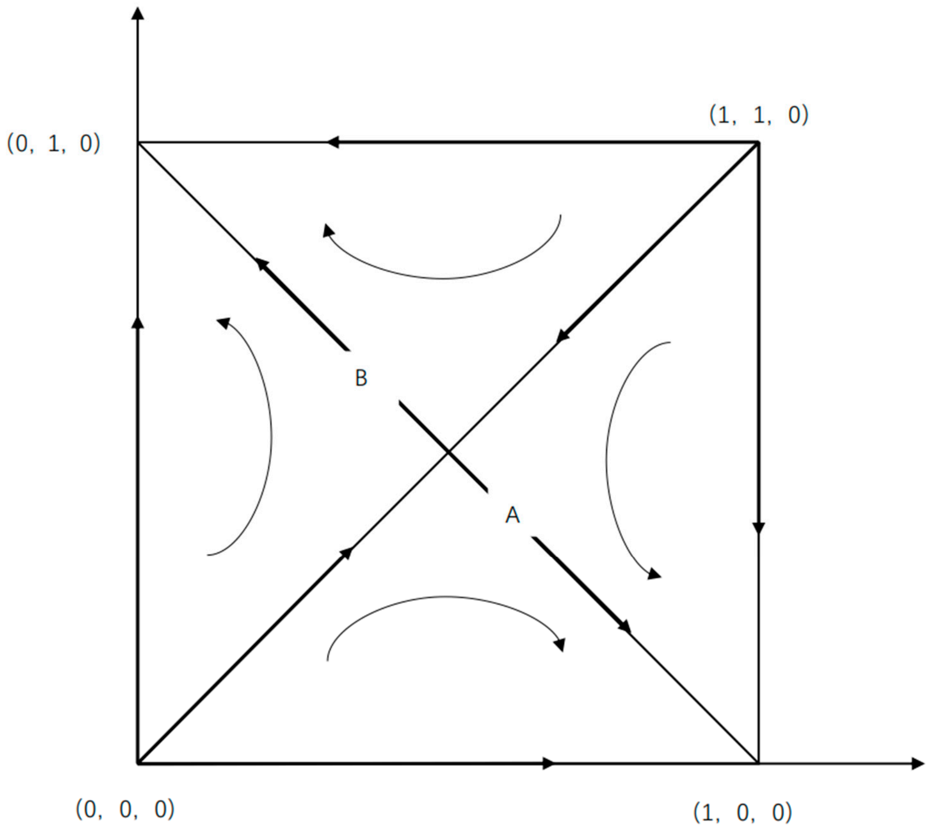

Figure 1. Evolutionary phase diagram (a).

Table 5. Correlation analysis of system parameters (a).

Parametric Variation	S_M Change	Evolutionary Direction
$a \uparrow$	$S_A \uparrow$	(1, 0, 0)
$E_1 \downarrow$	$S_A \uparrow$	(1, 0, 0)
$E_2 \uparrow$	$S_A \uparrow$	(1, 0, 0)

③ When $a\Delta\pi_1 - E_1 + L < 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$, the system's equilibrium point will be stable at (0, 1, 0). This will indicate that the income distribution coefficient a has decreased. For the designer, the income created as a result of choosing a "cooperation" strategy will be higher than the income generated as a result of the "private information" obtained by choosing "non-cooperation", so regardless of which strategy the constructer chooses, the designer's optimal strategy will be "cooperation". For the constructer, the benefits yielded by "private information" are much greater than those from choosing "cooperation" and will be sufficient to make up for the loss of liquidated damages. As such, the constructor will choose an "uncooperative" strategy.

④ When $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$, the system's equilibrium point will be stable at (1, 1, 0). This indicates that the added value of the benefits generated by cooperation or the payment of liquidated damages by the consortium is increased, so members of the consortium will tend to choose the "cooperation" strategy regardless of what the other party chooses, at which time they will obtain the greatest benefit.

(2) Stability analysis of the evolutionary game under the second design change.

In the second case of the possible design change initiated by the developer, $-S_2 + \Delta\pi_2 + G_1 - C > 0, -S_1 + \Delta\pi_2 + G_2 - C > 0$ holds, which indicates that for the developer, all strategy combinations result in the project reaching the green building standard, but if a design change is made, the design will be more reasonable and the construction process will be more convenient. Here, (1, 0, 1), (0, 1, 1), (1, 1, 0), and (1, 1, 1) are asymptotically stable points, and (1, 1, 1) is the most stable point.

① When $a\Delta\pi_1 - E_1 + L + D_1 + S_1 < 0$ and $(1-a)\Delta\pi_1 - E_2 + L + D_2 + S_2 < 0$—that is, when the added value produced by the members of the design and construction consortium is very low—the reputational loss suffered and the design change subsidy that must be paid by the developer will still be ignored. Under these conditions, there is a stable strategy, but it is not unique; that is, (1, 0, 1) or (0, 1, 1) can be taken as the stable point of the system's evolution. Both sides may choose to undertake opportunistic behaviors, resulting in one party cooperating and the other party not cooperating. At this point, the final result of the evolution of the system will be determined by the positions of the saddle point and the initial point of the system. As shown in the evolutionary phase diagram (Figure 2), if the initial strategy choice falls within the region of C, the system will eventually converge to (1, 0, 1); that is, the constructer will choose a cooperative strategy and the designer will choose a green, non-cooperative strategy. If the initial strategy choice falls within the area of D, the system will converge to (0, 1, 1); that is, the constructer will choose an uncooperative strategy and the designer will choose a cooperative strategy.

$$S_C = \frac{1}{2}\left(-\frac{D_1 + S_1 + L}{a\Delta\pi_1 - E_1} + \frac{(1-a)\Delta\pi_1 - E_2 + D_2 + S_2 + L}{(1-a)\Delta\pi_1 - E_2}\right) \tag{16}$$

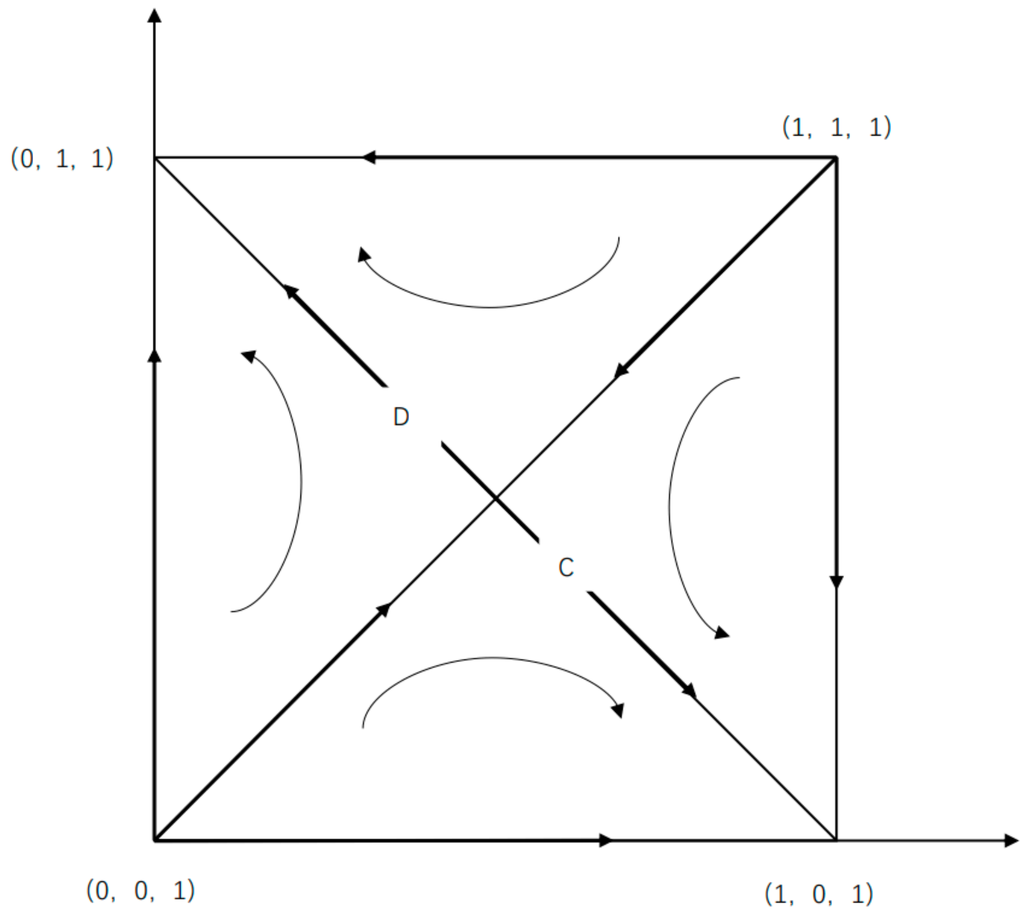

Figure 2. Evolutionary phase diagram (b).

According to Equation (16), the size of area S_C is affected by nine factors: a, $\Delta\pi_1$, E_1, E_1, D_1, D_2, S_1, S_2, and L. Here, the influences of factors $\Delta\pi_1$ and L on the area of C are uncertain, but the other seven parameters show a monotonically increasing or decreasing relationship with the area of C. The specific influences of these seven parameters on the choices of the developer and constructor are shown in Table 6.

Table 6. Correlation analysis of system parameters (b).

Parametric Variation	S_C Change	Evolutionary Direction
$a \uparrow$	$S_C \uparrow$	(1, 0, 1)
$E_1 \downarrow$	$S_C \uparrow$	(1, 0, 1)
$E_2 \uparrow$	$S_C \uparrow$	(1, 0, 1)
$D_1 \downarrow$	$S_C \uparrow$	(1, 0, 1)
$D_2 \uparrow$	$S_C \uparrow$	(1, 0, 1)
$S_1 \downarrow$	$S_C \uparrow$	(1, 0, 1)
$S_2 \uparrow$	$S_C \uparrow$	(1, 0, 1)

As shown in Table 6, the sizes of parameters $a, \Delta\pi_1, E_1, E_1, D_1, D_2, S_1, S_2$, and L will all affect the saddle point and the area of C. With increases in parameters a, E_1, D_1, and S_1, the saddle point will move to the upper left. With reductions in parameters E_2, D_2, and S_2, the saddle point will move to the upper left, and the area of region C will increase. Under these conditions, the probability that the system converges to (1, 0, 1) will be greater; that is, the constructer will be more willing to undertake a cooperative strategy, and the designer will be more willing to implement a non-cooperative strategy. On the other hand, when the opposite pertains, the probability that the system converges to (0, 1, 1) will be greater; the designer will be more willing to implement a cooperative strategy, and the constructer will be more willing to implement a non-cooperative strategy.

② When $-D_1 - S_1 < a\Delta\pi_1 - E_1 + L < 0$ and $(1-a)\Delta\pi_1 - E_2 + L + D_2 + S_2 < 0$, the system's equilibrium point will be stable at (1, 0, 1). This means that the income distribution coefficient a will have increased. For the constructor, due to the necessity of the payment of developer subsidies, the benefits induced by choosing a "cooperation" strategy will be sufficient to make up for the reputation loss caused by choosing "non-cooperation", so for the constructor, the optimal strategy is "cooperation". For the designer, the profit yielded by choosing "cooperation" will remain very low, and they would most likely rather bear the reputational loss and compensate for the liquidated damages. Therefore, the designer will most likely choose an "uncooperative" strategy.

③ When $a\Delta\pi_1 - E_1 + L + D_1 + S_1 < 0$ and $-D_2 - S_2 < (1-a)\Delta\pi_1 - E_2 + L < 0$, the system's equilibrium point will be stable at (0, 1, 1). This means that the income distribution coefficient a will have decreased. For the designer, because of the necessity of paying a developer subsidy, the income derived from choosing a "cooperation" strategy will be sufficient to make up for the reputational loss brought about by choosing "non-cooperation", so the optimal strategy for the designer is "cooperation". For the constructor, the benefits resulting from choosing "cooperation" remain very low, meaning they would most likely rather bear the reputational loss and compensate for the liquidated damages. As such, the constructor will most likely choose an "uncooperative" strategy.

④ When $-D_1 - S_1 < a\Delta\pi_1 - E_1 + L < 0$ and $-D_2 - S_2 < (1-a)\Delta\pi_1 - E_2 + L < 0$, if $-S_1 - S_2 + \Delta\pi_2 - C < 0$, the system has no stable equilibrium point, but if $-S_1 - S_2 + \Delta\pi_2 - C > 0$, the system's equilibrium point will be stable at (1, 1, 1). If the developer's net income is insufficient to pay the required subsidies to the cooperative enterprise, one or perhaps both parties in the consortium will choose not to cooperate; however, this situation is not optimal for the developer, so they will tend to choose to initiate a design change. When this happens, the consortium members tend to cooperate. However, when the developer recognizes the willingness of some members to cooperate, they will be more likely to not initiate any changes, meaning there will be no equilibrium and stability point in the system. When the developer can use the net income derived from design changes to pay the subsidy to the cooperative enterprise, they will most likely choose to initiate such changes, as long as the consortium members do not choose the strategy of (non-cooperation, non-cooperation); under these conditions, the consortium members will choose the cooperation strategy, and the system will show equilibrium and stability points (1, 1, 1).

⑤ When $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$, if $-S_1 - S_2 + \Delta\pi_2 - C < 0$, the system's equilibrium point will be stable at (1, 1, 0), but when $-S_1 - S_2 + \Delta\pi_2 - C > 0$, the system's equilibrium point will be stable at (1, 1, 1). This means that the added value of the benefits generated by cooperation or the liquidated damages paid by the design and construction consortium is increased, meaning the consortium members will tend to choose the "cooperation" strategy regardless of whether the developer gives subsidies or not. If the developer's net income is insufficient to pay the subsidy to the cooperative enterprise, the system's equilibrium point will be stable at (1, 1, 0). If the developer's net income can be used to pay the subsidy, the system's equilibrium point will be stable at (1, 1, 1).

5. Simulation Analysis and System Optimization

From the previous analysis, we can see that the evolutionary stability strategy and evolutionary path are different in different scenarios. In order to analyze the evolution trajectory and final stable state of the game process of related agents more intuitively, this paper uses Matlab2019 software to carry out numerical simulation analysis, and the specific simulation process is divided into two parts. In the first part, the evolutionary trajectory of ESS is numerically simulated by the equilibrium point of the tripartite evolutionary game. The second part simulates the influence of the additional income distribution coefficient, additional income, default cost, and subsidy on the evolution results.

Because there are many parameters involved in this study, the interaction between parameters is extremely complicated. In order to accurately reflect the actual situation, we primarily refer to relevant literature to determine some basic data. We also consulted experts from relevant enterprises to discuss and improve some missing data. Finally, the parameter values shown in Tables 7 and 8 are sorted.

Table 7. Parameter value setting—the first design change.

Parameter	a	$\Delta\pi_1$	$\Delta\pi_2$	C	D_1	D_1	E_1	E_2	S_1	S_2	G_1	G_2	F
numeric value	0.5	3.5	3	3.5	0.4	0.5	3	2.5	0.3	0.2	0.6	0.6	1

Table 8. Parameter value setting—the second design change.

Parameter	a	$\Delta\pi_1$	$\Delta\pi_2$	C	D_1	D_1	E_1	E_2	S_1	S_2	G_1	G_2	F
numeric value	0.5	3.5	3.8	3.5	0.4	0.5	3	2.5	0.3	0.2	0.2	0.1	1

5.1. Stability Analysis of the Equilibrium Point

Here, Matlab is used to simulate an evolutionary game within a tripartite system, and numerical simulations are carried out for A3 = (0, 1, 0), A4 = (1, 0, 0), A5 = (0, 1, 1), A6 = (1, 0, 1), A7 = (1, 1, 0), and A8 = (1, 1, 1) in order to more clearly characterize the behaviors within the three-party system and verify the correctness of the game model.

(1) The developer-initiated design is set as the first case, during which there are three asymptotic stability points, A3 = (0, 1, 0), A4 = (1, 0, 0), and A7 = (1, 1, 0). The initial values in the design are set to $a = 0.5, \Delta\pi_1 = 3.5, \Delta\pi_2 = 3, C = 3.5, E_1 = 3, E_2 = 2.5$, $D_1 = 0.4, D_2 = 0.5, S_1 = 0.3, S_2 = 0.2, G_1 = 0.6, G_2 = 0.6$, and $F = 1$. The results of the evolution are shown in Figure 3.

As shown in Figure 3, the initial values described above mean that $\Delta\pi_1 - E_1 + L < 0$, $(1-a)\Delta\pi_1 - E_2 + L < 0$ is true, and so the initial strategy that is selected falls into the area of N, meaning the equilibrium stability point is (0, 1, 0).

If we reduce the size of parameter a such that $a\Delta\pi_1 - E_1 + L < 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$ is true, then the equilibrium stability point is (0, 1, 0); on the other hand, if we increase the size of a, $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L < 0$ will hold, and the equilibrium stability point will be (1, 0, 0).

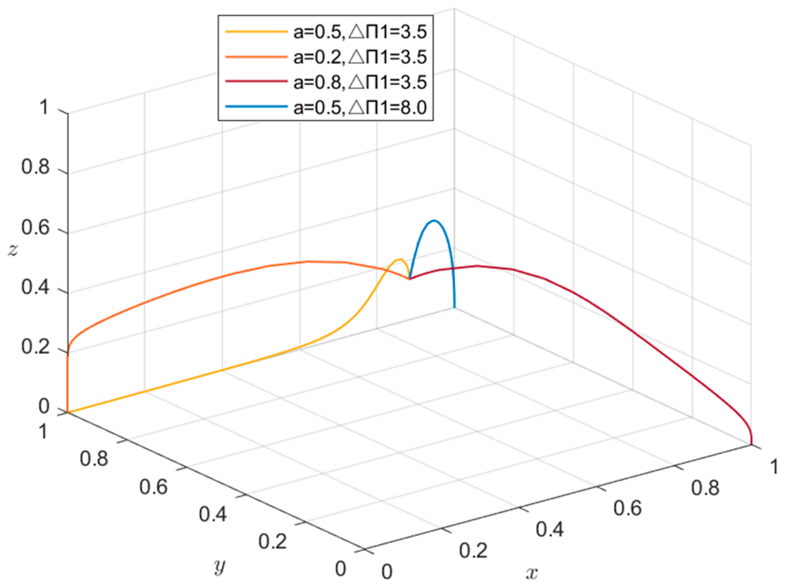

Figure 3. Evolution results in different situations—the first design change.

If we adjust parameter $\Delta\pi_1$ such that $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$ holds, the equilibrium stability point will be (1, 1, 0).

(2) Under the second developer-initiated design, there are four asymptotic stability points: A5 = (0, 1, 1), A6 = (1, 0, 1), A7 = (1, 1, 0), and A8 = (1, 1, 1). The initial values that we use are set to $a = 0.5, \Delta\pi_1 = 3.5, \Delta\pi_2 = 3.8, C = 3.5, E_1 = 3, E_2 = 2.5, D_1 = 0.4, D_2 = 0.5, S_1 = 0.3, S_2 = 0.2, G_1 = 0.2, G_2 = 0.1$ and $F = 1$, and the results of the evolution are shown in Figure 4.

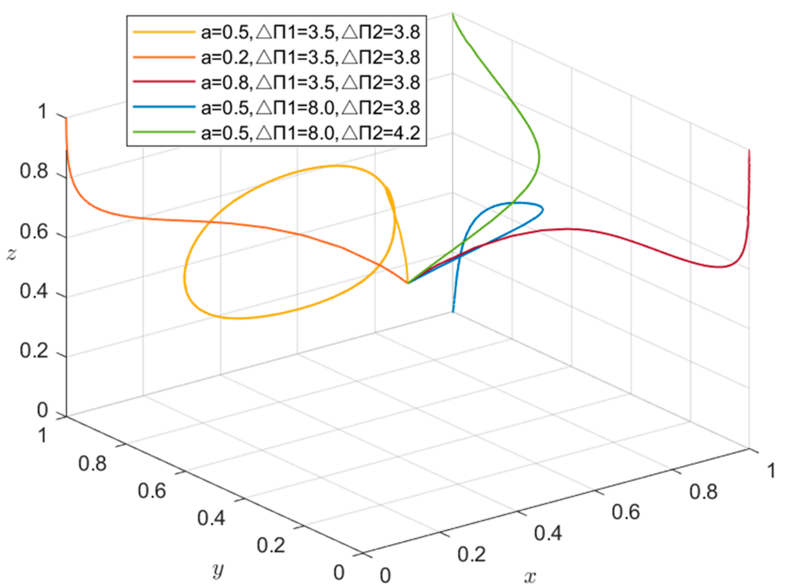

Figure 4. Evolution results in different situations—the second design change.

As shown in Figure 4, The initial value setting makes $-D_1 - S_1 < a\Delta\pi_1 - E_1 + L < 0$, $-D_2 - S_2 < (1-a)\Delta\pi_1 - E_2 + L < 0$ hold, but at this time, the benefits of the developer's choice to initiate design changes are not enough to subsidize the cooperative members, so the system is in a periodic state.

If we reduce the size of parameter a such that $a\Delta\pi_1 - E_1 + L + D_1 + S_1 < 0$ and $-D_2 - S_2 < (1-a)\Delta\pi_1 - E_2 + L < 0$ are true, then the equilibrium stability point will be (0,1,1); on the other hand, if the size of a is increased, such that $-D_1 - S_1 < a\Delta\pi_1 - E_1 + L < 0$

and $(1-a)\Delta\pi_1 - E_2 + L + D_2 + S_2 < 0$ are true, then the equilibrium stability point will be (1, 0, 1).

If we adjust the size of parameter $\Delta\pi_1$ so that $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$ are true, the equilibrium stability point will be (1, 1, 0); on this basis, $\Delta\pi_2 - C - S_1 - S_2 > 0$ holds, and as a result, the equilibrium point will change from (1, 1, 0) to (1, 1, 1) and system optimization will be achieved.

5.2. Correlation Parameter Analysis

Based on the above theoretical analyses performed under different circumstances, we next used Matlab2019 simulations to study the impacts of the benefit distribution coefficient, the revenue added value, and the default cost on the stability of the design–construction consortium.

5.2.1. The First Case of Contractor-Initiated Design Changes

Assume that the initial states of the constructor, designer, and developer are equal to 0.5. Table 7 shows a breakdown of the parameters.

(1) The influence of income distribution coefficient A on the stability of the design and construction consortium.

We have adjusted the size of the additional income distribution coefficient to observe its effects on the stability of the design–construction consortium; we set a = 0.2, a = 0.5, and a = 0.8 in respective simulations, and the results are shown in Figure 5.

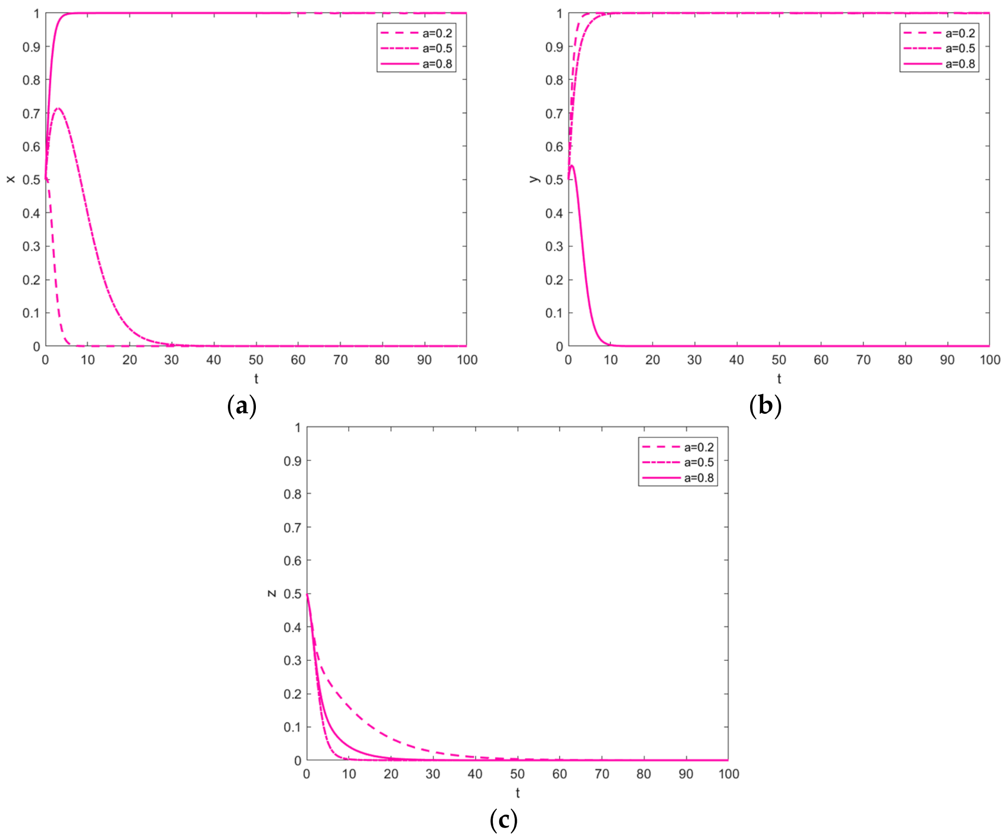

Figure 5. (**a**) Evolutionary path of the constructer with different additional income distribution coefficients a—The first design change; (**b**) evolutionary path of the designer with different additional income distribution coefficients a—The first design change; (**c**) evolutionary path of the developer with different additional income distribution coefficients a—The first design change.

Figure 5 shows that when the constructer's additional income distribution coefficient a is low, they will choose a cooperative strategy, but they will be relatively more inclined to choose a non-cooperation strategy so as to obtain income related to obtaining "private information" and the payment of liquidated damages. On the other hand, the designer's additional revenue distribution coefficient is $1 - a$, which is higher. This means that the designer's return as a result of choosing a cooperative strategy will be higher—sufficiently so to exceed the benefits derived from "private information". This means that regardless of which strategy the construction company chooses, the designer will choose a cooperation strategy. When the absolute value of the difference between the constructer's additional income distribution coefficient a and the designer's additional income distribution coefficient is $1 - a$—that is, when coefficient a is closer to 0.5—the constructer and designer's strategies tend to stabilize more slowly. Further, the additional income distribution coefficient a has little effect on the stability of the design and construction consortium, which is primarily affected by other factors. When the constructer's additional income distribution coefficient a is high, their income derived from the choice of a cooperative strategy will be higher—sufficiently so to exceed the returns generated by "private information", so they will tend to cooperate. However, the designer's additional income distribution coefficient at this time will be low, making them more inclined to choose a non-cooperation strategy in order to obtain the benefits of "private information" and the payment of liquidated damages.

In general, when the absolute value of the difference between a and $1 - a$ is smaller, the impact on the stability of the design and construction consortium will be smaller, and when the inverse is true, the impact on the design and construction consortium will be greater, making the design and construction consortium more unstable. For the developer, the smaller the absolute value of the difference between a and $1 - a$, the faster they will converge on the choice of not initiating design changes.

(2) The impact of revenue added value $\Delta\pi_1$ on the stability of the design and construction consortium.

We have adjusted the size of the revenue added value in order to observe its effect on the stability of the design and construction consortium; we set values of $\Delta\pi_1 = 2$, $\Delta\pi_1 = 3.5$ and $\Delta\pi_1 = 5$ in the simulations, and the results are shown in Figure 6.

As can be seen from Figure 6, for the constructor, although the extra revenue $\Delta\pi_1$ generated from cooperation is lower, making cooperation strategies less profitable, the increase in extra revenue $\Delta\pi_1$ will still direct their evolutionary path towards cooperation at the beginning, but the difference between the revenue derived from obtaining "private information" and the payment of liquidated damages remains higher than the benefits generated by cooperation, so the result of long-term evolution will still tend towards non-cooperation. However, with increases in the additional revenue $\Delta\pi_1$, the inhibition of the evolutionary trend's movement towards non-cooperative strategies will be greater, and this will ultimately tend towards a cooperative strategy. For the designer, the revenue derived from choosing a cooperation strategy will be sufficient to exceed the revenue derived from "private information", so no matter which strategy the construction company chooses, the designer will choose a cooperation strategy. However, when the final result of the evolution of the construction company is the choice of an uncooperative strategy, the speed at which the designer converges towards choosing a cooperative strategy will slow with the increase in the additional revenue $\Delta\pi_1$. When the final result of the evolution of the construction company is the choice of cooperation, as the additional revenue $\Delta\pi_1$ increases, the convergence of the designer towards a cooperation strategy will be accelerated.

In general, when the benefits related to the "private information" held by members of the design and construction consortium and the payment of liquidated damages are smaller than the benefits generated by cooperation, with the increase in additional revenue $\Delta\pi_1$, the speed of convergence towards an uncooperative strategy by members ultimately choosing this strategy will be inhibited, and the speed of convergence towards a cooperative strategy by members ultimately choosing this strategy will also be inhibited. When the benefits related to the "private information" held by members of the consortium and to the payment of liquidated damages are greater than the benefits generated by cooperation, the speed of convergence of the members towards a cooperation strategy will be increased with increases in the additional gain $\Delta\pi_1$. Therefore, the higher the additional gain $\Delta\pi_1$, the greater the impact on the stability of the design and construction consortium, and the design and construction consortium will be made relatively more stable. The developer's strategy will converge more quickly towards not initiating a design change as the additional revenue $\Delta\pi_1$ increases.

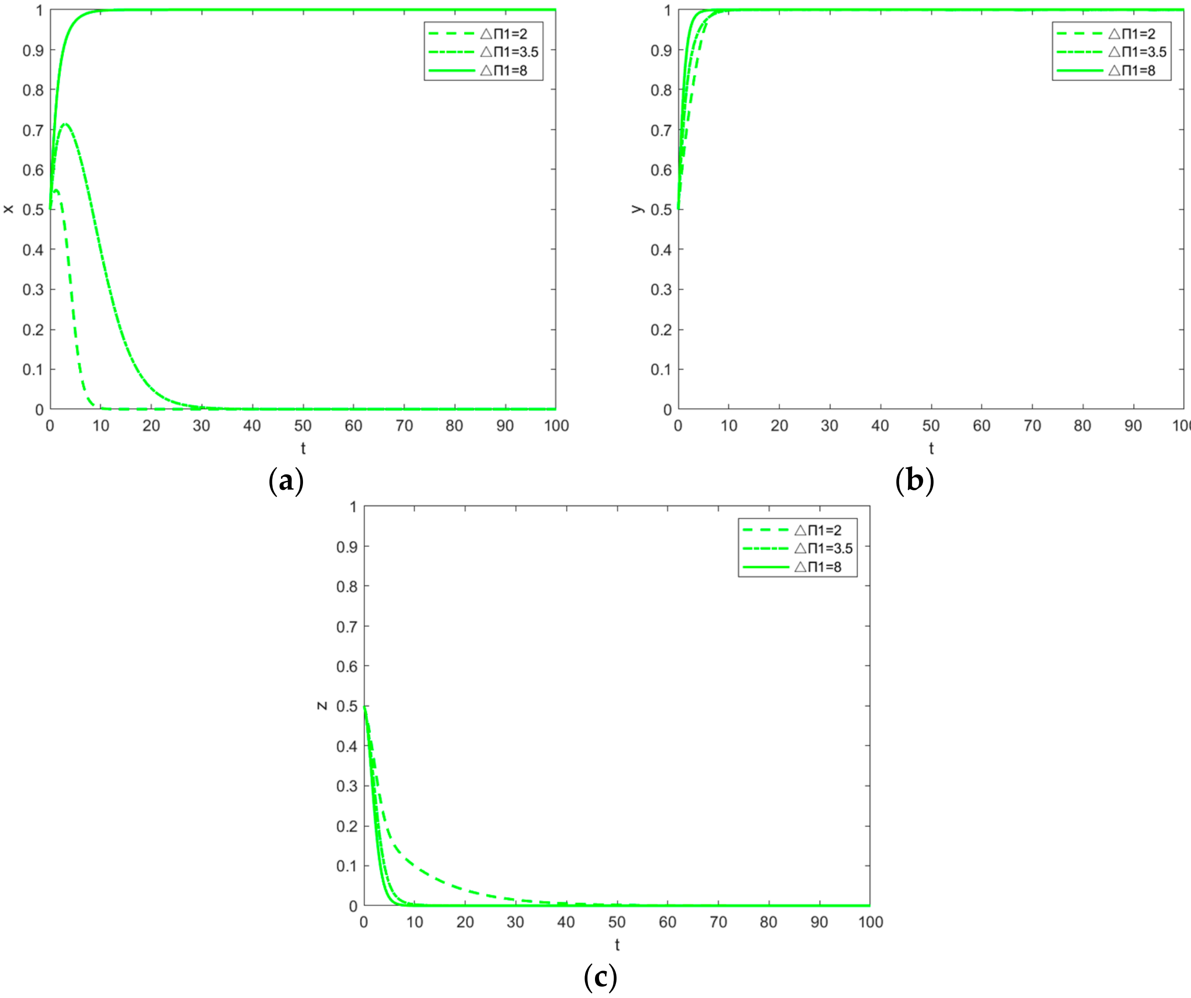

Figure 6. (**a**) Evolutionary path of the constructer under different values of additional revenue $\Delta\pi_1$—The first design change; (**b**) evolutionary path of the designer under different values of additional revenue $\Delta\pi_1$—The first design change; (**c**) evolutionary path of the developer under different values of additional revenue $\Delta\pi_1$—The first design change.

(3) The impact of default cost F on the stability of the design and construction consortium.

By adjusting the default cost, we can observe its effects on the stability of the design–construction consortium, and so we set the values of F = 0.5, F = 1, and F = 1.5 in the simulations. The results are shown in Figure 7.

As Figure 7 shows, with increases in the default cost f, the convergence of non-cooperative members of the consortium will be restrained, and the convergence of cooperative members will be accelerated. Therefore, the higher the default cost f, the more highly the cooperation within the design and construction consortium will be promoted, and the more stable it will be. In contrast, the lower the default cost F, the smaller the impact on the stability of the construction consortium. For a developer, with an increase in default cost F, their strategy will more quickly converge towards not initiating design changes.

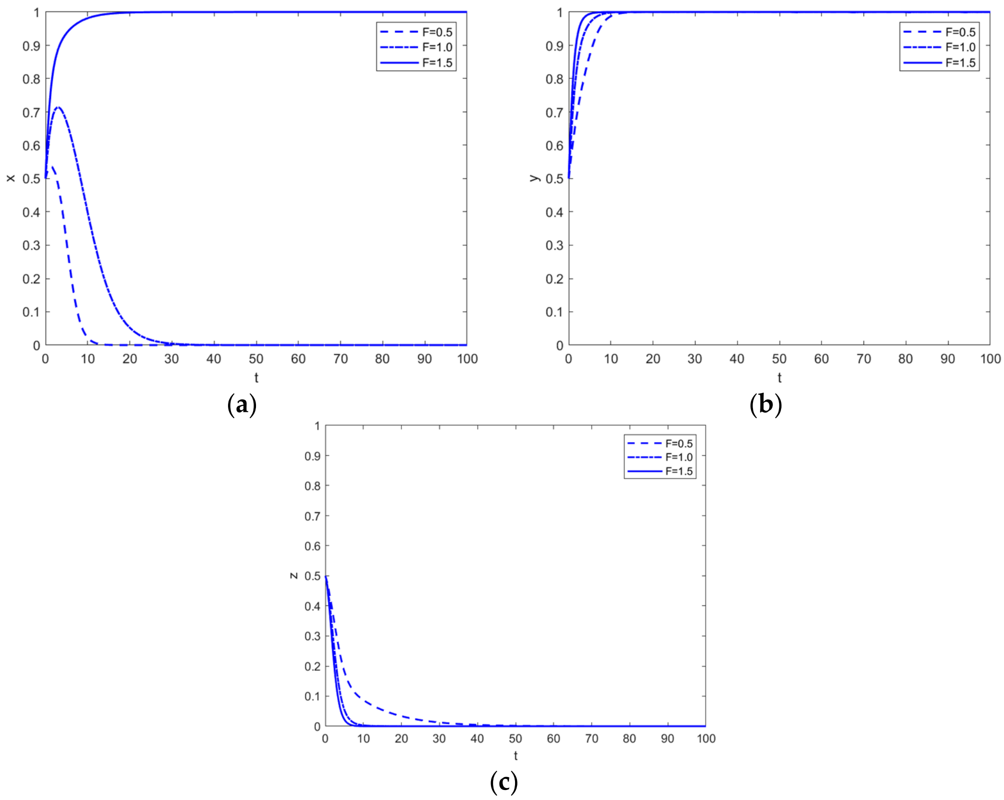

Figure 7. (**a**) Evolutionary path of the constructer with different default costs F—The first design change; (**b**) evolutionary path of the designer with different default costs F—The first design change; (**c**) evolutionary path of the developer with different default costs F—The first design change.

5.2.2. Developer—Initiated Design Changes in the Second Case

We assume that the initial states of the constructor, designer, and developer equal 0.5. Table 8 shows the parameter details.

(1) The influence of income distribution coefficient A on the stability of the design and construction consortium.

We have adjusted the size of the additional income distribution coefficient to observe its effects on the stability of the design–construction consortium; we set values of a = 0.2, a = 0.5, and a = 0.8 for the simulations, and the results are shown in Figure 8.

As Figure 8 shows, when the additional income distribution coefficient a of the constructor is low, they will quickly tend towards being "uncooperative". At this time, when the designer chooses a cooperative strategy, their income will be higher, so when the additional income distribution coefficient a approaches 0, the system will quickly converge towards (0, 1, 1). When the constructer's additional income distribution coefficient a approaches 0.5, this factor will have little influence on the stability of the consortium, of which stability will primarily be affected by opportunistic behavior, subsidies, and other factors. When their net income derived from a design change is greater than that derived from a subsidy paid to the enterprise, if the design and construction consortium chooses the (cooperation, cooperation) strategy, the developer will more likely choose to initiate said change. On the other hand, when the consortium chooses (cooperation, cooperation), the developer will not choose to initiate such changes; as such, in a certain case, if the developer tends to initiate design changes, the design and construction consortium tends to cooperate. However, when the design and construction consortium chooses (cooperation, cooperation), the developer's optimal strategy is not to initiate design changes, meaning their evolutionary direction changes from initiating design changes to not initiating design changes. As such, in certain cases, when the additional income distribution coefficient a of the constructor is high, their strategy selection will quickly tend towards "cooperation".

Under this circumstance, the designer's income when choosing a cooperation strategy will be low, and so when the additional income distribution coefficient a approaches 1, the system will quickly converge to (1, 0, 1).

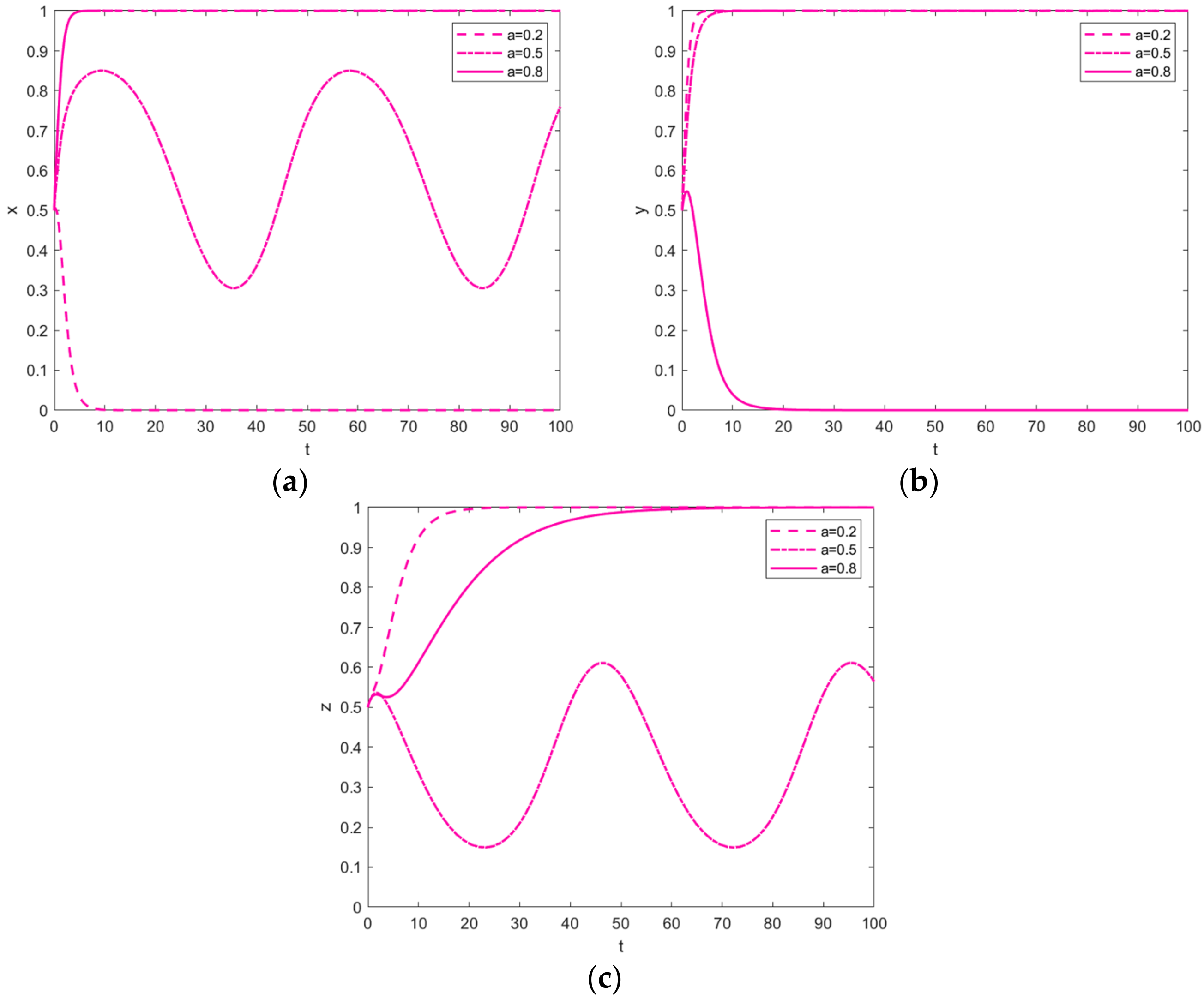

Figure 8. (**a**) Evolutionary path of the constructer with different additional income distribution coefficients a—The second design change; (**b**) evolutionary path of the designer with different additional income distribution coefficients a—The second design change; (**c**) evolutionary path of the developer with different additional income distribution coefficients a—The second design change.

Generally speaking, when the absolute value of the difference between a and 1 − a is smaller, its influence on the stability of the design and construction consortium is reduced, and in the converse case, its influence is increased, meaning the design and construction consortium will be more unstable. The greater the absolute value of the difference between a and 1 − a, the faster the constructor's strategy will converge towards initiating design changes, while when the absolute value of the difference between a and 1 − a is smaller, the extent to which it inhibits convergence in the direction of not initiating design changes is altered.

(2) The impact of revenue added value $\Delta\pi_1$ on the stability of the design and construction consortium.

By adjusting the size of the revenue added value, we have observed its influence on the stability of the design and construction consortium; values of $\Delta\pi_1 = 2, \Delta\pi_1 = 3.5$ and $\Delta\pi_1 = 5$ have been set for the simulations, and the results are shown in Figure 9.

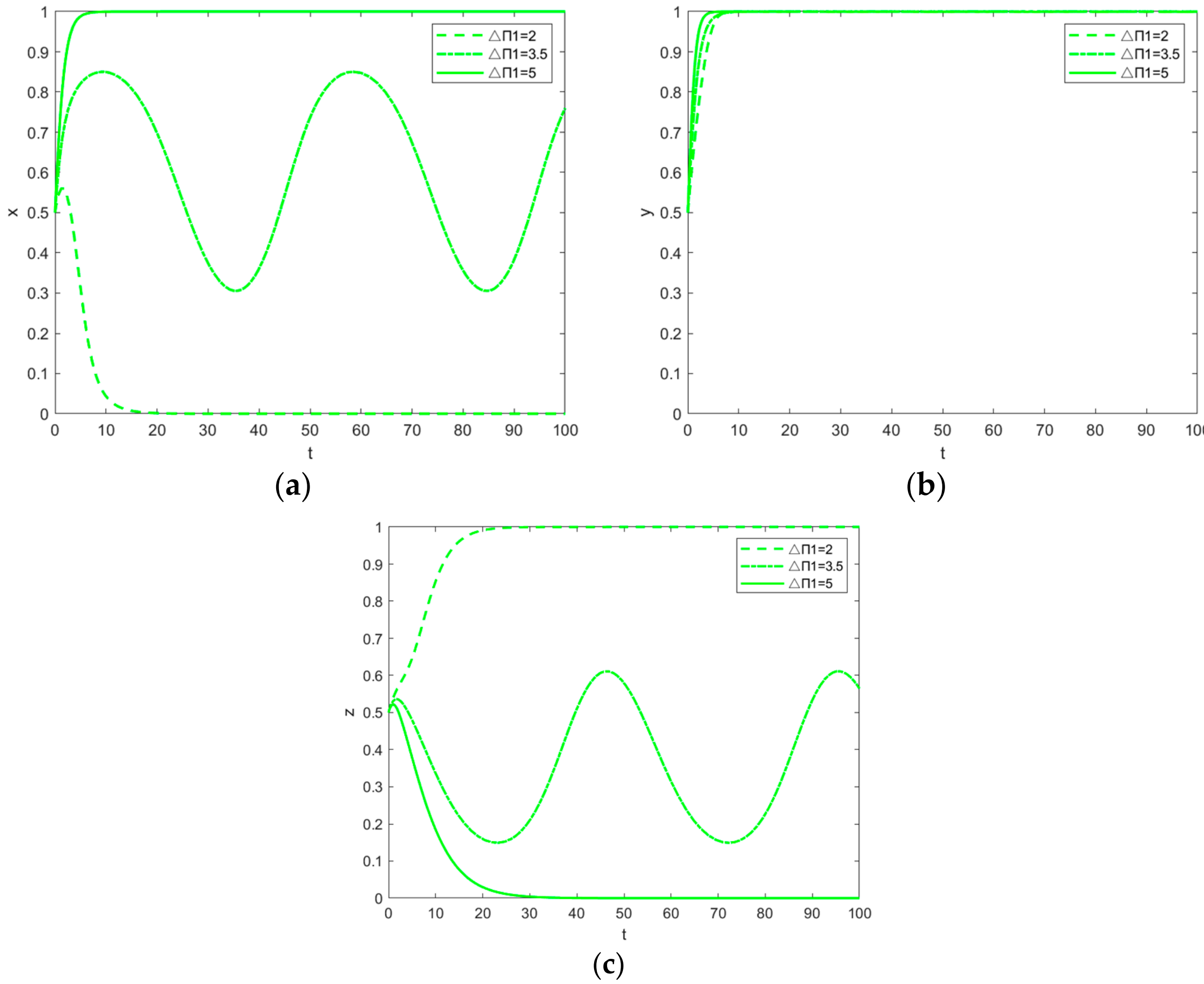

Figure 9. (**a**) Evolutionary path of the constructer with different additional revenue $\Delta\pi_1$—The second design change; (**b**) evolutionary path of the designer with different additional revenue $\Delta\pi_1$—The second design change; (**c**) evolutionary path of the developer with different additional revenue $\Delta\pi_1$—The second design change.

Generally speaking, when the constructor's $a\Delta\pi_1 - E_1 + L + D_1 + S_1 < 0$, as the additional income $\Delta\pi_1$ is increased, their convergence towards an uncooperative strategy will be inhibited, and their convergence towards a cooperative strategy will also be inhibited. When the designer's $(1-a)\Delta\pi_1 - E_2 + L + D_2 + S_2 < 0$, as the additional income $\Delta\pi_1$ is increased, the evolution path of their choice will be the same. When $-D_1 - S_1 < a\Delta\pi_1 - E_1 + L < 0$ and $-D_2 - S_2 < (1-a)\Delta\pi_1 - E_2 + L < 0$, the system will adopt a periodic state, but with the increase in additional income $\Delta\pi_1$, the volatility of the system will be enhanced. When $a\Delta\pi_1 - E_1 + L > 0$ and $(1-a)\Delta\pi_1 - E_2 + L > 0$, as the additional income $\Delta\pi_1$ is increased, its influence on the stability of the design and construction consortium will be increased, and the design and construction consortium will be made more stable. For the developer, when the additional income $\Delta\pi_1$ is increased, the convergence of its strategy towards not initiating design changes will be more restricted.

(3) The impact of default cost F on the stability of the design and construction consortium.

By adjusting the default cost, we can observe its influence on the stability of the design–construction consortium; as such, we set values of F = 0.5, F = 1, and F = 1.5 for the simulations. The results are shown in Figure 10.

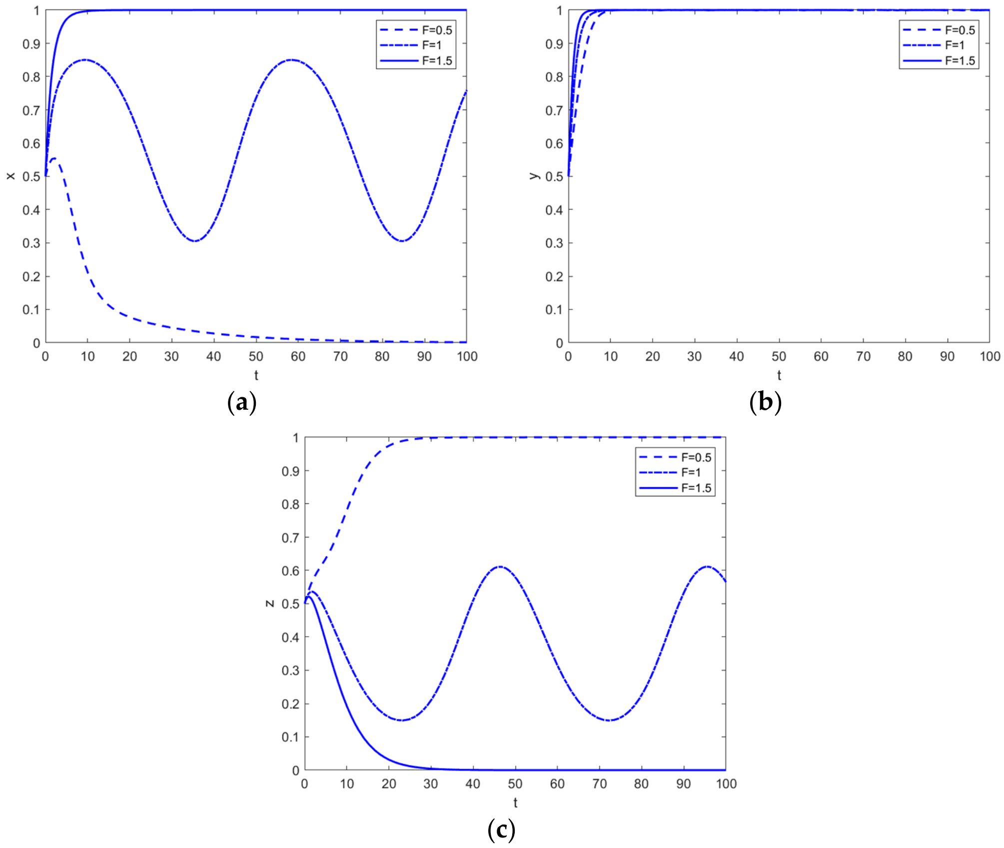

Figure 10. (**a**) Evolutionary path of the constructer with different default costs F—The second design change; (**b**) evolutionary path of the designer with different default costs F—The second design change; (**c**) evolutionary path of the developer with different default costs F—The second design change.

As Figure 10 shows, within the design and construction consortium, with increases in default cost F, the convergence of the non-cooperative members will be restrained, and that of cooperative members will be accelerated. Therefore, the higher the default cost F, the more strongly the cooperation amongst the design and construction consortium will be promoted, and the more stable the consortium will be. In contrast, the lower the default cost F, the lower the impact will be on the stability of the consortium. For the developer, as default cost F increases, it will restrain convergence in the direction of not initiating design changes, and the opposite case will accelerate convergence in the direction of initiating such change.

(4) The influence of the developer's subsidy S on the stability of the design and construction consortium.

By adjusting the size of the subsidy S paid to the cooperative members, we can observe its influence on the stability of the design and construction consortium; as such, four subsidy scenarios are established, namely, $S_1 = 0.1, S_2 = 0.1, S_1 = 0.1, S_2 = 0.3, S_1 = 0.3, S_2 = 0.1$, $S_1 = 0.3$, and $S_2 = 0.3$. The results are shown in Figure 11.

As can be seen from Figure 11, for the members of the design and construction consortium, if the subsidy paid to the other members is fixed, with an increase in the subsidy paid to one member, this member's evolutionary path will converge towards cooperation. If the subsidy paid to one member is fixed, increases in the subsidy paid to the other members will inhibit the convergence of its evolutionary path towards cooperation. For a developer, if the subsidies paid to the design and construction consortium are increased, the speed of convergence towards initiating design changes will slow down. If the system resides in a periodic state, increases in subsidies paid to the design and construction consortium will make the evolutionary path of the developer more volatile.

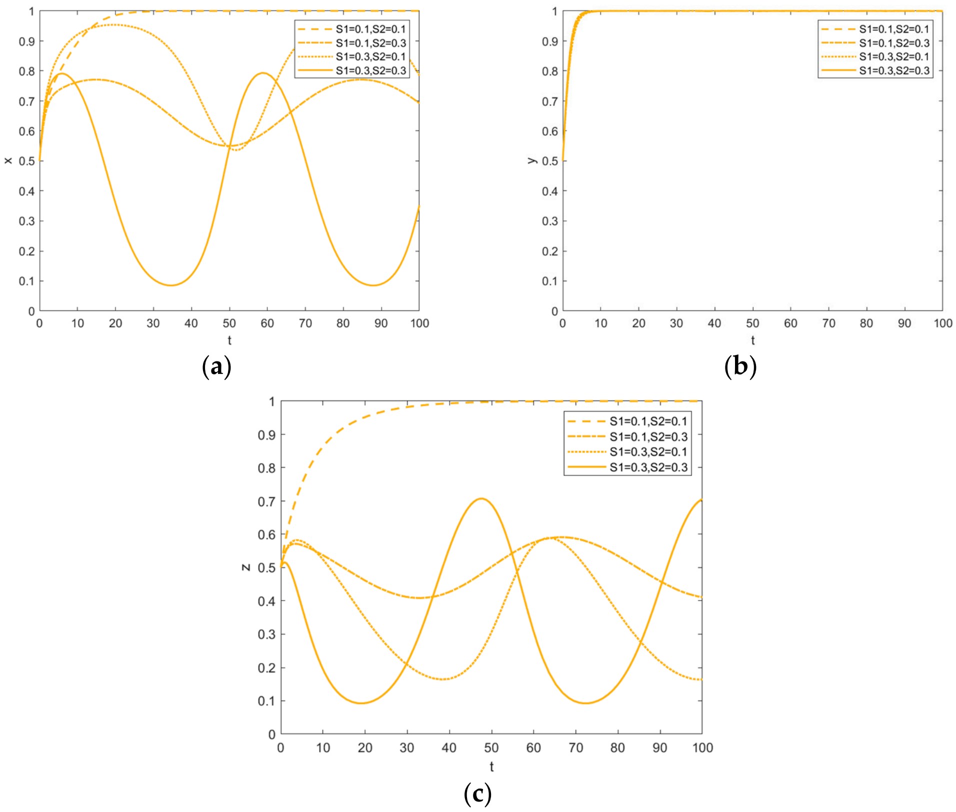

Figure 11. (**a**) Evolutionary path of the constructer with different change subsidies S_1,S_2—The second design change; (**b**) evolutionary path of the designer with different change subsidies S_1,S_2—The second design change; (**c**) evolutionary path of the developer with different change subsidies S_1,S_2—The second design change.

Generally speaking, if one member of the design and construction consortium is stable in their choice of a cooperative strategy, then as the subsidy paid by the developer to the other member increases, the opportunistic behavior of the other member will be inhibited, and the speed of their convergence towards non-cooperation will too. That is to say that, with increases in the subsidy paid by the developer to certain members, it may not be possible to stabilize the member's strategy selection at (1, 1), but the member's strategy selection may be prevented from stabilizing at (0, 0), (1, 0) or (0, 1). Therefore, the subsidy paid by the developer to the members of the design and construction consortium will promote the stability of the consortium to a certain extent, while the subsidy represents a cost demanded by the developer. If the subsidy is too high, it will inhibit the developer's design change behavior, which is not conducive to their management of green projects, meaning there is a threshold applied to this subsidy.

6. Conclusions and Suggestions

6.1. Conclusions

Based on the characteristics of bounded rationality and asymmetric information, this paper applies the evolutionary game theory to the research on the stability of the cooperative relationship of the design and construction consortium during the implementation of large-scale green building projects, establishes a tripartite evolutionary game model with the constructer, designer, and developer as the main body, and dynamically analyzes the influence of relevant parameters on the system evolution strategy. MATLAB2019b is used to simulate and analyze the data, which verifies the effectiveness of the evolutionary game and the influence of related factors on the stability of the consortium and obtains the stability conditions of the optimal strategy combination under different design changes. According to the influence relationship and stability conditions among various factors, corresponding countermeasures and suggestions are put forward for stakeholders. The main conclusions are as follows:

(1) A3 = (0, 1, 0), A4 = (1, 0, 0), A5 = (0, 1, 1), A6 = (1, 0, 1), A7 = (1, 1, 0), and A8 = (1, 1, 1) are evolutionary stability points, where A7 = (1, 1, 0) and A8 = (1, 1, 1) are ideal evolutionary stability points in two cases, respectively.

(2) If the absolute value of the difference between a and 1-a is smaller, its influence on the stability of the design and construction consortium will be reduced; if the opposite pertains, it will have greater influence, making the consortium more unstable.

(3) Increases in additional income $\Delta\pi_1$ will reduce the instability of the design and construction consortium at first. With continuous increases in $\Delta\pi_1$, the stability of the design and construction consortium will be strengthened.

(4) The payment of subsidies by the developer to the cooperative members will inhibit the non-cooperative behavior of the members and increase the stability of the design and construction consortium to a certain extent. In addition, the payment of such subsidies to the cooperative members will somewhat weaken the effects of extra income $\Delta\pi_1$ and default cost F on the stability of the consortium, but there is a threshold applied to the value of this subsidy.

(5) After adjusting the parameters in an attempt to optimize the game system, we found that values of A3 = (0, 1, 0), A4 = (1, 0, 0), A5 = (0, 1, 1), and A6 = (1, 0, 1) all contribute to the ideal state.

Therefore, this study not only investigates the role of the constructer, designer, and developer in the cooperation of the design and construction consortium from the perspective of design change management but also enriches the application of evolutionary game in the cooperation of the design and construction consortium, and also provides suggestions for the future development of green buildings in China. To summarize, this study provides a solution to the difficulties in the sustainable development of the cooperative relationship of China's Design and Construction Consortium. At the same time, the high-quality cooperation of the design and construction consortium is a method to solve the problem of design change, which is of great significance to the sustainable development of green buildings.

6.2. Suggestions

The three-way evolutionary game model can effectively promote the dynamic analysis of multi-stakeholder behavior strategy evolution in the process of design and construction consortium cooperation. In this study, by changing the assignment of relevant parameters and combining them with stability analysis, the main factors affecting evolutionary balance are identified and the evolutionary path of participants' behavior strategies is simulated. According to the research results of this paper, in order to strengthen the stability of the design and construction consortium, avoid the occurrence of design changes or improve the quality of cooperation after the changes, promote the standard of green engineering projects, and ensure the vigorous development of green buildings in China, we put forward the following suggestions:

First, the consortium members should have clear rights and responsibilities, and fair income distribution should be ensured. All work should be carried out by the members within the scope of their duties, according to the contents of the general contract signed with the developer and the provisions of the consortium cooperation agreement. In the cooperation agreement, the responsibilities and obligations of the cooperative members should be clearly defined, and a responsible party should be established who shall bear the consequences if other members suffer losses due to a breach of contract. The setting of clear rights and responsibilities can help to effectively improve the subjective motivations of members, actively promote the development of the consortium model, and thus facilitate the smooth completion of green building projects. The design and construction consortium should establish a reasonable income distribution plan based on the principles of fairness and justice, as well as a maximum total income. Before this is set out, the division of powers and responsibilities between members should be fully considered, as should the degree of contribution of each to the final green product, the resource investments, the risk-sharing distribution, effort, and other factors. However, an income distribution system is not static and will help to maintain a stable cooperative relationship within the consortium for a long time if it is flexibly adjusted according to the actual operational conditions of green building projects. In a word, problems arising from design changes necessitated by substandard green buildings can be effectively avoided or actively dealt with so as to minimize their impact on the environment during project implementation, and to further promote the sustainable development of green buildings.

Second, the punishment mechanism for breaches of contract should be strengthened. The costs related to a breach of contract represent an important factor affecting the stability of the cooperative relationship within the consortium. Regardless of whether the developer initiates design changes, members of the consortium will usually take the default cost into consideration when making strategic choices. In order to prevent members from adopting non-cooperative strategies due to opportunism in the performance process, it is necessary to establish a reasonable punishment mechanism, increase the costs demanded of members as a result of breaches of contract, and prevent members of the consortium from defaulting [44]. This can help to ensure the active cooperation of all members, the successful completion of all the work according to the fair division of rights and obligations, improve the degree of cooperation between members, extract their best performances in service of the construction project, improve the quality of green buildings, maximize the benefits derived by stakeholders throughout the project, form a virtuous circle, and promote the sustainable development of green buildings.

Third, the internal management system within the consortium should be improved, which will improve the income generated by the consortium. In terms of technical management, the constructor should seek to learn about and develop their own technology, as well as update their construction equipment, so as to keep pace with the times and adapt to the requirements of green construction in relation to the given design scheme. The design unit should regularly organize technical training among designers and actively implement new national green design specifications or standards so as to meet the environmental protection requirements related to design [45]. An efficient consortium management team, comprising individuals of outstanding talent jointly selected by the constructer and designer, should seek to do the best job possible in terms of design management in the early stage of the project, find and solve problems that might arise in the design process over time, avoid design changes necessitated by irregular design, carry out the best job possible in terms of construction management in the later stage of the project, supervise the construction process, and avoid further design changes necessitated in the protection of the environment and its benefits. At the same time, if the developer does initiate design changes, they should ensure firm supervision of these changes and pay attention to their rationality and effectiveness [46]. Furthermore, an information communication platform should be established to ensure effective information management. If the units participating in the design and construction consortium share mutual trust and understanding, it will be easier to communicate the design changes, meaning the project can be more successfully completed, and this will encourage the cooperative members to establish a long-term and stable partnership.

Fourthly, when selecting the members of the design and construction consortium, the developer should start from the basis of the project itself, comprehensively and systematically consider the strengths of the individual enterprises, select those who show a high degree of technological suitability to the project being implemented, and reduce the need for design changes necessitated by substandard green design or green construction (or actively and effectively deal with such design changes caused by project optimization). After design changes are initiated, implementing an effective reward and punishment system will be beneficial to the management of the cooperative relationship within the consortium. The cooperative members should be encouraged to strengthen their cooperation, as a result of which, the total benefits created can reach a certain theoretical value, such that additional benefits can be created on the basis of the original income distribution. At the same time, it is necessary to set up a severe punishment system to help regulate the behavior of the cooperative members. For those members who fail to deal with design changes properly, that is, those who default when the developer initiates a design change, the developer should blacklist them and thus reduce their reputational value, which will help to effectively reduce the instability amongst the consortium's members, facilitate the smooth development of green building projects, improve the environmental benefits, and promote the sustainable development of green buildings.

6.3. Limitations

This study still has some limitations. First of all, each building project is unique, and it is impossible to completely list the influencing factors. Moreover, there are many complicated influencing factors in actual green projects, so the parameter setting needs to be further supplemented and improved. Secondly, the setting of parameter values is abstract, and the data may not be completely close to reality. Matlab2019b software is used to simulate and analyze the gradual stable equilibrium point, and the simulation results are consistent with the model results, which proves the theoretical and practical significance of this study. In order to better match reality, more data collection is needed, and empirical analysis is also the next research direction. Finally, the evolutionary game model of this paper focuses on the key participants of design change management, namely the constructer, designer, and developer, without considering the analysis of other interest groups, and should discuss the role of other stakeholders in the stability of design and construction consortium under design change more completely. Determining how to establish a more practical model considering more participants and more information according to the relationship between participants is also a promising research direction in the future.

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