

## Article

# Incentives for Innovation in Robotics and Automated Construction: Based on a Tripartite Evolutionary Game Analysis

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**Abstract:** The current construction industry faces many challenges, such as low productivity, low material application rates, and poor environmental benefits. Robotic and automated construction (RAAC) technologies represent a breakthrough from traditional construction methods and are considered an effective way to improve productivity, ecological efficiency, and sustainability in the construction industry. However, the high cost of research and development and the lack of investment in the construction field have discouraged Chinese construction companies from innovating. In this paper, an evolutionary game model between the government, construction firms, and public universities is constructed around the choice of RAAC innovation, and the evolutionary stabilization strategy (ESS) of the three parties is discussed. Establishing a compound incentive policy of financial and reputational rewards and increasing the share of RAAC scores in academic evaluations can accelerate the realization of ESS among the government, construction companies, and public universities. This study informs policymakers to develop RAAC innovation strategies, and stakeholders such as the government, construction companies, and public universities should consider and jointly promote the development and application of RAAC technologies to improve productivity and environmental sustainability in the construction industry.

**Keywords:** robotic and automated construction; sustainability; evolutionary game; incentive strategies



**Citation:** Yi, L.; Hiroatsu, F.

Incentives for Innovation in Robotics and Automated Construction: Based on a Tripartite Evolutionary Game Analysis. *Sustainability* **2022**, *14*, 2475. <https://doi.org/10.3390/su14042475>

Academic Editors: Edmundas Kazimieras Zavadskas and Fausto Cavallaro

Received: 13 January 2022

Accepted: 18 February 2022

Published: 21 February 2022

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## 1. Introduction

The harmonization of environmental, economic, and sociocultural development is essential for modern society to pursue sustainability [1–3]. Dupuisani et al. [4,5] argue that the industry's sustainability can be improved by increasing productivity and economic efficiency. Among all sectors, the construction industry has been a significant part of the world's economy and contributes significantly to each country or region's gross domestic product (GDP). However, slow productivity growth is a crucial challenge for the industry [6]. With the accelerated development of China, the demand for sustainability and the desire for personalization in new building forms are increasing day by day for Chinese users. However, compared to other industries, the construction industry has a low productivity increase, low efficiency in material use, and low levels of automation in design and construction [7]. In parallel, the production model of the construction industry is outdated. The construction industry is still considered to be in the Industry 1.0 era. The integration of RAAC into the construction industry can enhance sustainability, increase productivity and safety, and save resources [8]. RAAC has been repeatedly identified as a possible solution to low productivity levels in the construction industry as early as the late 20th century [9]. In the development of RAAC, industrial robot arms were proven as a universal manufacturing medium [10]. The high degrees of freedom, relatively modest cost, high precision, velocity, and robustness, and universal design proven by other industries, combined with the increased flexibility offered by the proliferation of computer-aided

design software, have inspired a multifaceted exploration of the materialization potential of RAAC technology for advanced building forms [11]. Leading to an expansion of RAAC-based innovation-driven research efforts [12]. In addition to exploring new possibilities for new building forms [13], these studies show that RAAC, combined with new digital design methods, can be crucial in guiding the efficient application of materials and optimizing structural performance [14].

Modern construction companies need to innovate to promote increased productivity in the construction industry [15]. According to [16], while construction companies believe that RAAC contributes to increased productivity, sustainability, and safety, significant risks are associated with adoption, including commercial and technical risks. The high innovation costs and adoption risks discourage construction companies from proactively innovating [17]. Instead of being driven by market mechanisms alone, RAAC's development needs to be combined with government incentives [18]. Incentives are the driving force behind RAAC's results [19]. Mydin et al. [20] believe that financial compensation from the government can reduce the economic burden on construction companies and encourage them to adopt innovative decisions. The Green Building Action Plan, a policy document issued by the General Office of the State Council of China in 2013, states that China will vigorously develop green buildings and promote construction in a government-led and market-driven manner, with RAAC being the critical technology to achieve this target. However, the choices of construction companies are dynamic, and if the incentives are insufficient to compensate for the additional cost of innovation and the adoption of RAAC technology does not generate sufficient profits, construction companies will gravitate towards traditional construction methods [21]. Excessive incentives would put the government under great financial pressure, making the policy unsustainable [22].

Lack of expertise is also considered an essential factor hindering the development of RAAC technology [23]. Therefore, the education of technical personnel in universities is crucial. Design, construction, and operation methods in the construction industry need to be systematically altered in response to the needs of industrial upgrading [24]. The technical inventory of construction professionals is challenged. Architecture education needs to evolve to encourage adaptation to the new demands of the construction industry [25]. However, only 10% of architecture universities in China provide RAAC-related courses, and half of them cannot provide the necessary equipment [26]. According to [27], although Chinese universities have made some academic contributions to the development of RAAC, the lack of an overall teaching framework has prevented the education of professionals to a satisfactory level.

In this context, it is significant to explore the ESS of the Chinese government, public universities, and construction companies after a long-term evolutionary game and to identify the key influencing factors of ESS. This will help the government gain insight into setting appropriate incentives, better coordinating planning with public universities, and better balancing the government's, construction companies', and universities' interests and the distribution of innovation costs. In this paper, we do this by building a tripartite evolutionary game (TEG) model to focus on the following three issues: (i) How to balance the benefits and costs of the Chinese government, public universities, and construction companies and construct a benefits matrix in the TEG model? (ii) What is the ESS involved in the three parties, and what are the conditions for achieving them? (iii) How do the key parameters affect evolutionary outcomes and trajectories? The purpose of this paper is to contribute to existing research by applying an evolutionary game model to tripartite policymaking in RAAC development for the first time. Analyzing the asymptotic stability of the three parties under different conditions provides a compelling theoretical guide for promoting RAAC development in China.

The remainder of this paper is structured as follows: Section 2 briefly reviews the existing research on RAAC and evolutionary games and presents the literature gaps. Section 3 describes the construction of a TEG model. Section 4 discusses the ESS of the tripartite game between the government, the construction companies, and the public universities. Section 5

presents the numerical simulation of the evolutionary game model and discusses the effect of incentive-related parameters on the evolutionary results. Section 6 provides discussion of evolutionary results and policy implications. Section 7 presents the conclusions.

## 2. Literature Review

This paper briefly reviews the literature on RAAC and evolutionary game models with the above objectives.

### 2.1. RAAC in the Construction Industry

This paragraph briefly describes the different RAAC systems currently used in the construction industry. The classification method is based on the work of [28]. However, please note that these systems are differentiated, there is no precise definition within the industry, and the boundaries between categories continue to blur as technology develops and innovates. The classes presented here are intended to facilitate understanding of the complexity and diversity of the RAAC technical environment. The types of RAAC can be divided into three major categories [16]:

1. **Architectural prefabrication of RAAC.** This system originated from the successful industrialization of the Japanese automobile manufacturing industry utilizing robots [29]. This category includes the manufacture of sizeable prefabricated building elements. This method takes inspiration from the experience of other manufacturing industries that have applied RAAC to automate the industrialization of prefabricated building components using an automated approach. Various building materials (concrete, wood, steel, stone, etc.) and low-level components are transformed into high-level building components through a highly mechanized, automated, and robot-supported chain [24]. This category also contains additive manufacturing technologies (3D printing technologies) [30]. Perkins et al. [31] review many cases involving the application of 3D printing technology to the construction industry, discussing its application prospects, challenges, and advantages. Although limited by technology and material costs, additive manufacturing technology is still in the experimental stage [32]; it has progressed and can now be used to print large-scale components [33,34].
2. **On-site automation.** This type aims to achieve construction site automation—a controlled, automated environment established at an RAAC field factory [35]. Using single-task construction robots (usually industrial robotic arms) as automation tools, it can perform single repetitive tasks, or multiple machines can collaborate on complex assignments [36]. This method is popular with research institutes and architectural universities because of its flexibility, allowing it to be combined with other traditional construction methods. Wagner et al. [12,37,38] propose combining on-site automated systems with traditional timber frame construction, showing future robotic timber frame construction possibilities. Reichenbach et al. [8] review the current practice in integrating on-site automation and concrete production. Goessens et al. [39] present the feasibility of using industrial robotic arms to build masonry structures. Moreover, some Japanese, Korean, and German scholars focus on on-site automation for building demolition [40].
3. **Remotely operated equipment and exoskeletons.** This category addresses extreme and hazardous environmental problems that traditional construction methods cannot handle. It includes ground, air, sea, and even space robots [41] that can be remotely operated or require command. These robots have been developed for sampling studies in extreme environments, exploring and monitoring hazardous areas, and navigating and collecting data at construction sites, and have automated excavation and transportation [42–45]. This category also includes augmentation devices arch construction workers wear that can enhance workers' abilities, mitigate the effects of the environment on workers, help them lift heavy objects, and reduce fatigue to improve recognized productivity [46].

## 2.2. Evolutionary Game Theory

Evolutionary game theory (EGT) was introduced in the last century and gradually applied to various fields [47,48]. Game theory provides the mathematical framework for strategic choices based on anticipated benefit analysis [49]. In contrast to classical game theory, EGT does not require players to have complete rationality and complete information [50]. In contrast, the game's object is finitely rational participants, constantly learning and repeatedly playing games to maximize their benefits [51]. According to the above content, this theory fits this study well; firstly, the government, public universities, and construction companies will neither be fully aware of each other's intentions nor have complete information. Secondly, the government, public universities, and construction companies will dynamically update their strategic choices over time to respond to each other's strategies, which is consistent with the analytical mechanism of EGT.

This theory has been widely used in incentive-oriented multiparty policymaking in recent years. For example, JihongChen et al. [52] applied it to study the government's influence on the supply side of implementing shore-to-ship electricity. They observed that financial support plays a significant role in the project's upfront costs. By building an evolutionary game model of local government, tourism enterprises, and residents, YongSun et al. [53] analyzed the strategy choices of the game parties in ecotourism development and found that four stable strategies could be formed under different conditions. JunWang et al. [54] analyzed incentives for real estate firms to implement prefabrication, arguing that incentives should focus not only on real estate firms but also on consumers, manufacturers, and contractors. KunYang et al. [55], in their study on the sustainability of EGT analysis infrastructure projects, point out that excessive incentive subsidies can lead to "subsidy fraud" by companies. WangQiao et al. [56] found that incentives' effectiveness in the evolutionary energy transition game depends on consumers' attitudes toward the government.

## 2.3. Literature Gaps

Based on the literature mentioned above, extant literature gaps were identified. First, most studies on RAAC suggest that the development of RAAC technologies is an essential solution to the low productivity and inefficient application of materials in the construction industry and a key to the sustainable transformation of the construction industry. However, high research and development (R&D) costs and unaffordable innovation risks are also significant issues that hamper the change of construction companies. However, few pieces of literature focus on the impact of incentive policies on RAAC development. Second, EGT is widely used for multiparty policy decisions with incentive policies. However, combining the EGT model with RAAC is absent in the literature.

The following work has been done in this paper to fill these gaps. We capture the practical problems of RAAC development difficulties and analyze the Chinese government, public universities, and construction companies. We apply the EGT model to analyze RAAC development for the first time. The ESS of the three parties are analyzed by proposing hypotheses, establishing a revenue matrix, and establishing dynamic replication properties, respectively, and the ESS under different stability conditions are studied. This paper raises policy references for the three parties to promote the development and marketization of RAAC technology in China.

## 3. Methodology

### 3.1. Description of the Gamer

This paper aims to study the behavior of construction companies in adopting RAAC technology driven by government policies. The government and construction companies are the two leading players in the game. Meanwhile, whether public universities increase the training of RAAC technology talents directly affects the innovation cost of construction companies; therefore, public universities are identified as another player influencing the decision choice.

- **Government:** The government can promote the development of RAAC technology by developing programs, regulations, and incentives [57]. RAAC has been proven to increase productivity and promote sustainability in the construction industry [3,58]. The government aims to motivate construction companies to adopt RAAC through incentive policies. However, excessive subsidies will cause substantial financial pressure, and the government should consider the strength of the incentive policy.
- **Construction Company:** The ultimate pursuit of construction companies is financial gain [54]. RAAC is considered the key to increasing productivity and sustainability in the construction industry. However, higher R&D costs and investment risks have discouraged most construction companies from innovating. Construction companies doubt whether they can get sufficient compensation from government incentives and recruit relevant expertise from universities.
- **Public Universities:** For Chinese public universities, subject assessment scores (SAS) are an essential indicator. According to [59], the quality of talent training is the crucial factor affecting SAS. The quality of graduates depends on the employment situation and the evaluation of employers. Public universities need to weigh the ability of government fiscal policies to compensate them for the additional cost of training RAAC talent and the need of construction companies for RAAC talent.

Numbered lists can be added as follows:

### 3.2. Basic Assumptions

We have established the following hypotheses by analyzing the evolutionary game relationship between multiple stakeholders.

#### 1. Assumption I

An essential assumption of evolutionary games is that each player is finitely rational [60]. In the early stage of the game, it is difficult for the players to choose the perfect strategy. However, they can learn from each other, imitate, and exchange, and use this to adjust their strategy to pursue the maximum benefit [61].

#### 2. Assumption II

The government has two strategies: incentive or no incentive. The probability of the government choosing the incentive is  $x(x \in [0, 1])$ , and the probability of choosing no incentive is  $1 - x$ . Construction companies also have two strategies: innovate or do not innovate. The probability that the construction company chooses to innovate is  $y(y \in [0, 1])$ , and the probability of choosing not to innovate is  $1 - y$ . Public universities have two strategies as well: to cultivate RAAC talents or not to cultivate. The probability of the public universities choosing to cultivate is  $z(z \in [0, 1])$ , and the probability of choosing not to cultivate is  $1 - z$ .

#### 3. Assumption III

Players can only choose one strategy at one time. Other companies do not influence construction companies' strategic choices. Other universities do not influence public universities' strategic choices. Based on the above assumptions, the relevant symbols were further defined as shown in Table 1.

**Table 1.** Meaning of parameters.

| Parameters | Meanings   | Domain            |
|------------|--|-------------------|
| $B_1$      | The tax revenue of the government when construction companies choose not to innovate   | $B_1 \geq 0$      |
| $B_2$      | Extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government does not incentivize | $B_2 \geq 0$      |
| $B_3$      | Extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government incentivizes         | $B_3 \geq 0$      |
| $B_4$      | Government fines for poor environmental performance due to non-innovation by construction companies  | $B_4 \geq 0$      |
| $B_5$      | The cost of improved environmental benefits of traditional construction methods  | $B_5 \geq 0$      |
| $C_1$      | Economic benefits for construction companies when they do not innovate   | $C_1 \geq 0$      |
| $C_2$      | Economic benefits increment for construction companies when they innovate  | $C_2 \geq 0$      |
| $C_3$      | Reputation and brand value of construction companies for RAAC innovation   | $C_3 \geq 0$      |
| $C_4$      | Cost of RAAC innovation for construction companies   | $C_4 \geq 0$      |
| $C_5$      | Subsidies that construction companies gain from the government for RAAC innovation   | $C_5 \geq 0$      |
| $C_6$      | Innovation cost savings from acquiring RAAC talent from universities   | $C_6 \geq 0$      |
| $P_1$      | Subsidies that public universities gain from the government for RAAC talent cultivation  | $P_1 \geq 0$      |
| $P_2$      | Academic evaluation benefits of public universities for RAAC talent cultivation  | $P_2 \geq 0$      |
| $P_3$      | Academic evaluation penalties of public universities for RAAC talent cultivation   | $P_3 \geq 0$      |
| $P_4$      | Cost of RAAC talent cultivation for public universities  | $P_4 \geq 0$      |
| $x$        | Probability of the government choosing to incentivize  | $0 \leq x \leq 1$ |
| $1 - x$    | Probability of the government choosing not to incentivize  | $0 \leq x \leq 1$ |
| $y$        | Probability of the construction company choosing to innovate   | $0 \leq y \leq 1$ |
| $1 - y$    | Probability of the construction company choosing not to innovate   | $0 \leq y \leq 1$ |
| $z$        | Probability of the public universities choosing to cultivate   | $0 \leq z \leq 1$ |
| $1 - z$    | Probability of the public universities choosing not to cultivate   | $0 \leq z \leq 1$ |

3.3. Establishment of Payoff Model

The payoff matrix of government, construction companies, and public universities is shown in Table 2.

**Table 2.** Payoff matrix.

| Stakeholders                           |   | Construction Companies  |   |
|--|---|---|---|
|  |   | Innovate ( $y$ )  | Not to Innovate ( $1 - y$ )                                   |
| Government<br>Incentive ( $x$ )        | Public universities<br>Cultivate ( $z$ )            | $B_1 + B_3 - C_5 - P_1,$<br>$C_1 + C_2 + C_3 + C_5 + C_6 - C_4,$<br>$P_1 + P_2 - P_4$ | $B_1 + B_4 - B_5 - P_1,$<br>$C_1 - B_4,$<br>$P_1 + P_2 - P_4$ |
|  | Public universities<br>Not to cultivate ( $1 - z$ ) | $B_1 + B_3 - C_5,$<br>$C_1 + C_2 + C_3 + C_5 - C_4,$<br>$-P_3$                        | $B_1 + B_4 - B_5,$<br>$C_1 - B_4,$<br>$-P_3$                  |
| Government<br>No incentive ( $1 - x$ ) | Public universities<br>Cultivate ( $z$ )            | $B_1 + B_2,$<br>$C_1 + C_2 + C_3 + C_6 - C_4,$<br>$P_2 - P_4$                         | $B_1 - B_5,$<br>$C_1,$<br>$P_2 - P_4$                         |
|  | Public universities<br>Not to cultivate ( $1 - z$ ) | $B_1 + B_2,$<br>$C_1 + C_2 + C_3 - C_4,$<br>$0$                                       | $B_1 - B_5,$<br>$C_1,$<br>$0$                                 |

Assume that the expected utility of the government incentive strategy is  $\mathcal{H}_{11}$ , the expected utility of the government disincentive strategy is  $\mathcal{H}_{12}$ , and the average expected utility is  $\bar{\mathcal{H}}_1$ . Then:

$$\mathcal{H}_{11} = yz(B_1 + B_3 - C_5 - P_1) + (1 - y)z(B_1 + B_4 - B_5 - P_1) + y(1 - z)(B_1 + B_3 - C_5) + (1 - y)(1 - z)(B_1 + B_4 - B_5) = B_1 + B_4 - B_5 - zP_1 + y(B_3 - B_4 + B_5 - C_5) \tag{1}$$

$$\mathcal{H}_{12} = yz(B_1 + B_2) + (1 - y)z(B_1 - B_5) + y(1 - z)(B_1 + B_2) + (1 - y)(1 - z)(B_1 - B_5) = B_1 - B_5 + y(B_2 + B_5) \tag{2}$$

$$\bar{H}_1 = xH_{11} + (1 - x)(H_{11} - H_{12}) \tag{3}$$

The replicated dynamic equation [62] of government  $G(x)$  is:

$$G(x) = \frac{dx}{dt} = x(H_{11} - \bar{H}_1) = x(1 - x)(H_{11} - H_{12}) = x(1 - x)[B_4 - zP_1 + y(B_3 - B_4 - B_2 - C_5)] \tag{4}$$

Assume that the expected utility of the construction companies' innovation strategy is  $H_{21}$ , the expected utility of the construction companies that do not innovate is  $H_{22}$ , and the average expected utility is  $\bar{H}_2$ . Then:

$$\begin{aligned} H_{21} &= xz(C_1 + C_2 + C_3 + C_5 + C_6 - C_4) + (1 - x)z(C_1 + C_2 + C_3 + C_6 - C_4) \\ &\quad + x(1 - z)(C_1 + C_2 + C_3 + C_5 - C_4) + (1 - x)(1 - z)(C_1 + C_2 + C_3 - C_4) \\ &= C_1 + C_2 + C_3 - C_4 + zC_6 + xC_5 \end{aligned} \tag{5}$$

$$H_{22} = xz(C_1 - B_4) + (1 - x)z(C_1) + x(1 - z)(C_1 - B_4) + (1 - x)(1 - z)(C_1) = C_1 - xB_4 \tag{6}$$

$$\bar{H}_2 = yH_{21} + (1 - y)(H_{21} - H_{22}) \tag{7}$$

The replicated dynamic equation of construction companies  $D(x)$  is:

$$D(y) = \frac{dy}{dt} = y(H_{21} - \bar{H}_2) = y(1 - y)(H_{21} - H_{22}) = y(1 - y)[x(C_5 + B_4) + zC_6 + C_2 + C_3 - C_4] \tag{8}$$

Assume that the expected utility of the strategies for cultivating RAAC talent at public universities is  $H_{31}$ , the expected utility of the strategies for not cultivating RAAC talent at public universities is  $H_{32}$ , and the average expected utility is  $\bar{H}_3$ . Then:

$$\begin{aligned} H_{31} &= xy(P_1 + P_2 - P_4) + (1 - x)y(P_2 - P_4) + x(1 - y)(P_1 + P_2 - P_4) + (1 - x)(1 - y)(P_2 - P_4) \\ &= xP_1 + P_2 - P_4 \end{aligned} \tag{9}$$

$$H_{32} = xy(-P_3) + x(1 - y)(-P_3) = -xP_3 \tag{10}$$

$$\bar{H}_3 = zH_{31} + (1 - z)(H_{31} - H_{32}) \tag{11}$$

The replicated dynamic equation of public universities  $E(x)$  is:

$$E(z) = \frac{dz}{dt} = z(H_{31} - \bar{H}_3) = z(1 - z)(H_{31} - H_{32}) = z(1 - z)[x(P_1 + P_3) + P_2 - P_4] \tag{12}$$

In order to further discuss the evolutionary stable points of the TEG, the simultaneous equations are as follows:

$$\begin{cases} G(x) = \frac{dx}{dt} = x(H_{11} - \bar{H}_1)x(1 - x)(H_{11} - H_{12}) = x(1 - x)[B_4 - zP_1 + y(B_3 - B_4 - B_2 - C_5)] = 0 \\ D(y) = \frac{dy}{dt} = y(H_{21} - \bar{H}_2)y(1 - y)(H_{21} - H_{22}) = y(1 - y)[x(C_5 + B_4) + zC_6 + C_2 + C_3 - C_4] = 0 \\ E(z) = \frac{dz}{dt} = z(H_{31} - \bar{H}_3) = z(1 - z)(H_{31} - H_{32}) = z(1 - z)[x(P_1 + P_3) + P_2 - P_4] = 0 \end{cases} \tag{13}$$

From the above simultaneous equations, the evolutionary stability points of the government, construction companies, and public universities can be obtained:  $S_1(0, 0, 0)$ ,  $S_2(0, 0, 1)$ ,  $S_3(0, 1, 0)$ ,  $S_4(1, 0, 0)$ ,  $S_5(0, 1, 1)$ ,  $S_6(1, 0, 1)$ ,  $S_7(1, 1, 0)$ ,  $S_8(1, 1, 1)$  and  $S_s(x^*, y^*, z^*)$ , when  $S_s(x^*, y^*, z^*)$  satisfies the following simultaneous equations:

$$\begin{aligned} B_4 - zP_1 + y(B_3 - B_4 - B_2 - C_5) &= 0 \\ x(C_5 + B_4) + zC_6 + C_2 + C_3 - C_4 &= 0 \\ x(P_1 + P_3) + P_2 - P_4 &= 0 \end{aligned} \tag{14}$$

### 4. Evolutionary Stability Analysis

#### 4.1. Asymptotic Stability Analysis

According to the above equation and referring to the stability principle of the replicated dynamic equation [63], the asymptotic stability of the three parties, the government, the construction company, and the public university, can be obtained as follows:

1. Asymptotic stability analysis of government: Let  $\frac{dx}{dt} = 0$ ,  $x_1 = 0$ , and  $x_2 = 1$ ,  $y^* = \frac{zP_1 - B_4}{B_3 - B_4 - B_2 - C_5}$ . When  $y = y^*$ ,  $G(x) = 0$ . This means that the government will get the same benefits regardless of whether it chooses the incentive strategy or not. When  $y > y^*$ , the probability of construction companies choosing innovative strategies exceeds  $y^*$ . To satisfy  $G(x) \geq 0$ ,  $x_2 = 1$  is the evolutionary stable point, which indicates that the probability that the government will choose the incentive is increasing, and eventually, the government will determine the incentive strategy. When  $y < y^*$ , the probability of construction companies choosing innovative strategies are more diminutive than  $y^*$ . To protect  $G(x) \geq 0$ ,  $x_1 = 0$  is the evolutionary stable point. The probability that the government will choose to incentivize continues to decline and eventually choose not to incentivize. Let  $\frac{dx}{dt} = 0$ ,  $x_1 = 0$ , and  $x_2 = 1$ ,  $z^* = \frac{y(B_3 - B_4 - B_2 - C_5) + B_4}{P_1}$ . When  $z = z^*$ ,  $G(x) = 0$ . This means that the government's strategy will not change over time. When  $z > z^*$ , the probability that public universities will choose the strategy to develop RAAC talent exceeds  $z^*$ . To safeguard  $G(x) \geq 0$ ,  $x_2 = 1$  is the evolutionary stable point, suggesting that the government's probability of choosing incentives improves; ultimately, the government will choose an incentive strategy. When  $z < z^*$ , the probability of construction companies choosing strategies for RAAC talent cultivation is less than  $z^*$ . To guarantee  $G(x) \geq 0$ ,  $x_1 = 0$  is the evolutionary stable point. The government's probability of choosing to incentivize continues to decline and eventually chooses not to incentivize.
2. Asymptotic stability analysis of construction companies: Let  $\frac{dy}{dt} = 0$ ,  $y_1 = 0$ , and  $y_2 = 1$ ,  $x^* = \frac{C_4 - C_2 - C_3 - zC_6}{C_5 + B_4}$ . When  $x = x^*$ ,  $D(y) = 0$ . This means that the benefits of RAAC innovation for construction companies are the same as the benefits of maintaining traditional construction methods. When  $x > x^*$ , the probability that the government choosing to incentivize exceeds  $x^*$ . To secure  $D(y) \geq 0$ ,  $y_2 = 1$  is the evolutionary stable point. It shows that the strategy of construction companies will change from non-innovation to innovation and eventually get a stable innovation strategy. When  $x < x^*$ , the probability that the government choosing to incentivize is less than  $x^*$ . To guarantee  $D(y) \geq 0$ ,  $y_1 = 0$  is the evolutionary stable point. The probability that an architectural firm will choose to innovate continues to decline and eventually choose not to innovate. Let  $\frac{dy}{dt} = 0$ ,  $y_1 = 0$ , and  $y_2 = 1$ ,  $z^* = \frac{C_4 - C_2 - C_3 - x(C_5 + B_4)}{C_6}$ . When  $z = z^*$ ,  $D(y) = 0$ . This means that the benefits of RAAC innovation for construction companies are the same as the benefits of maintaining traditional construction methods. When  $z > z^*$ , the probability that public universities will choose the strategy to develop RAAC talent exceeds  $z^*$ . To secure  $D(y) \geq 0$ ,  $y_2 = 1$  is the evolutionary stable point. This suggests that the strategy of construction companies will shift from non-innovation to innovation and eventually acquire a stable innovation strategy. When  $z < z^*$ , the probability of construction companies choosing strategies for RAAC talent cultivation is less than  $z^*$ . To ensure that  $D(y) \geq 0$ ,  $y_1 = 0$  is the evolutionary stable point. Construction companies will move from innovation to non-innovation and ultimately choose not to innovate.
3. Asymptotic stability analysis of public universities: Let  $\frac{dz}{dt} = 0$ ,  $z_1 = 0$ , and  $z_2 = 1$ ,  $x^* = \frac{P_4 - P_2}{P_1 + P_3}$ . When  $x = x^*$ ,  $E(z) = 0$ . The probability that a public university chooses to train RAAC talent does not change over time. When  $x > x^*$ , the probability that the government choosing to incentivize exceeds  $x^*$ . To secure  $E(z) \geq 0$ ,  $z_2 = 1$  is the evolutionary stable point. This indicates that the strategy of public universities is gradually tending to cultivate RAAC talents and eventually acquire a stable cultivation strategy. When  $x < x^*$ , the probability that the government choosing to incentivize is less than  $x^*$ . To guarantee  $E(z) \geq 0$ ,  $z_1 = 0$  is the evolutionary stable point. The probability that public universities choose to train RAAC talent continues to decline and eventually decide not to cultivate.

#### 4.2. Analysis of the Trend of Tripartite Evolutionary Game

In order to analyze the ESS of the RAAC innovation TEG, according to [64], it can be determined by the local stability analysis of the Jacobi matrix. A Jacobi matrix  $\mathcal{J}(x, y, z)$  corresponding to the evolutionary game model in this paper appears as follows:

$$\mathcal{J}(x, y, z) = \begin{pmatrix} \frac{\partial G(x)}{\partial x} & \frac{\partial G(x)}{\partial y} & \frac{\partial G(x)}{\partial z} \\ \frac{\partial D(y)}{\partial x} & \frac{\partial D(y)}{\partial y} & \frac{\partial D(y)}{\partial z} \\ \frac{\partial E(z)}{\partial x} & \frac{\partial E(z)}{\partial y} & \frac{\partial E(z)}{\partial z} \end{pmatrix} \quad (15)$$

where  $\frac{\partial G(x)}{\partial x} = [(1-2x)[\mathcal{B}_4 - z\mathcal{P}_1 + y(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)]$ ,  $\frac{\partial G(x)}{\partial y} = x(1-x)(\mathcal{B}_3 - \mathcal{B}_4 - \mathcal{B}_2 - \mathcal{C}_5)$ ,  $\frac{\partial G(x)}{\partial z} = x(1-x)(-\mathcal{P}_1)$ ,  $\frac{\partial D(y)}{\partial x} = y(1-y)(\mathcal{C}_5 + \mathcal{B}_4)$ ,  $\frac{\partial D(y)}{\partial y} = (1-2y)[x(\mathcal{C}_5 + \mathcal{B}_4) + z\mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4]$ ,  $\frac{\partial D(y)}{\partial z} = y(1-y)\mathcal{C}_6$ ,  $\frac{\partial E(z)}{\partial x} = z(1-z)(\mathcal{P}_1 + \mathcal{P}_3)$ ,  $\frac{\partial E(z)}{\partial y} = 0$ ,  $\frac{\partial E(z)}{\partial z} = (1-2z)[x(\mathcal{P}_1 + \mathcal{P}_3) + \mathcal{P}_2 - \mathcal{P}_4]$ .

The eigenvalues of the respective Jacobi matrices are obtained by banding the eight equilibrium points:  $S_1(0,0,0)$ ,  $S_2(0,0,1)$ ,  $S_3(0,1,0)$ ,  $S_4(1,0,0)$ ,  $S_5(0,1,1)$ ,  $S_6(1,0,1)$ ,  $S_7(1,1,0)$ ,  $S_8(1,1,1)$  into Equation (15), as shown in Table 3. When all eigenvalues of the Jacobi matrix are negative simultaneously, the equilibrium point satisfies ESS [64,65].

**Table 3.** ESS analysis of Jacobi matrix.

| Equilibrium Point | Eigenvalue 1  | Eigenvalue 2  | Eigenvalue 3  | Conditions  | Stability |
|-------------------|---|---|---|---|-----------|
| $S_1(0,0,0)$      | $\mathcal{B}_4$   | $\mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4$   | $\mathcal{P}_2 - \mathcal{P}_4$                                 |   | Unstable  |
| $S_2(0,0,1)$      | $\mathcal{B}_4 - \mathcal{P}_1$                                 | $\mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 - \mathcal{C}_4$                                 | $\mathcal{P}_4 - \mathcal{P}_2$                                 | $\mathcal{P}_1 > \mathcal{B}_4$ ,<br>$\mathcal{C}_4 > \mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3$ ,<br>$\mathcal{P}_4 < \mathcal{P}_2$   | ESS       |
| $S_3(0,1,0)$      | $\mathcal{B}_3 - \mathcal{C}_5 - \mathcal{B}_2$                 | $\mathcal{C}_4 - \mathcal{C}_3 - \mathcal{C}_2$   | $\mathcal{P}_2 - \mathcal{P}_4$                                 | $\mathcal{B}_3 < \mathcal{C}_5 + \mathcal{B}_2$ ,<br>$\mathcal{C}_4 < \mathcal{C}_2 + \mathcal{C}_3$ ,<br>$\mathcal{P}_4 > \mathcal{P}_2$   | ESS       |
| $S_4(1,0,0)$      | $-\mathcal{B}_4$  | $\mathcal{C}_5 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{B}_4 - \mathcal{C}_4$                 | $\mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3 - \mathcal{P}_4$ | $\mathcal{C}_4 > \mathcal{C}_5 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{B}_4$ ,<br>$\mathcal{P}_4 > \mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3$  | ESS       |
| $S_5(0,1,1)$      | $\mathcal{B}_3 - \mathcal{B}_2 - \mathcal{C}_5 - \mathcal{P}_1$ | $\mathcal{C}_4 - \mathcal{C}_3 - \mathcal{C}_2 - \mathcal{C}_6$                                 | $\mathcal{P}_4 - \mathcal{P}_2$                                 | $\mathcal{B}_3 < \mathcal{C}_5 + \mathcal{B}_2 + \mathcal{P}_1$ ,<br>$\mathcal{C}_4 < \mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3$ ,<br>$\mathcal{P}_4 < \mathcal{P}_2$   | ESS       |
| $S_6(1,0,1)$      | $\mathcal{P}_1 - \mathcal{B}_4$                                 | $\mathcal{C}_5 + \mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{B}_4 - \mathcal{C}_4$ | $\mathcal{P}_4 - \mathcal{P}_2 - \mathcal{P}_3 - \mathcal{P}_1$ | $\mathcal{P}_1 < \mathcal{B}_4$ ,<br>$\mathcal{C}_4 > \mathcal{C}_5 + \mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{B}_4$ ,<br>$\mathcal{P}_4 < \mathcal{P}_2 + \mathcal{P}_3 + \mathcal{P}_1$                                 | ESS       |
| $S_7(1,1,0)$      | $\mathcal{C}_5 + \mathcal{B}_2 - \mathcal{B}_3$                 | $\mathcal{C}_4 - \mathcal{B}_4 - \mathcal{C}_3 - \mathcal{C}_2 - \mathcal{C}_5$                 | $\mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3 - \mathcal{P}_4$ | $\mathcal{B}_3 > \mathcal{C}_5 + \mathcal{B}_2$ ,<br>$\mathcal{C}_4 < \mathcal{B}_4 + \mathcal{C}_3 + \mathcal{C}_2 + \mathcal{C}_5$ ,<br>$\mathcal{P}_4 > \mathcal{P}_1 + \mathcal{P}_2 + \mathcal{P}_3$                                 | ESS       |
| $S_8(1,1,1)$      | $\mathcal{C}_5 + \mathcal{B}_2 + \mathcal{P}_1 - \mathcal{B}_3$ | $\mathcal{C}_4 - \mathcal{B}_4 - \mathcal{C}_3 - \mathcal{C}_2 - \mathcal{C}_5 - \mathcal{C}_6$ | $\mathcal{P}_4 - \mathcal{P}_2 - \mathcal{P}_3 - \mathcal{P}_1$ | $\mathcal{B}_3 > \mathcal{C}_5 + \mathcal{B}_2 + \mathcal{P}_1$ ,<br>$\mathcal{C}_4 < \mathcal{C}_5 + \mathcal{C}_2 + \mathcal{C}_3 + \mathcal{B}_4 + \mathcal{C}_6$ ,<br>$\mathcal{P}_4 < \mathcal{P}_2 + \mathcal{P}_3 + \mathcal{P}_1$ | ESS       |

1. When  $\mathcal{P}_1 > \mathcal{B}_4$ ;  $\mathcal{C}_4 > \mathcal{C}_6 + \mathcal{C}_2 + \mathcal{C}_3$ ;  $\mathcal{P}_4 < \mathcal{P}_2$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_2(0,0,1)$  are negative, indicating that  $S_2(0,0,1)$  is ESS. This represents when the cost of the government subsidies for public schools is larger than the fines the government imposes on construction companies for non-innovation; the cost of RAAC innovation for construction companies is greater than the sum of the economic and the reputational and innovation cost savings from acquiring RAAC talent from universities; and the cost of RAAC talent cultivation for public universities is less than the academic evaluation benefits of public universities for RAAC talent cultivation. (No incentive, Non-innovative, Cultivation) is ESS.

2. When  $B_3 < C_5 + B_2$ ;  $C_4 < C_2 + C_3$ ;  $P_4 > P_2$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_3(0, 1, 0)$  are negative, indicating that  $S_3(0, 1, 0)$  is ESS. This stands for when satisfying the extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government incentives is less than the sum of the extra benefits by the entire construction industry chain when construction companies innovate with RAAC when the government does not incentivize and the subsidies that construction companies gain from the government for RAAC innovation; the cost of innovation for construction companies is less than the sum of the economic benefits increment for construction companies when they innovate and the reputation and the brand value of construction companies for innovation; and the cost of RAAC talent cultivation for public universities is more than the academic evaluation benefits of public universities. (No incentive, Innovative, Non-cultivation) is ESS.
3. When  $C_4 > C_5 + C_2 + C_3 + B_4$ ;  $P_4 > P_1 + P_2 + P_3$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_4(1, 0, 0)$  are negative, indicating that  $S_4(1, 0, 0)$  is ESS. This means that the cost of innovation for construction companies is greater than the sum of the government's subsidies and the economic benefits and brand value gained from innovation versus the penalty for not innovating. (Incentive, Non-innovative, Non-cultivation) is ESS.
4. When  $B_3 < C_5 + B_2 + P_1$ ;  $C_4 < C_6 + C_2 + C_3$ ;  $P_4 < P_2$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_5(0, 1, 1)$  are negative, indicating that  $S_5(0, 1, 1)$  is ESS. This represents when satisfying the benefits from RAAC innovation with government incentives is less than the sum of the innovative government subsidies for construction companies and benefits from RAAC innovation without government incentives and government subsidies for universities; the RAAC innovation costs for construction companies is less than the sum of the innovation cost savings from acquiring RAAC talent from universities and economic and the reputational benefits for construction companies when they innovate; and the cost of RAAC talent cultivation for public universities is less than the academic evaluation benefits of public universities for RAAC talent cultivation. (No incentive, Innovative, Cultivation) is ESS.
5. When  $P_1 < B_4$ ;  $C_4 > C_5 + C_6 + C_2 + C_3 + B_4$ ;  $P_4 < P_2 + P_3 + P_1$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_6(1, 0, 1)$  are negative, indicating that  $S_6(1, 0, 1)$  is ESS. This represents when meeting the government proceeds from fines for poor environmental performance due to non-innovation by construction companies is more than the government financial subsidies for public universities; the RAAC innovation costs for construction companies is greater than the sum of the government financial subsidies for construction companies and the innovation cost savings from acquiring RAAC talent from universities and the economic and the reputational benefits for construction companies when they innovate, and the government fines for non-innovation of construction companies; and the cost of developing talent at public universities is less than the sum of academic evaluation benefits of public universities and subsidies received by public universities from the government and academic evaluation penalties of public universities for RAAC talent cultivation. (Incentive, Non-innovative, Cultivation) is ESS.
6. When  $B_3 > C_5 + B_2$ ;  $C_4 < B_4 + C_3 + C_2 + C_5$ ;  $P_4 > P_1 + P_2 + P_3$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_7(1, 1, 0)$  are negative, indicating that  $S_7(1, 1, 0)$  is ESS. This represents when satisfying the benefits from RAAC innovation with government incentives is more than the sum of the government subsidies to construction companies and additional revenue generated by construction company innovation when government incentives are not available; the RAAC innovation costs for construction companies is less than the sum of the government fines for construction companies and the economic and the reputational benefits for construction companies from innovating and the government subsidies

for construction companies; and the cost of the RAAC talent cultivation for public universities is higher than the sum of the government subsidies granted to universities and the academic evaluation benefits of public universities for RAAC talent cultivation and the academic evaluation penalties of public universities for RAAC talent cultivation. (Incentive, Innovative, Non-cultivation) is ESS.

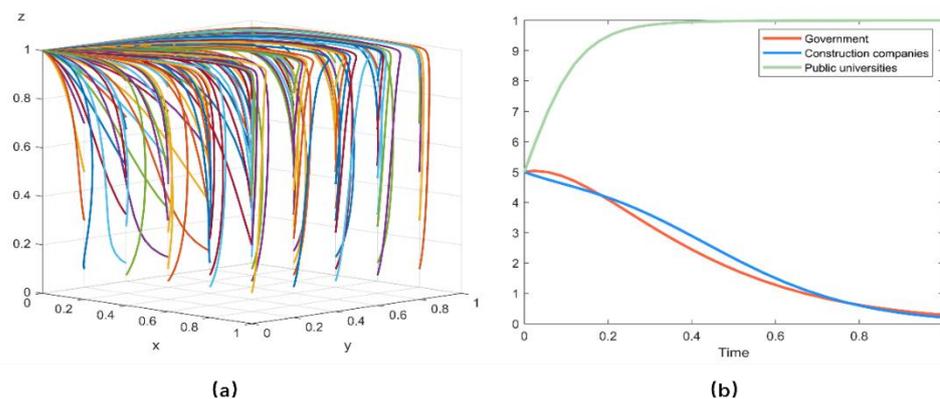
7. When  $B_3 > C_5 + B_2 + P_1$ ;  $C_4 < C_5 + C_2 + C_3 + B_4 + C_6$ ;  $P_4 < P_2 + P_3 + P_1$ . The eigenvalues of the Jacobi matrix corresponding to the evolutionary stability point  $S_8(1, 1, 1)$  are negative, indicating that  $S_8(1, 1, 1)$  is ESS. This represents when meeting the benefits from RAAC innovation with government incentives is more than the sum of the government subsidies to construction companies and universities and additional revenue generated by construction company innovation when government incentives are not available; the RAAC innovation costs for construction companies is lower than the sum of the government fines for construction companies and the economic and the reputational benefits for construction companies from innovating and the government subsidies for construction companies and the innovation cost savings from acquiring RAAC talent from universities; and the cost of the RAAC talent cultivation for public universities is lower than the sum of the government subsidies granted to universities and the academic evaluation benefits of public universities for RAAC talent cultivation and the academic evaluation penalties of public universities for RAAC talent cultivation. (Incentive, Innovative, Cultivation) is ESS.

## 5. Numerical Simulation

### 5.1. The Evolutionary Trajectory of ESS

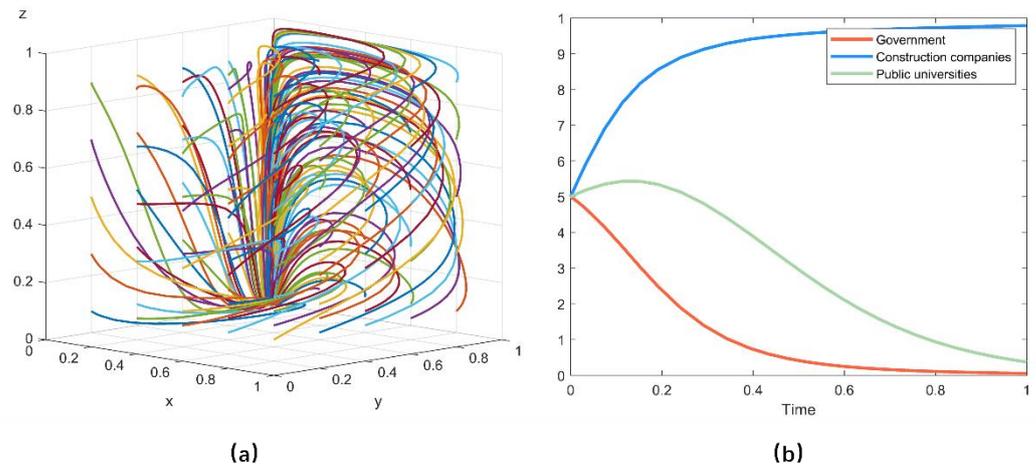
For analyzing the dynamic evolution process, the strategy evolution process of the tripartite game in different scenarios can be simulated by changing the parameter settings. Based on replicator dynamic equations, different stability conditions are brought into MATLAB R2021b to simulate the evolutionary trajectory of ESS mentioned in Section 4.2.

1. Assumption i  $B_2 = 30, B_3 = 40, B_4 = 6, C_2 = 8, C_3 = 4, C_4 = 20, C_5 = 4, C_6 = 2, P_1 = 10, P_2 = 15, P_3 = 10, P_4 = 10$ . The evolutionary trajectory of  $S_2(0, 0, 1)$  is featured in Figure 1a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 1b.



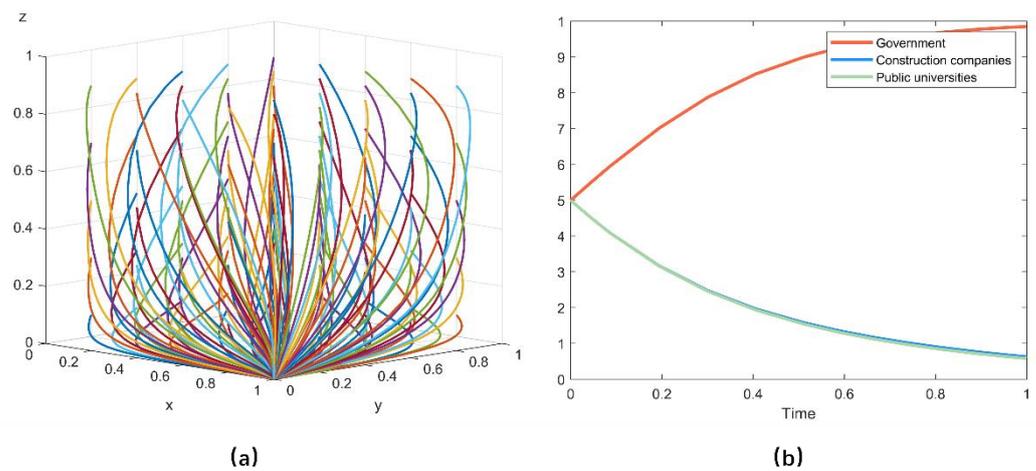
**Figure 1.** (a) Three-dimensional situation of evolutionary trajectory of  $S_2(0, 0, 1)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_2(0, 0, 1)$ .

2. Assumption ii  $B_2 = 30, B_3 = 40, B_4 = 6, C_2 = 8, C_3 = 13, C_4 = 20, C_5 = 13, C_6 = 2, P_1 = 10, P_2 = 5, P_3 = 5, P_4 = 10$ . The evolutionary trajectory of  $S_3(0, 1, 0)$  is featured in Figure 2a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 2b.



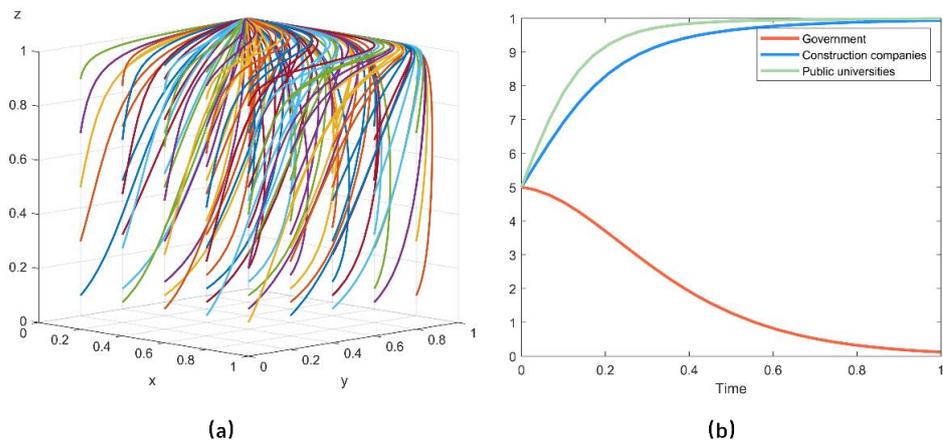
**Figure 2.** (a) Three-dimensional situation of evolutionary trajectory of  $S_3(0, 1, 0)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_3(0, 1, 0)$ .

3. Assumption iii  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 4, \mathcal{C}_2 = 8, \mathcal{C}_3 = 3, \mathcal{C}_4 = 20, \mathcal{C}_5 = 3, \mathcal{C}_6 = 2, \mathcal{P}_1 = 2, \mathcal{P}_2 = 3, \mathcal{P}_3 = 3, \mathcal{P}_4 = 10$ . The evolutionary trajectory of  $S_4(1, 0, 0)$  is featured in Figure 3a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 3b.



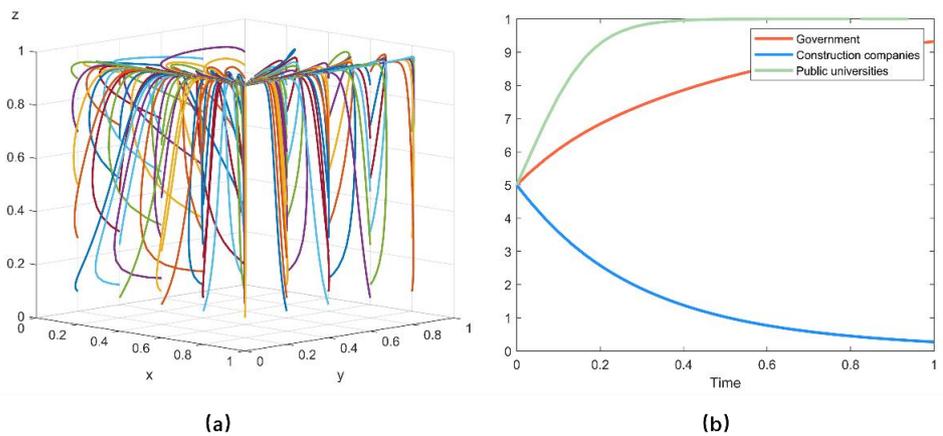
**Figure 3.** (a) Three-dimensional situation of evolutionary trajectory of  $S_4(1, 0, 0)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_4(1, 0, 0)$ .

4. Assumption iv  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 4, \mathcal{C}_2 = 8, \mathcal{C}_3 = 13, \mathcal{C}_4 = 20, \mathcal{C}_5 = 8, \mathcal{C}_6 = 2, \mathcal{P}_1 = 7, \mathcal{P}_2 = 13, \mathcal{P}_3 = 13, \mathcal{P}_4 = 10$ . The evolutionary trajectory of  $S_5(0, 1, 1)$  is featured in Figure 4a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 4b.



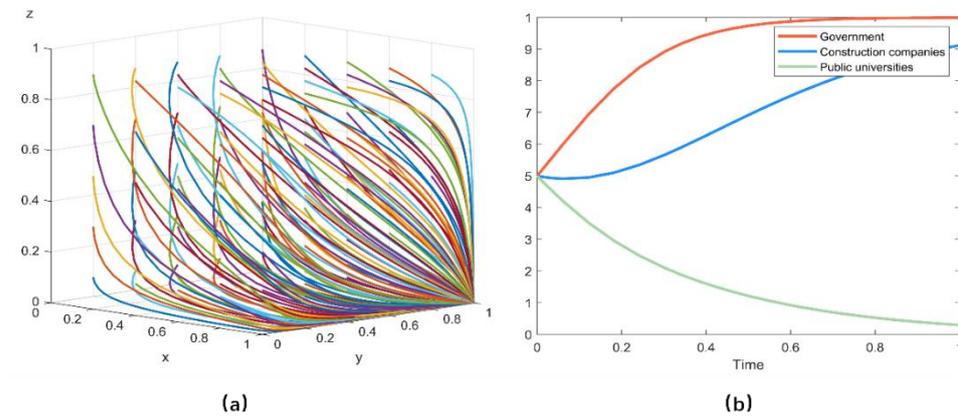
**Figure 4.** (a) Three-dimensional situation of evolutionary trajectory of  $S_5(0, 1, 1)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_5(0, 1, 1)$ .

5. Assumption v  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 5, \mathcal{C}_2 = 8, \mathcal{C}_3 = 1, \mathcal{C}_4 = 20, \mathcal{C}_5 = 2, \mathcal{C}_6 = 2, \mathcal{P}_1 = 3, \mathcal{P}_2 = 13, \mathcal{P}_3 = 13, \mathcal{P}_4 = 10$ . The evolutionary trajectory of  $S_6(1, 0, 1)$  is featured in Figure 5a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 5b.



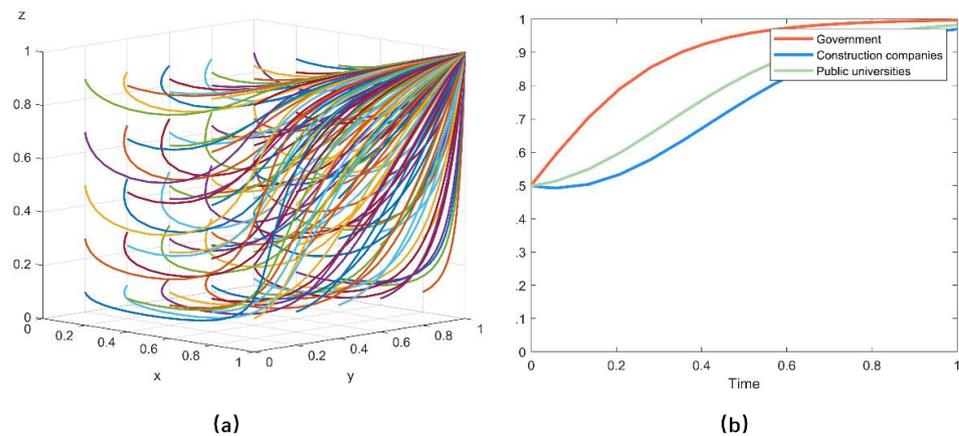
**Figure 5.** (a) Three-dimensional situation of evolutionary trajectory of  $S_6(1, 0, 1)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_6(1, 0, 1)$ .

6. Assumption vi  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 8, \mathcal{C}_2 = 8, \mathcal{C}_3 = 5, \mathcal{C}_4 = 20, \mathcal{C}_6 = 2, \mathcal{P}_1 = 3, \mathcal{P}_2 = 2, \mathcal{P}_3 = 2, \mathcal{P}_4 = 10$ . The evolutionary trajectory of  $S_7(1, 1, 0)$  is featured in Figure 6a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 6b.



**Figure 6.** (a) Three-dimensional situation of evolutionary trajectory of  $S_7(1, 1, 0)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_7(1, 1, 0)$ .

7. Assumption vii  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 8, \mathcal{C}_2 = 8, \mathcal{C}_3 = 5, \mathcal{C}_4 = 20, \mathcal{C}_5 = 2, \mathcal{C}_6 = 2, \mathcal{P}_1 = 3, \mathcal{P}_2 = 6, \mathcal{P}_3 = 6, \mathcal{P}_4 = 10$ . The evolutionary trajectory of  $S_8(1, 1, 1)$  is featured in Figure 7a. When the initial probabilities of all three parties are 0.5, the evolutionary trajectory is displayed in Figure 7b.



**Figure 7.** (a) Three-dimensional situation of evolutionary trajectory of  $S_8(1, 1, 1)$ . (b) Two-dimensional situation of evolutionary trajectory of  $S_8(1, 1, 1)$ .

5.2. Impact of Incentive Policy on Evolutionary Results and Trajectories

To evaluate the impact of government incentives on the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS, numerical simulations were conducted in this paper. Set the initial parameters as follows:  $S_4(1, 0, 0)$ :  $\mathcal{B}_2 = 30, \mathcal{B}_3 = 40, \mathcal{B}_4 = 4, \mathcal{C}_2 = 8, \mathcal{C}_3 = 3, \mathcal{C}_4 = 20, \mathcal{C}_5 = 5, \mathcal{C}_6 = 5, \mathcal{P}_1 = 2, \mathcal{P}_2 = 3, \mathcal{P}_3 = 3, \mathcal{P}_4 = 10$  and  $x = 0.5, y = 0.5, z = 0.5$ .

The effect of  $\mathcal{C}_5$

Let  $\mathcal{C}_5 = 0, 10, 20, 30, 40, 50$  and keep other parameters constant; the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS are as shown in Figure 8. This indicates that as the financial subsidies granted by the government to construction companies increase, the probability that the government is willing to maintain the incentives gradually decreases and eventually converges to zero. Excessive financial subsidies will exert pressure on the government’s finances and will both reduce the government’s willingness to provide incentives and accelerate the rate of evolution. For construction companies, government subsidies have a positive effect on their choice of RAAC innovation. When the government chooses to incentivize and increases the incentive amount, the

probability of construction companies choosing to innovate increases, but as the subsidy amount increases, the probability of the government choosing not to incentivize increases, and the probability of construction companies choosing to innovate decreases and finally tends to zero. For public universities,  $C_5$  does not affect their decision choice.

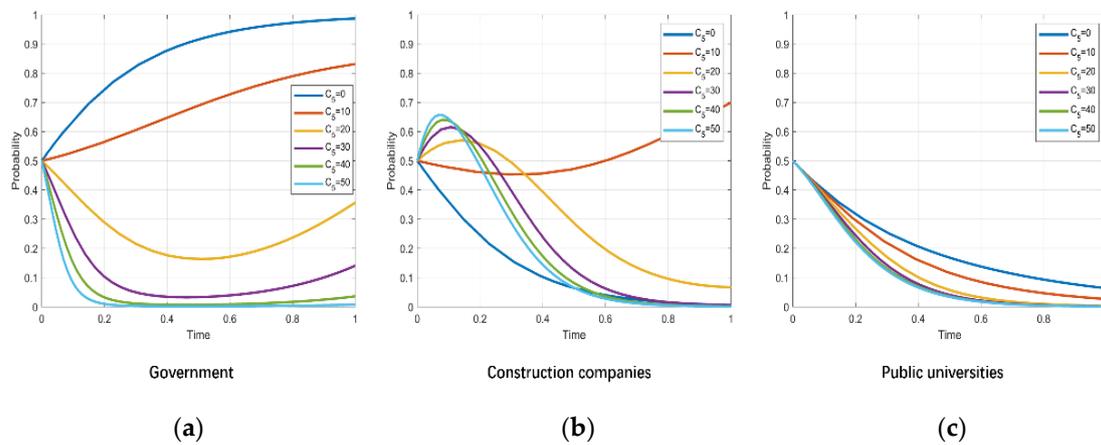


Figure 8. Impact of  $C_5$  on evolutionary outcomes and trajectories.

1. The effect of  $C_3$

Let  $C_3 = 0, 3, 6, 9, 12, 15$  and keep other parameters constant; the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS are as shown in Figure 9. Reputation and brand value gained by construction companies with RAAC innovations have no impact on government and public university decision-making choices. However, for construction companies, it can effectively increase the probability that they will choose to innovate and will accelerate the rate of evolution.

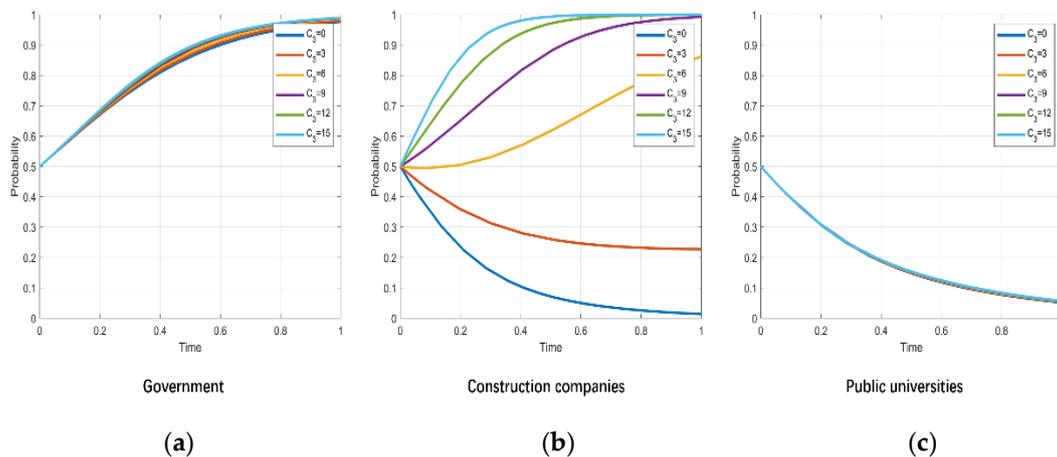


Figure 9. Impact of  $C_3$  on evolutionary outcomes and trajectories.

2. The effect of  $P_1$

Let  $P_1 = 0, 6, 12, 18, 24, 30$  and keep other parameters constant; the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS are as shown in Figure 10. For the government, excessive subsidies will reduce the probability that the government chooses to incentivize and will accelerate the rate of evolution. For public universities, higher subsidies increase the probability of choosing RAAC talent development, but as the probability of government choice incentives decreases, the probability of public schools developing talent decreases until it approaches zero. For construction companies, this has a limited impact on their strategy choice, but only accelerates the rate of evolution.

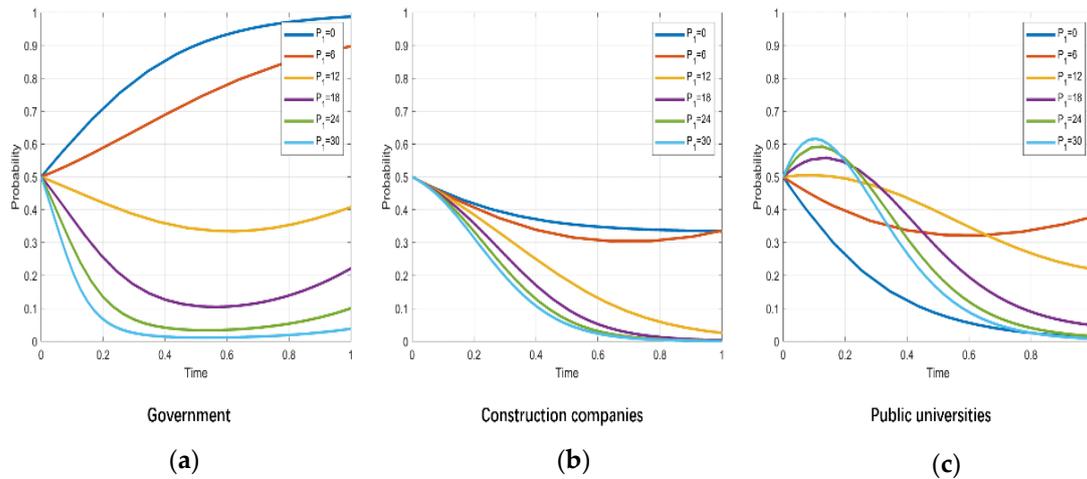


Figure 10. Impact of  $\mathcal{P}_1$  on evolutionary outcomes and trajectories.

### 3. The effect of $\mathcal{P}_2$

Let  $\mathcal{P}_2 = 0, 2, 4, 6, 8, 10$  and keep other parameters constant; the evolutionary outcomes and trajectories of the RAAC innovation tripartite ESS are as shown in Figure 11. The academic evaluation effectiveness has little impact on government policy choices. For public universities, academic evaluation benefits are the main concern. Increasing academic evaluation benefits will increase the probability that public universities will choose to train and will accelerate the rate of evolution. For construction companies, academic evaluation is not their main concern, but the willingness of universities to decide to cultivate talent can indirectly affect the cost of acquiring innovative talent for construction companies, so improving the academic evaluation benefit can also increase the probability of construction companies choosing RAAC innovations.

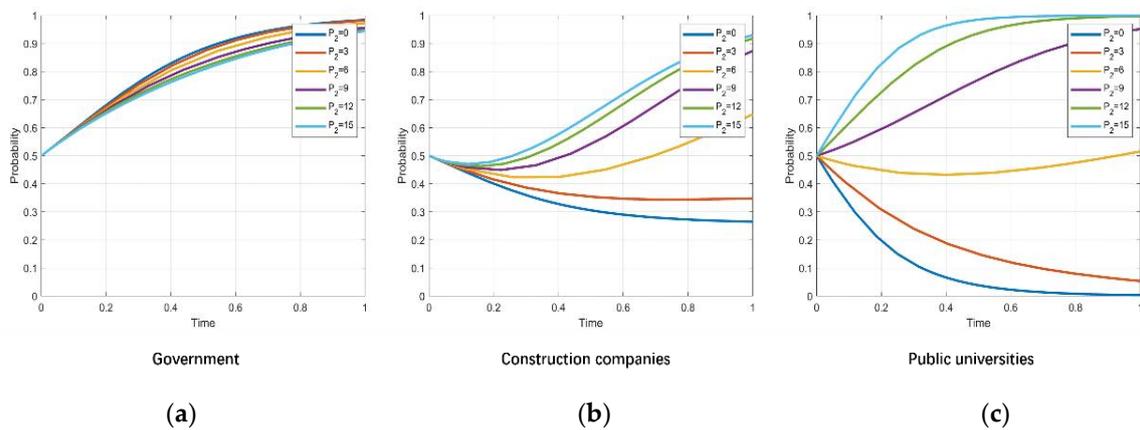


Figure 11. Impact of  $\mathcal{P}_2$  on evolutionary outcomes and trajectories.

## 6. Discussion and Policy Implications

### 6.1. Comparison with Previous Studies and Working Hypotheses

RAAC innovation is critical to improving sustainability in the construction industry. Stakeholders' conflicting benefits and costs then directly influence their strategic choices, which in turn affect RAAC innovation. Consistent with the literature, the results of our analysis confirm that the high cost of innovation is one of the reasons why construction companies are reluctant to innovate [66,67]. Inadequate financial support for the education sector is also a major impediment to RAAC R&D and talent development in public schools [68]. However, contrary to our hypothesis, simply raising financial incentives

does not help much in achieving RAAC innovation, with the reason being that excessive fiscal spending leads to a decrease in the government's willingness to choose incentives. Improving the reputation that RAAC innovations bring to construction companies and the academic ratings given to public universities can effectively contribute to the implementation of RAAC innovations, which is consistent with our previous assumptions.

### 6.2. Policy Implications

Our research results suggest that innovation costs, financial incentives, and prestige incentives are determinants of responsible stakeholder behavior. Therefore, this paper offers the following policy insights:

1. Construction companies need to continuously improve their strength to meet the technical requirements of RAAC innovation, reduce the cost of innovation, and improve their risk degree capability. Public universities should establish a plan for RAAC talent training, gradually accumulate research technologies and talents in related directions, and reduce the cost of talent training.
2. Government can promote the development and implementation of RAAC technology by implementing policies that create compound incentives and developing a policy mix of financial and reputational incentives. On the one hand, the government needs to introduce a system to regulate industry standards, and on the other hand, the government needs to provide some financial support to help construction companies to relieve their worries about the high cost of RAAC innovations. At the same time, the government can increase the brand benefits of RAAC innovation for construction companies by organizing exhibitions and granting "progress awards" to active companies. For construction companies that refuse to innovate, the government needs to fine them for poor environmental performance resulting from their construction methods.
3. At present, China's construction companies are reluctant to innovate due to insufficient investment in R&D in the construction field [68]. The government needs to provide research funding support to public universities for the purchase of relevant equipment. In addition, RAAC-related academic achievements and the employment rate of RAAC talents should be taken into consideration in the academic evaluation.

### 7. Conclusions

The behavioral decisions of government, construction companies, and public universities affect the implementation of RAAC innovations, and their behavioral strategies are relatively understudied. This paper analyzes the dynamic evolution of RAAC innovation strategy choices by modeling the TEG between the government, construction companies, and public universities. The following conclusions are drawn:

1. Through EGT analysis, the strategic decisions of government, construction companies, and public universities interact, and the ESS (Incentive, Innovative, Cultivation) can be achieved.
2. Financial incentives can motivate construction companies to innovate as well as universities to train talent. Still, once the financial incentive becomes too large, financial pressure is put on the government, which thus chooses not to incentivize.
3. Improving reputational incentives for construction firms and academic evaluations of public universities can increase the probability that construction companies and universities respond to promoting RAAC innovation and accelerate the realization of the tripartite ESS.
4. High financial subsidies do not necessarily work well. Our research shows that higher financial subsidies tend to make the final decision of the tripartite non-innovative. In contrast, appropriately increasing reputational and academic evaluation rewards can effectively increase the likelihood that construction companies and public universities will choose RAAC innovations.

5. For the government, construction companies, and public universities to achieve the ultimate ESS, they need a reasonable set of compounding incentives. The government should set a reasonable financial cost and reputational reward for incentives. Construction companies need to accelerate technology upgrades and reduce the cost of innovation. Public universities need to accelerate the construction of experimental environments to prepare for the training of relevant technical talents.

The above research results provide a good reference for policymakers to develop strategies for RAAC innovation. However, some limitations of this study still exist: this study only considers the case where all three policymakers act as a single subject and does not consider the evolution between construction companies and other construction companies, and between public universities and other public universities. These complex evolutionary relationships still need to be studied in depth in the future.

**Author Contributions:** The authors of this paper have respectively contributed to the following: conceptualization, L.Y. and F.H.; methodology, software, writing—original draft preparation, L.Y.; writing—review and editing, supervision, funding acquisition, F.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are available on request to the authors.

**Conflicts of Interest:** We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service, or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled “A tripartite evolutionary game analysis of innovations in robotics and automated construction”.

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