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Blockchain Technology Adoption by Critical Stakeholders in Prefabricated Construction Supply Chain Based on Evolutionary Game and System Dynamics

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Abstract: Blockchain technology (BT) is a promising solution to address information asymmetry and trust issues in the prefabricated construction supply chain (PCSC). However, its practical application in PCSC remains limited under the influence of stakeholders' adoption strategies. While previous studies have analyzed drivers and barriers to BT adoption, they often take a static view, neglecting the long-term dynamic decision-making interactions between stakeholders. This study addresses this gap by examining the interests of owners, general contractors, and subcontractors, and by developing a tripartite evolutionary game model to analyze the interaction mechanism of the strategy of adopting BT in PCSC. Additionally, a system dynamics simulation validates the evolution of stabilization strategies and examines the impact of key parameters. The results indicate that successful BT adoption requires technology maturity to surpass a threshold between 0.5 and 0.7, along with a fair revenue and cost-sharing coefficient between general contractors and subcontractors, ranging from 0.3 to 0.5 at the lower limit and 0.7 to 0.9 at the upper limit. Notably, general contractors play a pivotal role in driving BT adoption, acting as potential leaders. Furthermore, appropriate incentives, default compensation, and government subsidies can promote optimal adoption strategies, although overly high incentives may reduce owners' willingness to mandate BT adoption. This study provides practical insights and policy recommendations for critical stakeholders to facilitate the widespread adoption of BT in PCSC.

Keywords: blockchain technology; prefabricated construction supply chain; critical stakeholders; evolutionary game; system dynamics

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1. Introduction

Prefabricated construction has emerged as a vital option to help the construction industry transform from low efficiency and high pollution to lean production and low carbon [1]. The successful completion of prefabricated construction projects relies on an efficient prefabricated construction supply chain (PCSC) [2]. PCSC is a complex network comprising many stakeholders, such as owners, manufacturers, transporters, and contractors, as well as procedures like factory production, component delivery, and on-site assembly [3]. This complexity creates high demands for information symmetry and visibility within the supply chain. However, in the current management process, stakeholders tend to maintain their own information independently and are often reluctant to share it due to self-interest [1]. This results in asymmetric information flow between upstream and downstream entities, leading to frequent issues such as incomplete or inaccurate data, which causes temporary production plan changes and scheduling delays [4]. Furthermore, the ad hoc nature of current supply chain partnerships and the challenges of benefit sharing among stakeholders often lead to claims, opportunistic behaviors, and substandard practices [5]. These issues erode trust and further hinder long-term cooperation.

Blockchain technology (BT) is seen as a transformative solution to these supply chain management issues [6,7]. BT is a distributed ledger technology that utilizes basic technologies such as cryptography, consensus algorithms, and asymmetric encryption [8,9]. It enables real-time information sharing, logistics visualization, product authenticity verification, dispute tracing, and automated secure payments in construction projects. Adopting BT will improve the efficiency of the overall process and enhance trust among members in PCSC, promoting the sustainable development of prefabricated construction [9,10]. Given the transformative potential of BT, countries worldwide have recently developed action plans to promote its adoption. For instance, Japan and Singapore have established sandbox environments to test the boundaries of BT and its integration with other digital systems [11,12]. Similarly, China has released Blockchain Whitepaper 2023, offering guidelines for the industry's growth and regulatory framework within the country [13]. In the construction sector, recent years have seen a growing body of research focused on designing system frameworks and developing BT solutions to address challenges in supply chain management, contract management, and construction management [14].

Despite policy support and growing research in BT development, the adoption of BT in the construction industry has progressed much more slowly than anticipated. This necessitates an exploration of strategies to accelerate its adoption. Recent studies on BT adoption have primarily focused on identifying the impediments and drivers [15–17]. For instance, Waqar et al. investigated 17 challenges across five areas, involving technology, working environment, economics and planning, operational barriers, and privacy and regulation, affecting the implementation of BT in small-scale construction projects in Malaysia [18]. Similarly, Li et al. developed a conceptual model of blockchain adoption in the construction industry using the technology-organization-environment framework, finding that factors such as compatibility, top management support, and comparative advantage significantly influence BT adoption [19]. While these studies offer valuable insights into improving the adoption of BT, they often take a static perspective, failing to account for the dynamic interactions between stakeholders. In reality, BT adoption in PCSC is a complex and dynamic process that involves strategic interactions among potential adopters. The adoption strategies of stakeholders with different interests influence each other and are impacted by the varying effectiveness of BT. This complexity and dynamism often make it challenging for these stakeholders to reach a consensus, hindering BT adoption.

Evolutionary game (EG) theory is commonly used to assess and understand cooperation and conflict in multi-subject decision-making processes with limited rationality, as well as to analyze and predict strategy stability [20–22]. For example, Hu et al. used an EG model to examine the interaction of interests and the evolution of decision-making among the three limited-rational subjects, namely the central government, local governments, and developers, in the implementation of green buildings within China's multilevel governance framework, to provide policy insights into the promotion of green buildings [22]. Further, to obtain a more holistic understanding of the interaction mechanism in a complex system, some studies combined system dynamics (SD) to analyze the dynamic feedback structure of the game and simulate the strategic evolution process on the basis of EG analysis. For example, Xue et al. applied the EG theory and the SD model to optimize safety regulation strategies with different stakeholders in major infrastructure projects [23]. Zuo et al. integrated the EG theory with SD method to simulate the impacts of factors on participants' rent-seeking decisions [24]. However, limited attempts have been made to examine the long-term and dynamic interaction of critical stakeholders adopting BT in PCSC using the combination of EG theory and SD model.

Against this backdrop, this study aims to provide a comprehensive analysis of the dynamic strategy interaction mechanisms of adopting BT among the critical stakeholders in PCSC. Specifically, this study seeks to answer the following questions. (1) What are the interaction relationships of BT adoption by critical stakeholders? (2) What are the stakeholders' strategic choices and corresponding conditions in the process of adopting BT in PCSC? (3) How do stakeholders' strategies and relevant factors influence the systemic stable strategies? To achieve these objectives, this research first investigates the interests of the critical stakeholders involving owners, general contractors, and subcontractors in BT adoption, then develops an EG model to analyze their decision-making processes and interaction mechanisms. Finally, a SD simulation model is employed to present the dynamic evolutionary processes of steady strategy and examine the impact of key parameters, validating the stability analysis provided by the EG model.

This study represents one of the preliminary investigations into BT adoption in PCSC, contributing to a deeper understanding of the adoption strategy interaction mechanism among owners, general contractors, and subcontractors. It also reveals the effect of stakeholders' strategies and relevant factors, providing valuable insights for stakeholders in PCSC to make informed and rational decisions under different circumstances. Additionally, some policy implications for the government are proposed to promote the adoption of BT in PCSC.

The rest of this study is organized as follows: Section 2 reviews the existing literature related to this research and examines the interest considerations of three critical stakeholders. Section 3 illustrates the methodology of this study. Section 4 establishes a tripartite evolutionary game model of BT adoption. Section 5 develops a system dynamics model based on the evolutionary game model and simulates the system's stability and different influencing factors. Section 6 discusses the important findings and provides some practical implications. Section 7 summarizes the study and suggests future research directions.

2. Literature Review

To ensure a logical progression from understanding the technology to analyzing stakeholder adoption interactions, the existing literature can be categorized into four key areas: BT and its potential in PCSC, BT adoption in construction, critical stakeholders' adoption of BT in PCSC, and combination of evolutionary game theory and system dynamics. First, it is essential to understand BT and its potential in PCSC by exploring its basic features, research developments, and applications, which is the basis for the development of the article. Next, the role of adopters in BT adoption and the research status of BT adoption in the construction industry were reviewed, identifying the research gap in analyzing BT adoption in PCSC from a dynamic and interactive perspective of stakeholder relationships. Then, considering that the strategic interactions of critical stakeholders largely determine the success of BT adoption in PCSC, the roles and interest considerations of owners, general contractors, and subcontractors are further examined, summarizing the interactions and factors influencing their adoption decisions. Finally, to provide a framework for analyzing the complex and dynamic interactions between stakeholders, this study reviews and analyzes the applicability and validity of combining evolutionary game theory and system dynamics from both theoretical and practical perspectives.

2.1. Blockchain Technology and Its Potential in PCSC

BT is a decentralized peer-to-peer distributed ledger [25]. It transfers control and decision-making power from a centralized entity to distributed network participants through a peer-to-peer network, achieving highly transparent information sharing, traceability, and immutability [26]. Specifically, BT records transaction data in interconnected data blocks, with each block containing a cryptographic hash, timestamp, and the transaction data of the previous block. This structure ensures that transaction information cannot be tampered with, deleted, or falsified [25]. Moreover, the transaction ledger is kept in the form of copies distributed across multiple nodes in the network. This setup allows all nodes to track and access information, without relying on intermediaries [27]. Any update to transaction information requires authentication from the majority of network participants, making the information highly transparent and traceable [28]. Additionally, BT supports smart contracts, which automatically transfer ownership of assets and values when preset conditions are met, thereby improving contract fulfillment efficiency.

Blockchain technology (BT), characterized by decentralization, traceability, transparency, and tamper-proof features, has garnered significant attention from both industry practitioners and academics, particularly in supply chain management [29,30]. Deloitte's Global Blockchain Survey highlights that BT will be a transformative agent for organizations even though it is identified as a technology experiment. Companies like Walmart and IBM have already leveraged BT to successfully enhance food supply chain traceability, ensuring food safety and quality management. Renault Group has also developed XCEED, a blockchain-based solution for creating a trusted network between suppliers and manufacturers to guarantee the consistency of vehicle components [30]. However, the current practical applications of BT are primarily limited to experimental efforts by large corporations, and its broader implementation remains relatively constrained [29].

In academia, research on BT has grown rapidly over the past five years, with an increasing exploration of its potential in enhancing supply chain transparency, collaboration efficiency, sustainability, risk management, and supply chain finance [30,31]. For instance, Akhavan et al. analyzed the impact of BT on supply chain performance, concluding that BT creates decentralized systems with high security and transparency to enhance trust, information sharing, and collaboration among supply chain members. This ultimately leads to reduced costs and improved overall performance [32]. Friedman et al. investigated the impact of BT on the sustainability of food supply chains, revealing that its decentralization and traceability features ensure fairness and verify the authenticity of food sources. BT also fosters a sustainability mindset in the food supply chain [33]. Hong and Hales found that BT gives Indian manufacturing firms a competitive edge by improving supply and demand risk management, as well as cybersecurity, enhancing financial and information reliability [34]. Moreover, recent studies have combined BT with emerging technologies such as digital twins (DT), the Internet of Things (IoT), and artificial intelligence (AI) to automate and optimize supply chain management [29,30]. This integration enables more efficient and transparent real-time data sharing and tracking. For example, Zhen et al. explored how DT and BT facilitate continuous monitoring and validation of supply chain processes, improving transparency, security, and decision-making [35]. Hong and Xiao investigated the role of combining BT and AI to enhance supply chain sustainability, finding that this integration optimizes production processes and decision-making while promoting responsible resource management and reducing the environmental footprint of supply chain operations [36].

In PCSC, BT holds significant potential for enhancing information sharing [6,7], information traceability [37,38], and contract fulfillment [39,40]. For example, in information sharing, Lu et al. identified that the decentralized, immutable, and consensus-based nature of BT enhances coordination and collaboration among stakeholders in prefabricated construction projects [41]. Zhao et al. proposed Chain PM as a blockchain 3.0 paradigm. Their experimental results showed that information synchronization delays are significantly reduced in prefabricated construction projects using BT [42]. Regarding information traceability, Yoon et al. summarized the benefits of BT in construction supplier selection and evaluation, blockchain-assisted claim audit, evidence analysis, and dispute resolution [43]. Wang et al. developed a blockchain-based framework to improve supply chain traceability and information sharing during prefabricated construction [6]. As for contract fulfillment, Olawumi et al. demonstrated that BT offers considerable capabilities to the construction industry, such as transparency, smart contracts, increased trust, and timely resolution of contractual obligations [39]. The applications of BT in PCSC are summarized in Table 1.

2.2. Blockchain Technology Adoption in Construction

BT is a network technology that involves interaction among adopting organizations [44]. BT adoption requires joint participation and collective agreement among inter-organizational stakeholders to maximize the technology's potential [5,45,46]. Research on BT adoption has expanded into various industries, such as supply chain management, healthcare, finance, and agri-food. In the construction industry, research on BT adoption mainly falls into two categories: factors influencing adoption and adoption strategies. Studies on influencing factors identify and analyze what affects the adoption of BT. For example, Li et al. discussed challenges and opportunities related to blockchain implementation in construction based on both the academic and gray literature [7]. Wang et al. created a model combining Technology Acceptance Model (TAM) with Technology-Organization-Environment (TOE) to determine the factors influencing blockchain adoption in construction [17]. Xu et al. identified 11 barriers to BT adoption and used the interpretative structural modeling method (ISM) and decision-making trial and evaluation laboratory (DEMATEL) to explore their interdependencies [15].

The second category is adoption strategy research, primarily employing game theory to examine stakeholder interactions. Xu et al. utilized evolutionary game theory to study the interactions among manufacturers, contractors, and developers in adopting a quality tracking system based on BT. They identified technological maturity, costs and benefits, and subsidies and incentives for owners as key factors influencing adoption strategies [47]. Ding et al. combined evolutionary game theory with system dynamics to analyze the interactional relationships and diffusion mechanisms among government and construction enterprises during the adoption of BT in the construction industry. They highlighted the effects of competition, cooperation, and government subsidies on technology diffusion [48]. Zhang et al. applied sequential game theory to investigate the decision-making process for adopting BT by owners, manufacturers, and contractors in prefabricated construction projects. They found that benefits, costs, and government subsidies primarily influence BT adoption in these projects [49]. Wu et al. explored the adoption strategies of BT by owners and general contractors in construction quality management using evolutionary game theory. They emphasized the dynamic interaction between the two parties, focusing on the trade-off between the added value from reducing opportunism and the development and operational costs of adopting BT [5].

Table 1. Potential applications of BT in PCSC.

Application Direction	Specific Application	References
Information sharing	a1: Transparency of information on the production, transport and installation of prefabricated components	[7,50–52]
	a2: Real-time management of the entire supply chain	[42,50,52,53]
	a3: Coordination of production and construction programs	[41,54]
	a4: Improve the accuracy of information sharing for on-site assembly of components	[42,55,56]
Information traceability	a5: Verification of the authenticity of the origin of the components	[41,57,58]
	a6: Provision of evidence of claimed events	[40,43]
	a7: Analysis of progress delays	[40,53]
Contract execution	a8: Automatic execution of construction progress payments	[39,40]
	a9: Automatic execution of quality checks	[58,59]

Research on adoption strategies in the construction industry is still in its early stages, with limited literature available [5,48]. This may be due to the relatively recent development and adoption of BT in the sector [48]. Specifically, within PCSC, Xu et al. are the only researchers, to the author's knowledge, who focus on the adoption strategy of blockchain-based quality tracking for prefabricated components [47]. However, their research lacks a comprehensive consideration of the impacts generated by BT in PCSC. Adoption of BT in PCSC involves complex interactions among stakeholder strategies [5,47]. Different stakeholders have diverse interests and are affected by BT in various ways, making it challenging to form a common adoption goal [60]. This complexity often hinders BT adoption in PCSC. Therefore, it is necessary to study the interaction of stakeholders' BT adoption strategies to promote its adoption in PCSC. Additionally, investigating BT adoption strategies will help address management issues and promote the development of prefabricated construction, which is significant for the sustainable development of the construction industry.

2.3. Critical Stakeholders' Adoption of Blockchain Technology in PCSC

To facilitate the study of the interactive relationship among BT adoption strategies in PCSC, this research focused on three critical stakeholders: owners, general contractors, and subcontractors. Subcontractors include prefabricated component manufacturers transportation providers, and assembly subcontractors who sign contracts with general contractors. The existing literature and engineering practices have explored integrating the Engineering, Procurement, and Construction (EPC) contracting model with prefabricated construction [61,62]. This integration aims to leverage the general contractors' role in overall planning and coordination, thus mitigating issues such as fragmentation and miscommunication in PCSC [63,64]. In the EPC model, owners initiate an order for a prefabricated construction project and general contractors then accept the commission, forming agreements with the aforementioned subcontractors [65,66]. Acting as the core of the PCSC, general contractors engage in construction activities, supervise and manage the production, logistics, and assembly activities of subcontractors, and ultimately deliver the prefabricated building products to owners [3,67,68]. It is undeniable that many other parties, such as supervisors, financial institutions, and the government, support the operation of PCSC. However, general contractors and subcontractors are the primary executors, while owners are the decision-makers and receivers. These three stakeholders play decisive roles in the performance of PCSC. The study investigates the benefit considerations and interactive influence during the adoption of BT among these stakeholders. The details are outlined as follows.

Owners are the initiators and decision-makers of PCSC orders [10,49]. For owners, BT helps reduce the risk of selecting contractors, control the supply chain process more accurately and timely, and reduce opportunistic behavior by general contractors. It improves supply chain performance by increasing information transparency and ensuring information integrity [69,70]. However, adopting BT comes with high development, deployment, and operational costs [5]. Especially when the technology is immature, the benefits may not be as apparent, and the cost investment is greater [47]. Wu et al. claimed that owners have greater incentives to innovate and possess decision-making power [5]. Owners usually aim to improve supply chain efficiency and reduce costs through technological innovation, ensuring that construction projects are completed on time and with high quality [49,71]. For the reason that BT adoption by general contractors and subcontractors is necessary to reap benefits like enhanced supply chain performance, owners may use incentives and penalties to compel general contractors to adopt BT for supply chain management [47,72]. Additionally, with government support for BT, owners promoting its use could receive subsidies, which helps offset the adoption costs [49].

General contractors are at the center of PCSC management [61]. For general contractors, BT facilitates accurate and timely supervision and management of subcontractors' activities, ensuring the controllability of project quality, cost, and schedule [49]. It also increases trust between stakeholders [27], reduces disputes, and improves the general contractors' reputation [5]. Additionally, the smart contract function of BT can prevent owners' opportunistic behavior of delayed payments [56]. However, general contractors must bear the additional costs and potential revenue losses from adopting BT. When the technology is immature, significant investment is required to update systems, train employees, and acquire professional talent [9]. Furthermore, highly transparent information sharing reduces general contractors' original competitive advantage in information and opportunistic gains [5,73], and may also expose them to the risk of data leakage [46]. General contractors are often financially driven [20,47], and these costs and losses can deter them from adopting BT. However, their willingness to adopt BT may change due to the benefits received from other stakeholders' adoption strategies. For instance, general contractors responding to owners' requirements to adopt BT can earn rewards but pay default compensation if they default [47]. Additionally, the full benefits of a complete end-to-end blockchain solution can be realized when general contractors and subcontractors adopt BT simultaneously [5,48]. This can lead to greater synergistic benefits than adopting it alone [47,74], such as full traceability, interoperability, and efficient supply chain collaboration [9]. Profit sharing between general contractors and subcontractors can incentivize the latter to adopt the technology, achieving greater synergies and mitigating their respective adoption costs [48,71,75]. Similarly, government subsidies for BT adoption can mitigate the adoption costs for general contractors. This collaboration with other stakeholders and government subsidies will further influence the general contractors' interest considerations and strategic choices.

Subcontractors are key participants in the PCSC process [76]. For subcontractors, the smart contract feature of BT can help solve the problem of late payments by general contractors [56]. The transparency and immutability of supply chain information provided by BT can also prove the quality of their manufactured components [47]. However, adopting BT incurs additional costs and risks for subcontractors. Enhanced PCSC information transparency subjects subcontractors to continuous monitoring, increasing their management pressure and concerns about data leakage [50,77]. Smaller subcontractors may find it more challenging to bear the costs and risks of blockchain adoption compared to general contractors, which diminishes their incentive to adopt the technology [9,73]. Despite these challenges, subcontractors are essential for achieving synergistic benefits in the supply chain. To incentivize their participation, profits of the general contractor are often shared with subcontractors, and they are required to sign default compensation contracts mandated to ensure BT adoption [48]. Furthermore, subcontractors adopting BT can receive government subsidies, which increase their financial benefits of adoption. These factors collectively modify the cost-benefit dynamics for subcontractors and influence their willingness to adopt BT.

In summary, owners, general contractors, and subcontractors make their decisions by considering both the direct impacts of BT and the outcomes of decisions made by other parties, as well as external policy impacts. Although there is a conflict of interest among them in adopting BT, the development of BT and the continuous evolution of the collaboration system among stakeholders can help resolve this. They can weigh costs and benefits in real-time, continuously adjusting their adoption strategies based on the actual situation [5,48]. The adoption relationship of BT adoption between owners, general contractors, and subcontractors in PCSC is shown in Figure 1.

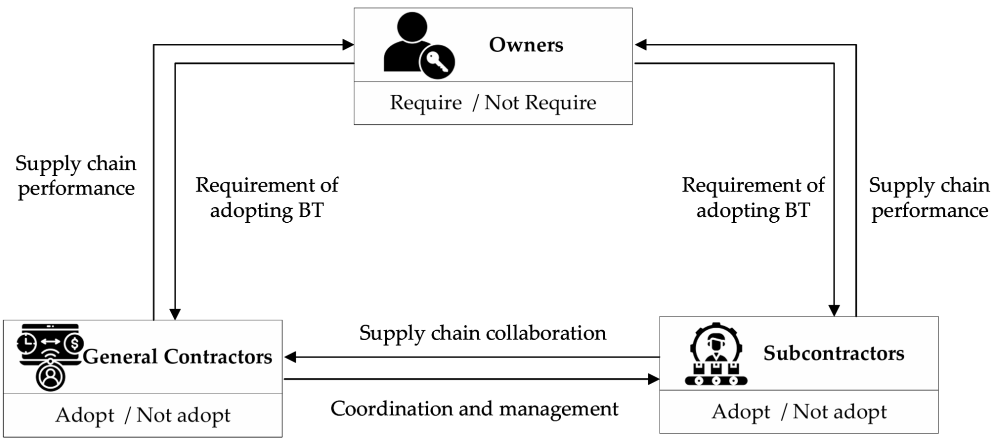


Figure 1. Blockchain technology adoption relationship between the three stakeholders.

2.4. Combination of Evolutionary Game Theory and System Dynamics

Game theory is one of the most influential tools for understanding and analyzing cooperation and conflict among rational decision-makers [78]. It typically examines the interactions and equilibrium strategies between decision-makers through mathematical models. In supply chain management, conflicts and cooperation among stakeholders are common, and game theory offers an effective approach to analyzing these dynamics. For instance, Patare et al. applied Stackelberg and Bayesian games to model the competition between manufacturers and retailers in supply chains, analyzing optimal decisions on product quality, pricing, and marketing strategies under both horizontal and vertical competition [79]. Ocampo used the Stackelberg game model to analyze the behavioral interactions between individual manufacturers and multiple suppliers in the steel industry's order production supply chain, providing key managerial insights for supply chain planning [80].

However, the assumption in traditional game theory that participants are fully rational often fails to align with real-world conditions. Evolutionary game theory addresses this limitation by emphasizing bounded rationality and dynamic equilibrium [81]. It proposes that players continuously trial and error, imitating, learning, and adjusting strategy, which better reflects real-world decision-making behaviors [20]. Consequently, evolutionary game theory has become an important tool for analyzing, predicting, and assessing the stability of an organization's strategy portfolio in actual complex environments [81,82]. For example, Zhang et al. constructed a financing evolution game model between agricultural product suppliers and urban residents to analyze the equilibrium stabilization strategy of the financing game between the two parties in the transition process of green agricultural product supply chain [83]. Long et al. constructed a three-party evolution game model of green-sensitive government, enterprises and consumers to explore the benefits of interaction between the three parties and the stabilization strategies for implementing green supply chains under the influence of green sensitivity [84].

SD, as a modeling technique, enhances understanding, simulation, and analysis of complex system structures [85,86]. SD is particularly effective for presenting the feedback structure of the game and the dynamic processes of strategic evolution towards stable equilibrium, which EG theory has difficulty explaining. It also does not require highly precise parameters but instead focuses on studying system structure and dynamic behavior, making it well-suited for research with limited data availability [87]. For example, Du et al. developed an SD model to analyze the environmental and economic factors influencing carbon emissions from prefabricated buildings. This model was employed to simulate the carbon emission reduction effects within the prefabricated building supply chain under varying environmental policies and economic measures, providing actionable guidance for companies to implement low-carbon strategies and for governments to formulate environmental policies [88]. Similarly, Liu et al. explored the factors influencing corporate knowledge stock and their causal relationships by constructing an SD model of knowledge transfer in large-scale project innovation. They simulated the driving mechanisms for enhancing corporate knowledge stock using data gathered from observations and qualitative discussions [89].

In recent years, to obtain a more specific dynamic interaction between game subjects, some scholars have begun to combine system dynamics with evolutionary game models to reveal the evolutionary stable strategy formation process and role of influencing factors. For example, Guo et al. developed a system dynamics model based on evolutionary game theory to optimize quality supervision procedures in construction management, which describes the complex and dynamic interactions among three stakeholders, including the project owner, construction supervising engineer, and construction contractor. The model proves the necessity of changing the supervision mode and provides practical solutions by simulating equilibrium solutions in different penalty–reward scenarios [90]. Likewise, Li et al. used a hybrid model combining evolutionary game theory and system dynamics to develop a stable strategy for digital alliances in the construction industry, where the evolutionary game is utilized to analyze the competition and cooperation relationship of the digital alliance of construction enterprises under bounded rationality, revealing the factors affecting coopetition of digital alliances and the evolutionary stability strategy (ESS), while SD was used for numerical simulations to investigate the impact of these factors on the stability of digital alliances [82]. Similarly, Ding et al. applied the evolutionary game-system dynamics model to interorganizational diffusion of BT in the construction industry to promote BT adoption practices. The EG model describes the complicated relationships in the economic aspect between government and construction enterprises in the process of BT adoption and provides the mathematical relationship between variables for the SD model. The SD model was used to reveal the evolution of BT adoption in general contractor enterprises and subcontractor enterprises, and identify the effects of relevant factors on BT diffusion [48]. The integration of EG and SD not only contributes to analyzing and presenting the interactions of multiple participants but also provides a tool for simulating equilibrium solutions of the system and the impacts of different factors on the stability of strategy [48].

Despite the successful applications of integrating EG and SD, there is still limited literature on the adoption of BT in the construction industry using a combination of evolutionary game theory and system dynamics, especially in the field of the PCSC, where it has the potential for further exploration. In view of this gap and motivated by the practicability of integrating evolutionary game and SD, this research develops the evolutionary game with SD model on BT adoption in PCSC, aiming to analyze the BT adoption interaction of owners, general contractors, and subcontractors in PCSC, intuitively show the dynamics evolution process of stable strategies, and simulate the effects of different variable changes on the equilibrium solutions.

3. Methodology

According to Section 2.3, the three critical stakeholders, i.e., owners, general contractors, and subcontractors, are boundedly rational, meaning they cannot fully understand each other's intentions and adoption status at the outset. They dynamically adjust their adoption strategies and make optimal decisions through continuous trial and error, observation, and mutual learning. Therefore, EG theory is well-suited to studying the long-term dynamic interactions of these boundedly rational players in the context of BT adoption [5,48].

This research also integrates SD with EG theory to analyze and simulate the long-term dynamic game of BT adoption. On the one hand, considering the complex interactions among critical stakeholders and the limitations of EG theory in explaining the dynamic evolutionary process of reaching a stable strategy, SD was employed to depict the feedback structure of the game and the dynamic processes leading to a stable equilibrium [23]. On the other hand, SD serves as a practical numerical simulation tool to verify the results of theoretical analyses in evolutionary game theory [24]. Given the limited data availability on BT adoption in the construction industry due to its rare application, SD is particularly advantageous as it does not require highly precise parameters but focuses on understanding system structure and dynamic behavior [91]. The methodology of this research is illustrated in Figure 2.

The first part involves analyzing and summarizing the considerations and conflicts of interest among critical stakeholders through a literature review. In the second part, the EG model is constructed. The assumptions and parameters of the model are based on the previously identified interactions of interest. The payoff matrix and replicator dynamic equations for the three stakeholders are then calculated according to evolutionary game theory. Stability analysis is conducted to determine the strategic stability of each stakeholder and the stability of the system's equilibrium strategy. In the third part, the SD model is developed using the parameters, payoff matrix, and replicator dynamic equations from the evolutionary game model. Multi-stage dynamic evolution simulations are performed to validate the theoretical stability analysis of the EG model and to conduct scenario analysis for the SD model. The impact of key variables on strategic stability is also simulated, providing more detailed insights and practical recommendations for stakeholders considering BT adoption.

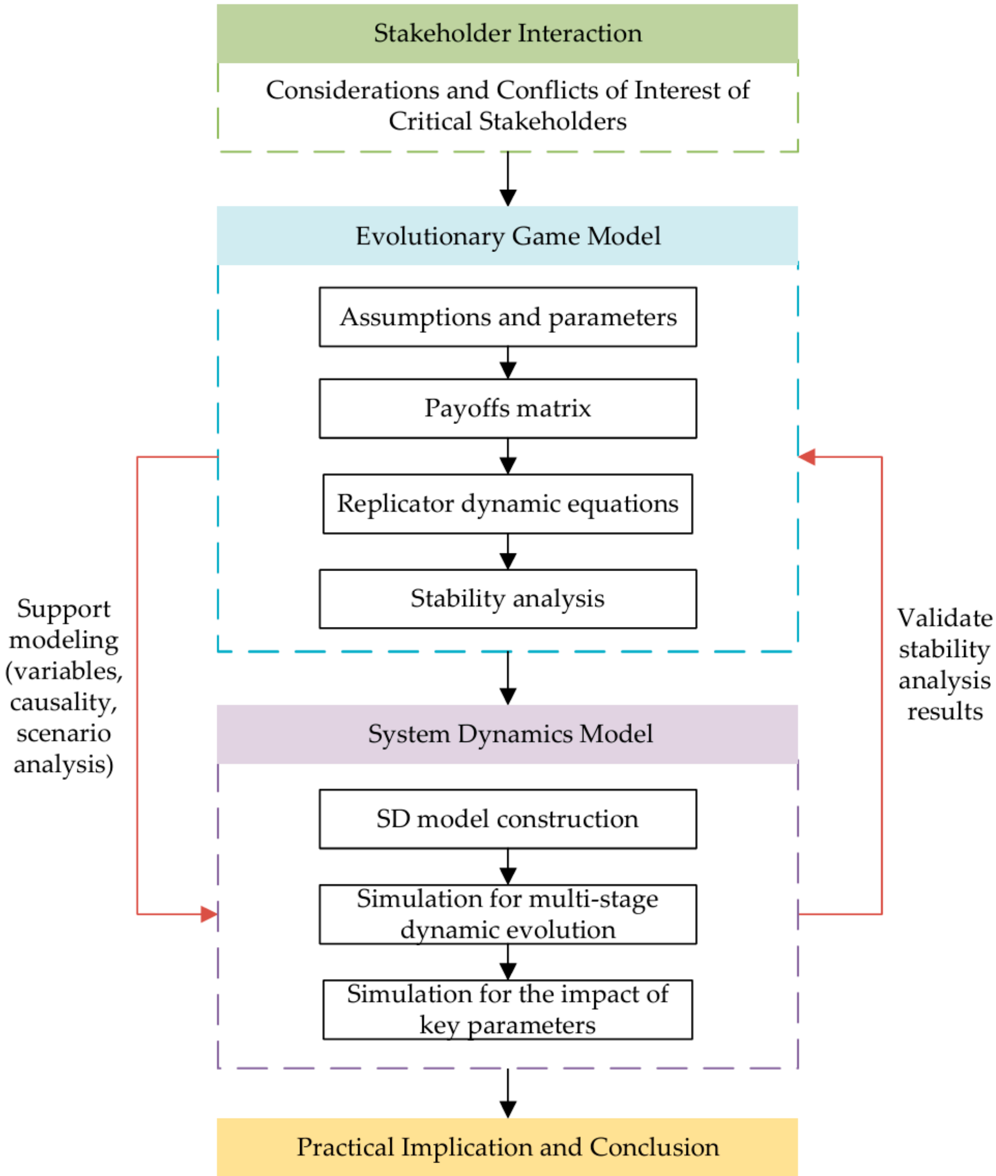


Figure 2. Research methodology.

4. Tripartite Evolutionary Game Modeling

This section analyzes the interaction mechanism of the three parties' adoption strategies using evolutionary game modeling. Specifically, Section 4.1 outlines the model assumptions and parameter settings, establishing the foundation for the modeling. Section 4.2 examines stakeholders' payoffs under different strategies based on evolutionary game theory and develops dynamic equations to describe their strategic changes. Section 4.3 explores the stable strategies of each party and their corresponding conditions, as well as the combined stable strategies of all three parties, revealing the mechanism behind the long-term dynamic strategy changes within the game system. This analysis provides a theoretical foundation for the subsequent simulation and analysis of system dynamics.

4.1. Model Assumptions and Parameters

Based on the interactive relationship of BT adoption between the three stakeholders analyzed in Section 2.3, the assumptions are put forward as follows and the parameters of the evolutionary game model are also set up in Table 2.

Table 2. Parameters and corresponding descriptions.

Parameters	Descriptions	Reference
$P_1,\ P_2,\ P_3$	Basic revenue for owners, general contractors, and subcontractors	[48,49]
$D_1,\ D_2$	Extra benefits for owners from general contractors' and subcontractors' adoption	[48,49]
G_0	Incremental benefits for owners' requirement (such as social benefit, corporate image, and internal efficiency)	[69,70]
C_0	Incremental costs for owners' requirement (such as technology deployment, training and maintenance costs)	[48,49]
E_1	Incentive for general contractors from owners	[47,72]
R_1	Default compensation for owners from general contractors	[47,72]
R_2	Default compensation for general contractors from subcontractors	[48]
$S_1, S_2,\ S_3$	Government subsidy for owners, general contractors, and subcontractors	[48,49]
g	Discount coefficient of D_1 when owners do not require adoption	[69,70]
h	Discount coefficient of D_2 when owners do not require adoption	[69,70]
B_1, B_2	Incremental benefits for general contractors' and subcontractors' adoption	[47–49]
C_1, C_2	Incremental costs for general contractors' and subcontractors' adoption	[47–49]
ΔB	Synergistic benefits of adoption by general contractors collaborating with subcontractors	[5,48]
ΔC	Cooperative cost of adoption by general contractors collaborating with subcontractors	[5,48]
α	Revenue-sharing between general contractors and subcontractors	[48]
β	Cost-sharing between general contractors and subcontractors	[48]
φ	Technology maturity	[47]

Assumption 1. *The evolutionary game model includes three stakeholders: owners, general contractors, and subcontractors. They are all boundedly rational individuals capable of imitating, learning, and dynamically adjusting their strategy choices.*

Assumption 2. *Owners' strategy is (require, not require), with probabilities x $(0 \le x \le 1)$ and $1 - x$, respectively. The general contractors' strategy is (adopt, not adopt), with probabilities y $(0 \le y \le 1)$ and $1 - y$, respectively. Subcontractors' strategy is (adopt, not adopt), with probabilities z $(0 \le z \le 1)$ and $1 - z$, respectively, and x, y, and z are all functions of time t.*

Assumption 3. *The basic revenue when owners do not require the adoption of BT is P_0, and the incremental benefits are G_0 when BT adoption is required, considering factors such as technology cost and benefit. Owners also bear incremental costs C_0, such as technology deployment, training, and maintenance costs. When general contractors respond to owners' requirement for adoption, owners' incentive for general contractors is E_1. If general contractors do not respond due to excessive technology adoption costs and risks, general contractors pay default compensation R_1 to owners.*

Assumption 4. *If general contractors and subcontractors adopt BT, owners gain extra benefits are D_1 and D_2, such as increased transparency of project information and improved supply chain performance. If owners do not require adoption, and general contractors and subcontractors still adopt BT, owners receive a discounted extra benefit of gD_1 and hD_2, respectively.*

Assumption 5. *The synergistic benefits of simultaneous adoption of BT by general contractors and subcontractors are ΔB, and the costs of collaboration are ΔC. Profit sharing between general contractors and subcontractors is determined by the revenue-sharing coefficient α and the cost-sharing coefficient β.*

Assumption 6. *The basic revenues of general contractors and subcontractors without adopting BT are P_1 and P_2. The incremental benefits of adopting BT alone are B_1 and B_2, and the incremental costs are C_1 and C_2. If subcontractors default by not adopting BT, they pay compensation R_2 to general contractors.*

Assumption 7. *The government provides policy support for enterprises that adopt BT. When owners require adoption, and both general contractors and subcontractors choose to adopt BT, all three receive government subsidies $S_1, S_2,$ and S_3.*

Assumption 8. *The maturity level of BT is defined as* φ. *As the technology and support services mature, the benefit growth coefficient of technology adoption is* $\left(1-e^{-\varphi}\right)$, *and the cost reduction coefficient is* $e^{-\varphi}$ *[92], leading to improved work efficiency, enhanced enterprise reputation and competitiveness, and reduced infrastructure investment [47].*

4.2. Model Establishment

In evolutionary systems, the "survival of the fittest" mechanism dictates that when a strategy's fitness surpasses the population average, its adoption rate increases. A strategy's fitness reflects its value, and successful strategies yield above-average returns. Thus, players in a long-term dynamic game select the most favorable strategies based on perceived payoffs, the higher the payoff; the more likely the strategy will be chosen [22].

Building on these principles and previous assumptions, the payoff matrix that includes the payoffs of owners, general contractors, and subcontractors under different combinations of strategies was established as shown in Table 3. After that, the expected payoffs for each player's two strategies and the average expected payoffs were calculated. These calculations of payoffs enable the three stakeholders to evaluate the effectiveness of strategies for maximizing benefits. Specifically, the owners will compare the expected payoffs of the "require" and "not require" strategies, while the general contractor and subcontractors will assess the expected payoffs of adopting versus not adopting BT.

Table 3. Payoffs matrix for owners, general contractors, and subcontractors.

Strategy and Payoff				Owners	
				Require (x)	**Not Require ($1-x$)**
General contractors	Adopt (y)	Subcontractors	Adopt (z)	$P_0+\left(1-e^{-\varphi}\right)(D_1+D_2)$ $-e^{-\varphi}C_0-E_1+S_0+G_0$	$P_0+\left(1-e^{-\varphi}\right)(gD_1+hD_2)$
				$P_1+\left(1-e^{-\varphi}\right)\alpha\Delta B$ $-e^{-\varphi}\beta\Delta C+E_1+S_1$	$P_1+\left(1-e^{-\varphi}\right)\alpha\Delta B$ $-e^{-\varphi}\beta\Delta C+S_1$
				$P_2+\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B$ $-e^{-\varphi}(1-\beta)\Delta C+S_2$	$P_2+\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B$ $-e^{-\varphi}(1-\beta)\Delta C+S_2$
			Not adopt ($1-z$)	$P_0+\left(1-e^{-\varphi}\right)D_1$ $-e^{-\varphi}C_0-E_1+S_0+G_0$	$P_0+\varphi gD_1$
				$P_1+\left(1-e^{-\varphi}\right)B_1$ $-e^{-\varphi}C_1+E_1+R_2+S_1$	$P_1+\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1$ $+R_2+S_1$
				P_2-R_2	P_2-R_2
	Not adopt ($1-y$)	Subcontractors	Adopt (z)	$P_0+\left(1-e^{-\varphi}\right)D_2$ $-e^{-\varphi}C_0+R_1+S_0+G_0$	$P_0+\left(1-e^{-\varphi}\right)hD_2$
				P_1-R_1	P_1
				$P_2+\left(1-e^{-\varphi}\right)B_2$ $-e^{-\varphi}C_2+S_2$	$P_2+\left(1-e^{-\varphi}\right)B_2$ $-e^{-\varphi}C_2+S_2$
			Not adopt ($1-z$)	$P_0-e^{-\varphi}C_0+R_1$ $+S_0+G_0$	P_0
				P_1-R_1	P_1
				P_2	P_2

In order to quantify this trade-off process of payoffs, replicator dynamics are introduced to represent the change in players' strategies. The replicator dynamic equation describes the rate of change in the prevalence of a strategy in the long-term game [93]. In this study, the replicator dynamic equations were built to indicate the rate of change of the "require" and "adopt" strategies, representing the dynamic strategy adjustment of owners, general contractors, and subcontractors. The positive or negative value of the replicator dynamic equations implies an increase or decrease in strategy probability. For example, *F(x)* represents the rate of change of the owner's strategy of choosing the "require" strategy; when *F(x)* > 0, it means that the owner is more likely to require the adoption of the blockchain technology, whereas *F(x)* < 0, the owner prefers the strategy of "not require" the adoption of BT. The tripartite dynamic replicator equation set is shown in Equation (1). The above calculation process is shown in Appendix A.

$$\begin{cases} F(x) = x(1-x)\left[y(1-g)\left(1-e^{-\varphi}\right)D_1 + z(1-h)\left(1-e^{-\varphi}\right)D_2 - e^{-\varphi}C_o + S_o + G_0 + (1-y)R_1 - yE_1\right] \\ F(y) = y(1-y)\left\{z\left[\left(1-e^{-\varphi}\right)\alpha\Delta B - e^{-\varphi}\beta\Delta C\right] + (1-z)\left[\left(1-e^{-\varphi}\right)B_1 - e^{-\varphi}C_1 + R_2\right] + x(E_1+R_1)\right] + S_1\right\} \\ F(z) = z(1-z)\left\{y\left[\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C\right] + (1-y)\left[\left(1-e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] + yR_2 + S_2\right\} \end{cases} \quad (1)$$

4.3. Model Solution and Stability Analysis

The EG model employs replicator dynamics equation to quantify how players with limited rationality adjust their strategies over time. By solving the replicator dynamics equation and conducting a stability analysis, the stable strategy for each player in the game can be determined.

4.3.1. Unilateral Stabilization Strategy Analysis

Based on the stability theorem and the dynamic game theory of replicator [93], when the equation set equals zero and the partial derivatives are simultaneously less than zero, the strategy remains unchanged, indicating that the evolutionary game system has reached a stable equilibrium state. Thus, the equilibrium points of owners, general contractors, and subcontractors can be determined. The details of steady states are analyzed as follows:

(1) For owners

When $F(x) = 0$, there are 3 equilibrium points, $x = 0$, $x = 1$, and $z^* = \frac{e^{-\varphi}C_o - y(1-g)\left(1-e^{-\varphi}\right)D_1 - S_o - G_0 - (1-y)R_1 + yE_1}{(1-h)\left(1-e^{-\varphi}\right)D_2}$. Let:

$$G(z) = \left(1-e^{-\varphi}\right)\left[y(1-g)D_1 + z(1-h)D_2\right] - e^{-\varphi}C_o + S_o + G_0 + (1-y)R_1 - yE_1 \quad (2)$$

Then, $\frac{d(F(x))}{dx} = (1-2x)G(z)$. The first order partial derivative of $G(z)$ is $\frac{\partial G(z)}{\partial z}$, $\frac{\partial G(z)}{\partial z} = \left(1-e^{-\varphi}\right)(1-h)D_2$, the function $G(z)$ is an increasing function of z.

When $z = z^*$, $G(z) = 0, F(x) \equiv 0, \frac{d(F(x))}{dx} \equiv 0$, indicating that all points on the x-axis are in a steady state, at which point owners' choice of strategy does not change over time. Owners cannot determine a stable strategy.

When $z \neq z^*$, there are two cases. When $0 < z < z^*$, $G(z) < 0$, $\frac{d(F(x))}{dx|_{x=0}} < 0$, $\frac{d(F(x))}{dx|_{x=1}} > 0$, indicating that $x = 0$ is owners' ESS, at which point owners choose the "not require" strategy. When $z^* < z < 1$, $G(z) > 0$, $\frac{d(F(x))}{dx|_{x=0}} > 0$, $\frac{d(F(x))}{dx|_{x=1}} < 0$, indicating that $x = 1$ is owners' ESS, at which point owners choose the "require" strategy.

Therefore, it means that the greater the probability of subcontractors that choose the strategy of "adopt" is, the greater the probability of owners choosing the strategy of "require". The phase diagram of owners' ESS is shown in Figure 3a.

Corollary 1. *The influence of the probability of general contractors choosing the "adopt" strategy on the probability of owners choosing the "require" strategy depends on specific conditions. When the relative incremental benefits of the "require" strategy (*$\left(1-e^{-\varphi}\right)(1-g)D_1$*) surpass the sum of default compensation for owners and the incentive for general contractors (*$R_1 + E_1$*), the greater the probability of general contractors choosing the strategy of "adopt", the greater the probability of owners choosing the strategy of "not require". Otherwise, the greater the probability of general contractors choosing the strategy of "adopt", the greater the probability of owners choosing the strategy of "require".*

Corollary 2. *The owners would be more willing to choose the "require" strategy when default compensation for owners from general contractors, and government subsidy rise or when the incentive for general contractors from owners falls.*

The proofs of Corollary 1 and Corollary 2 are given in Appendices B.1 and B.2.

(2) For general contractors

When $F(y) = 0$, there are 3 equilibrium points, $y = 0$,$y = 1$, and $x^* = \frac{-z\left[(1-e^{-\varphi})\alpha\Delta B - e^{-\varphi}\beta\Delta C\right]-(1-z)\left[(1-e^{-\varphi})B_1 - e^{-\varphi}C_1 + R_2\right]-S_1}{E_1+R_1}$. Let:

$$H(x) = z\left[\left(1-e^{-\varphi}\right)\alpha\Delta B - e^{-\varphi}\beta\Delta C\right] + (1-z)\left[\left(1-e^{-\varphi}\right)B_1 - e^{-\varphi}C_1 + R_2\right] + x(E_1+R_1) + S_1 \tag{3}$$

Then, $\frac{d(F(y))}{dy} = (1-2y)H(x)$. The first order partial derivative of $H(x)$ is $\frac{\partial H(x)}{\partial x}$, $\frac{\partial H(x)}{\partial x} = E_1 + R_1$, the function $H(x)$ is an increasing function of x.

When $x = x^*$, $H(x) = 0$, $F(y) \equiv 0$, $\frac{d(F(y))}{dy} \equiv 0$, indicating that all points on the y-axis are in a steady state, at which point the general contractors' choice of strategy does not change over time. General contractors cannot determine a stable strategy.

When $x \neq x^*$ there are two cases. When $0 < x < x^*$, $H(x) < 0$, $\frac{d(F(y))}{dy|_{y=0}} < 0$, $\frac{d(F(y))}{dy|_{y=1}} > 0$, indicating that $y = 0$ is the general contractors' ESS, at which point general contractors choose the "not adopt" strategy. When $x^* < x < 1$, $H(x) > 0$, $\frac{d(F(y))}{dy|_{y=0}} > 0$, $\frac{d(F(y))}{dy|_{y=1}} < 0$, indicating that $y = 1$ is the general contractors' ESS, at which point general contractors choose the "adopt" strategy.

Therefore, it means that the greater the probability of owners that choose the strategy of "require" is, the greater the probability of general contractors that choose the strategy of "adopt" is. The phase diagram of general contractors' ESS is shown in Figure 3b.

Corollary 3. *The influence of the probability of subcontractors that choose the "adopt" strategy on the probability of general contractors that choose the "adopt" strategy depends on the comparison between the returns to cooperative adoption and the returns to adoption alone. If the returns to cooperative adoption surpass the returns to adoption alone, the greater the probability of subcontractors choosing the strategy of "adopt", the greater the probability of general contractors choosing the strategy of "adopt". Otherwise, if the returns to adoption alone are larger than those to cooperative adoption, the greater the probability of subcontractors choosing the strategy of "adopt", the greater the probability of general contractors choosing the strategy of "not adopt".*

Corollary 4. *The general contractors would be more willing to choose the "adopt" strategy when revenue-sharing, default compensation for owners from general contractors, default compensation for general contractors from subcontractors, and government subsidy rise or when cost-sharing falls.*

The proofs of Corollary 3 and Corollary 4 are given in Appendices B.3 and B.4.

(3) For subcontractors

When $F(z) = 0$, there are 3 equilibrium points, $z = 0$, $z = 1$, and $y^* = \frac{-\left[(1-e^{-\varphi})B_2 - e^{-\varphi}C_2\right]-S_2}{\left[(1-e^{-\varphi})(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C\right]-\left[(1-e^{-\varphi})B_2 - e^{-\varphi}C_2\right]+R_2}$. Let:

$$I(y) = y\left[\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C\right] + (1-y)\left[\left(1-e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] + yR_2 + S_2 \tag{4}$$

Then, $\frac{d(F(z))}{dz} = (1-2z)I(y)$. The first order partial derivative of $I(y)$ is $\frac{\partial I(y)}{\partial y}$, $\frac{\partial I(y)}{\partial y} = \left[\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C\right] - \left[\left(1-e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] + R_2$, whether positive or negative are uncertain.

When $y = y^*$,$I(y) = 0$, $F(z) \equiv 0$, $\frac{d(F(y))}{dy} \equiv 0$, $\frac{d(F(z))}{dz} \equiv 0$, indicating that all points on the z-axis are in a steady state, at which point subcontractors' choice of strategy does not change over time. Subcontractors cannot determine a stable strategy.

When $y \neq y^*$, $z = 0$ and $z = 1$ are two equilibrium points. There are two cases according to the positivity and negativity of $\frac{\partial I(y)}{\partial y}$.

(a) If $\left(1 - e^{-\varphi}\right)(1 - \alpha)\Delta B - e^{-\varphi}(1 - \beta)\Delta C > \left[\left(1 - e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] - R_2$, then $I(y)$ is an increasing function on y. At this time, there are two steady states. When $0 < y < y^*$, $I(y) < 0$, $\frac{d(F(z))}{dz|_{z=0}} < 0$, $\frac{d(F(z))}{dz|_{z=1}} > 0$, indicating that $z = 0$ is subcontractors' ESS, at which point subcontractors choose the "not adopt" strategy. When $y^* < y < 1$, $I(y) > 0$, $\frac{d(F(z))}{dz|_{z=0}} > 0$, $\frac{d(F(z))}{dz|_{z=1}} < 0$, indicating that $z = 1$ is subcontractors' ESS, at which point subcontractors choose the "adopt" strategy. In this condition, the greater the probability of general contractors that choose the strategy of "adopt" is, the greater the probability of subcontractors that choose the strategy of "adopt" is. The phase diagram of subcontractors' ESS is shown in Figure 3c.

(b) If $\left(1 - e^{-\varphi}\right)(1 - \alpha)\Delta B - e^{-\varphi}(1 - \beta)\Delta C < \left[\left(1 - e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] - R_2$ then $I(y)$ is a decreasing function on y. At this time, there are two steady states. When $0 < y < y^*$, $I(y) > 0$, $\frac{d(F(z))}{dz|_{z=0}} > 0$, $\frac{d(F(z))}{dz|_{z=1}} < 0$, indicating that $z = 1$ is subcontractors' ESS, at which point subcontractors choose the "adopt" strategy. When $y^* < y < 1$,$I(y) < 0$, $\frac{d(F(z))}{dz|_{z=0}} < 0$, $\frac{d(F(z))}{dz|_{z=1}} > 0$, indicating that $z = 0$ is subcontractors' ESS, at which point subcontractors choose the "not adopt" strategy. At this time, the greater the probability of general contractors that choose the strategy of "adopt" is, the greater the probability of subcontractors that choose the strategy of "not adopt" is. The phase diagram of subcontractors' ESS is shown in Figure 3d.

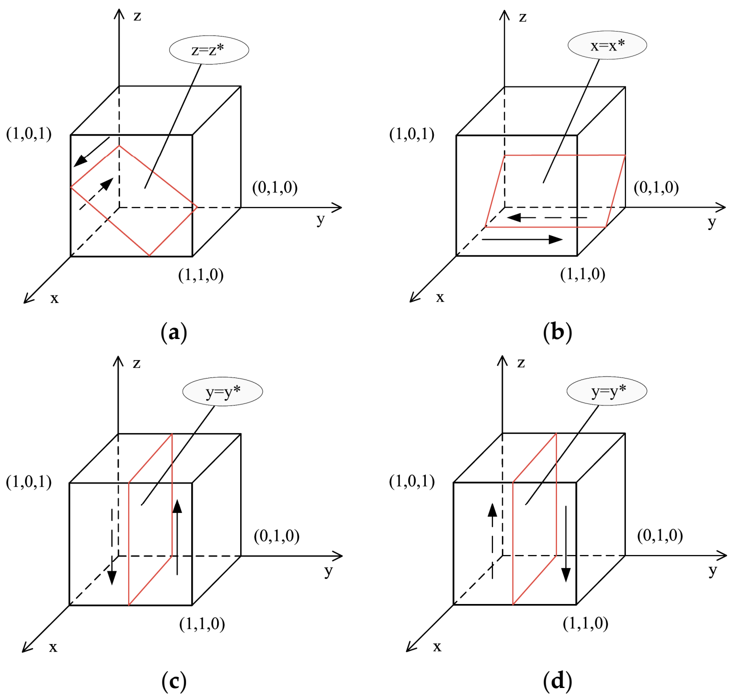


Figure 3. Dynamic evolutionary phase diagram. (**a**) Dynamic evolutionary phase diagram of owners; (**b**) Dynamic evolutionary phase diagram of general contractors; (**c**) Dynamic evolutionary phase diagram of subcontractors when $\left(1 - e^{-\varphi}\right)(1 - \alpha)\Delta B - e^{-\varphi}(1 - \beta)\Delta C > \left[\left(1 - e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] - R_2 > 0$; (**d**) Dynamic evolutionary phase diagram of subcontractors when $\left(1 - e^{-\varphi}\right)(1 - \alpha)\Delta B - e^{-\varphi}(1 - \beta)\Delta C < \left[\left(1 - e^{-\varphi}\right)B_2 - e^{-\varphi}C_2\right] - R_2$.

Corollary 5. *The effect of revenue-sharing, cost-sharing, default compensation for general contractors from subcontractors, and government subsidy on the subcontractors' strategy depends on the comparison between the returns to cooperative adoption and the returns to non-cooperative adoption. If the returns to cooperative adoption surpass the returns to non-cooperative adoption, the subcontractors would be more willing to choose the "adopt" strategy when cost-sharing, default compensation for general contractors from subcontractors, and government subsidy rise or when revenue-sharing falls. Otherwise, if the returns to non-cooperative adoption are larger than those to cooperative adoption, the subcontractors would be more willing to choose the "adopt" strategy when revenue-sharing rises or when cost-sharing, default compensation for general contractors from subcontractors, and government subsidy fall.*

The proof of Corollary 5 is given in Appendix B.5.

In summary, the unilateral stability analysis above identifies the local stabilization points for the three parties, examines the interactions among their strategies, and assesses the sensitivity of these stabilization points to key parameters. This provides a foundational reference for validating and determining stabilization strategy for the system and serves as a basis for subsequent numerical simulations.

4.3.2. Stabilization Strategy Analysis of the System

It is important to clarify that the strategic equilibrium of a single participant does not necessarily correspond to the stable strategy for the system's evolution [22]. Unilateral stability is a consideration of individual behavior stability, while the stable strategy for the entire system requires a global stability analysis, taking into account the strategies of all participants to achieve a shared strategic equilibrium [91]. To determine the evolutionary stabilization strategy of the three-party game system, this study assesses the stability of the system's equilibrium by applying the asymptotic stabilization method to the Jacobian matrix [94]. The analysis is as follows:

The system of Equation (1) is the replicator dynamics equations of measuring the extent to which the strategies of the group change over time. When $F(x) = F(y) = F(z) = 0$, eight pure-strategy local equilibrium points of the system can be determined: $e_1(0,0,0)$, $e_2(0,0,1)$, $e_3(0,1,0)$, $e_4(1,0,0)$, $e_5(1,1,0)$, $e_6(1,0,1)$, $e_7(0,1,1)$, $e_8(1,1,1)$. There is also a mixed-strategy equilibrium point $e^*(x^*, y^*, z^*)$ when $0 \le x^* \le 1$, $0 \le y^* \le 1$, $0 \le z^* \le 1$ are satisfied at the same time.

However, only the eight pure-strategy local equilibrium points are asymptotically stable, under which, the equilibrium point is an evolutionary stable strategy (ESS) [95]. e^* is a mixed-strategy equilibrium point but not asymptotically stable. Therefore, this study only analyzed the asymptotic stability of the eight pure-strategy equilibrium points. By judging the eigenvalues of the Jacobian matrix of the replicator dynamic system, the asymptotic stability of the eight pure strategy equilibrium points can be verified. Equation (5) describes the Jacobi matrix for this tripartite evolutionary game system. The equilibrium points are asymptotically stable only when all eigenvalues of the Jacobi matrix are negative [94,95]. The eigenvalues of the eight pure-strategy equilibrium points are listed in Table 4.

$$J = \begin{bmatrix} (1-2x)G(z) & x(1-x)\left[(1-g)(1-e^{-\varphi})D_1 - R_1 - E_1\right] & x(1-x)(1-h)(1-e^{-\varphi})D_2 \\ y(1-y)(E_1+R_1) & (1-2y)H(x) & y(1-y)\begin{bmatrix}(1-e^{-\varphi})(\alpha\Delta B - B_1) - \\ e^{-\varphi}(\beta\Delta C - C_1) - R_2\end{bmatrix} \\ 0 & z(1-z)\begin{Bmatrix} (1-e^{-\varphi})[(1-\alpha)\Delta B - B_2] \\ -e^{-\varphi}[(1-\beta)\Delta C - C_2] + R_2 \end{Bmatrix} & (1-2z)I(y) \end{bmatrix} \quad (5)$$

According to Table 4, the eight equilibria can evolve to asymptotically stable states if they satisfy the corresponding conditions. However, due to the fact that there are few real applications of BT in PCSC [5], the analysis of stability conditions lacks a real data base. Therefore, based on the diffusion of innovations theory [96], this study divided the process of BT adoption by critical stakeholders in PCSC into four stages, allowing for a more detailed analysis aimed at achieving the ideal stable state.

Table 4. Eigenvalues of evolutionary equilibrium points.

Equilibrium Points	Eigenvalues		
	λ_1	λ_2	λ_3
$e_1(0,0,0)$	$-e^{-\varphi}C_o + S_o + G_0 + R_1$	$(1-e^{-\varphi})B_1 - e^{-\varphi}C_1 - e^{-\varphi}C_1(1-e^{-\varphi})B_1$	$(1-e^{-\varphi})B_2 - e^{-\varphi}C_2 + S_2$
$e_2(0,0,1)$	$(1-h)(1-e^{-\varphi})D_2 - e^{-\varphi}C_o + S_o + G_0 + R_1$	$(1-e^{-\varphi})\alpha\Delta B - e^{-\varphi}\beta\Delta C + S_1$	$-\left[(1-e^{-\varphi})B_2 - e^{-\varphi}C_2 + S_2\right]$
$e_3(0,1,0)$	$(1-g)(1-e^{-\varphi})D_1 - e^{-\varphi}C_o + S_o + G_0 - E_1$	$-\left[(1-e^{-\varphi})B_1 - e^{-\varphi}C_1 + R_2 + S_1\right]$	$(1-e^{-\varphi})(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C + R_2 + S_2$
$e_4(1,0,0)$	$-[-e^{-\varphi}C_o + S_o + G_0 + R_1]$	$(1-e^{-\varphi})B_1 - e^{-\varphi}C_1 + R_2 + E_1 + R_1 + S_1$	$(1-e^{-\varphi})B_2 - e^{-\varphi}C_2 + S_2$
$e_5(1,1,0)$	$-\left[(1-g)(1-e^{-\varphi})D_1 - e^{-\varphi}C_o + S_o + G_0 - E_1\right]$	$-\left[(1-e^{-\varphi})B_1 - e^{-\varphi}C_1 + R_2 + E_1 + R_1 + S_1\right]$	$(1-e^{-\varphi})(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C + R_2 + S_2$
$e_6(1,0,1)$	$-\left[(1-h)(1-e^{-\varphi})D_2 - e^{-\varphi}C_o + S_o + G_0 + R_1\right]$	$(1-e^{-\varphi})\alpha\Delta B - e^{-\varphi}\beta\Delta C + E_1 + R_1 + S_1$	$-\left[(1-e^{-\varphi})B_2 - e^{-\varphi}C_2 + S_2\right]$
$e_7(0,1,1)$	$(1-g)(1-e^{-\varphi})D_1 + (1-h)(1-e^{-\varphi})D_2 - e^{-\varphi}C_o + S_o + G_0 - E_1$	$-\left[(1-e^{-\varphi})\alpha\Delta B - e^{-\varphi}\beta\Delta C + S_1\right]$	$-\left[(1-e^{-\varphi})(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C + R_2 + S_2\right]$
$e_8(1,1,1)$	$-\left[(1-g)(1-e^{-\varphi})D_1 + (1-h)(1-e^{-\varphi})D_2 - e^{-\varphi}C_o + S_o + G_0 - E_1\right]$	$-\left[(1-e^{-\varphi})\alpha\Delta B - e^{-\varphi}\beta\Delta C + E_1 + R_1 + S_1\right]$	$-\left[(1-e^{-\varphi})(1-\alpha)\Delta B - e^{-\varphi}(1-\beta)\Delta C + R_2 + S_2\right]$

Stage 1: In the initial stage, BT is immature, with a high technical threshold, and the benefits and risks are not yet clear. Owners, general contractors, and subcontractors all refrain from adopting BT. Therefore, the initial stage of adoption corresponds to $e_1(0,0,0)$. According to Table 4, three stabilizing conditions need to be met simultaneously. ① $S_o + G_0 + R_1 < e^{-\varphi}C_o$, owners will not require adoption when the costs are greater than the benefits from the "require" strategy. ② $\left(1-e^{-\varphi}\right)B_1 + R_2 + S_1 < e^{-\varphi}C_1$, general contractors will not adopt BT, when the costs of adopting alone exceed the additional benefits, compensation, and subsidy. ③ $\left(1-e^{-\varphi}\right)B_2 + S_2 < e^{-\varphi}C_2$, subcontractors will not adopt BT, when the costs of adopting alone are greater than the additional benefits and subsidy.

Stage 2: In the budding stage, with the gradual realization of technological advantages and the government's recognition and encouragement of BT, owners begin to require the adoption of BT. This stage corresponds to the stabilization strategy point $e_4(1,0,0)$. According to Table 4, the parameter conditions that should be satisfied are as follows. ① $e^{-\varphi}C_o < S_o + G_0 + R_1$, it can be seen that owners will require adoption when the benefits from the requirement for adoption are greater than the costs. ② $\left(1-e^{-\varphi}\right)B_1 + R_2 + E_1 + R_1 + S_1 < e^{-\varphi}C_1$, general contractors will not adopt BT when the costs of adopting alone exceed the benefits from BT and other parties. ③ $\left(1-e^{-\varphi}\right)B_2 + S_2 < e^{-\varphi}C_2$, subcontractors will not adopt BT when the costs of adopting alone are greater than the additional benefits and subsidy.

Stage 3: In the growth stage, as technology develops, government subsidies increase, and owners continue to demand adoption, general contractors begin to adopt BT. Meanwhile, subcontractors remain cautious and choose not to adopt BT. Therefore, the steady state of the growth stage corresponds to $e_5(1,1,0)$. Three stabilizing conditions need to be satisfied simultaneously. ① $e^{-\varphi}C_o + E_1 < (1-g)(1-e^{-\varphi})D_1 + S_o + G_0$, when the strategy of general contractors makes owners' benefits exceed the costs, owners will require adoption. ② $e^{-\varphi}C_1 < (1-e^{-\varphi})B_1 + R_2 + E_1 + R_1 + S_1$, when the benefits, incentives, and compensation are greater than the costs, general contractors will adopt

BT. ③ $(1-e^{-\varphi})(1-\alpha)\Delta B + R_2 + S_2 < e^{-\varphi}(1-\beta)\Delta C$, subcontractors will not adopt BT when the costs of adopting it in collaboration with general contractors are greater than the benefits.

Stage 4: In the maturity stage, the adoption of BT in PCSC becomes more mature and stable, gradually spreading and gaining popularity. Under the influence of subsidies, incentives and compensation, the proportion of stakeholders choosing to adopt BT increases, reaching the optimal equilibrium point $e_8(1,1,1)$. This stage needs to satisfy three stabilizing conditions. ① $e^{-\varphi}C_o + E_1 < (1-e^{-\varphi})[(1-g)D_1 + (1-h)D_2] + S_o + G_0$, when the strategy of general contractors and subcontractors makes owners' benefits exceed the costs, owners will require adoption. ② $e^{-\varphi}\beta\Delta C < (1-e^{-\varphi})\alpha\Delta B + E_1 + R_1 + S_1$, general contractors will adopt BT when the benefits of collaborative adoption with subcontractors are greater than the costs. ③ $e^{-\varphi}(1-\beta)\Delta C < (1-e^{-\varphi})(1-\alpha)\Delta B + R_2 + S_2$, subcontractors will choose to adopt BT when the benefits of collaborating with general contractors exceed the costs.

Based on the above analyses, it is evident that the strategic interactions among the three stakeholders in the BT adoption process are complex and influenced by numerous variables. In Section 4.3.1, the unilateral stability analysis explores how the strategies of the three players interact and how key parameters positively or negatively affect the strategic equilibrium points of the owner, general contractor, and subcontractors. However, the specific processes through which these influences occur remain unclear. Additionally, certain parameter relationships, such as the exponential function between technology maturity and strategy payoffs, are too intricate to derive clear impacts on stable strategy points solely through theoretical analysis.

Furthermore, in Section 4.3.2, while the stable equilibrium strategies of the system can be identified by confirming that the eigenvalues of the Jacobi matrix are all negative, the formation process of these stable strategies is not fully understood, and their validity requires further verification. To address these uncertainties, this study employs SD to numerically simulate various scenarios under different parameter conditions, allowing for a more detailed analysis of the evolutionary game process among the three stakeholders.

5. Simulation Based on System Dynamics (SD)

SD is an effective method for modeling changes in complex systems over time by analyzing the causal relationships and feedback loops between variables. In the context of BT adoption by the three stakeholders, i.e., owner, general contractor, and subcontractors, they continuously imitate and learn from each other's strategies, observe and compare the payoffs of their own strategies, and then adjust their adoption strategies accordingly. These interactive behaviors form a dynamic feedback loop within the system. Together with the fact that the evolutionary game model provides a functional relationship for strategy changes, the SD model is therefore developed in Section 5.1. Given the lack of real-world applications of BT, determining accurate parameter data can be challenging. However, SD simulations do not require precise real data and can still effectively illustrate the evolving dynamics within the system. This makes SD a valuable experimental platform for verifying the dynamic interactions among the owner, general contractor, and subcontractors during the BT adoption process, as analyzed in Section 5.2. Furthermore, it assesses the stability of strategies and the influence of various parameters on that stability in Section 5.3.

5.1. System Dynamics Modeling

Based on the evolutionary game model, an SD model for adopting BT by critical stakeholders in PCSC was developed using Vensim PLE 7.3.5 software, as shown in Figure 4.

The model consists of three subsystems with a total of 3 level variables, 3 rate variables, 6 intermediate variables, and 24 external variables. The functional relationships of these variables in the model are determined by the replicator dynamic Equation (1) of the evolutionary game model. The probabilities of strategy of owners, general contractors, and subcontractors (x, y, z) represent the state of the system and can change over time as the three level variables of the model. The change rate in the probabilities of owners, general contractors, and subcontractors choosing the "require", "adopt" and "adopt" strategies ($F(x) = \frac{dx}{dt}, F(y) = \frac{dy}{dt}, F(z) = \frac{dz}{dt}$), respectively, are represented by three rate variables. The expected payoffs of the three parties under different strategy choices are the intermediate variables of the model, while other factors affecting the strategy choices are the external variables. The SD model is built based on the parameters and replicator dynamic equations in the EG model, and its variable and causal chain settings are consistent with the requirements of the EG model, which ensures the correctness and rationality of the structure of the SD model.

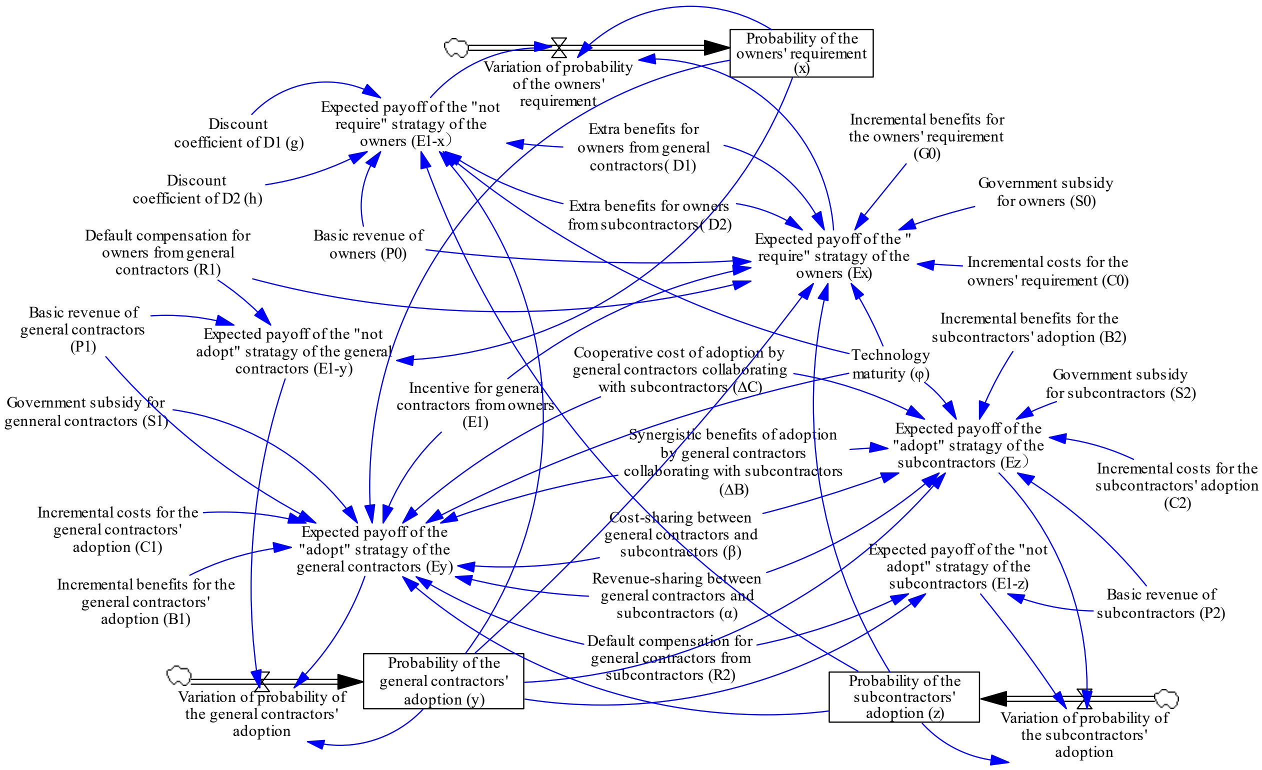


Figure 4. System dynamics model of BT adoption by three critical stakeholders.

5.2. Multi-Stage Dynamic Evolution Results

According to the system stability analysis of the evolutionary game model, the adoption process of BT will progress through four stable stages. SD simulation can be used to verify the analysis of these stabilization strategies, while also helping the three stakeholders better predict and understand the system's stable states and the corresponding external parameter conditions.

In the SD model, the initial simulation values of the external variables are determined as shown in Table A1 in Appendix C. These values were established by referring to the settings of evolution game model parameters in existing studies [47,48]. Each parameter value satisfies the stability conditions at each stage. Additionally, three level variables, which are also the probabilities of strategy, were initially set to 0.5.

Stage 1: The evolution of the strategies in the initial stage is shown in Figure 5a. x, y, and z eventually all converge to 0, reaching the stabilization point $e_1(0,0,0)$. It means that the ESS for owners, general contractors, and subcontractors is (not require, not adopt, not adopt), which aligns with the previous theoretical stability analysis in Section 4.3.2. Specifically, in the initial stage, confidence in BT within PCSC is generally low, influenced by the high technological risks and costs of information management system changes, as well as the lack of obvious economic benefits. In this context, owners will not require the adoption of BT. Prioritizing interests, general contractors tend not to adopt BT, believing that the costs outweigh the benefits. Subcontractors will also not adopt BT due to their limited knowledge of BT and their inability to bear the costs of adoption.

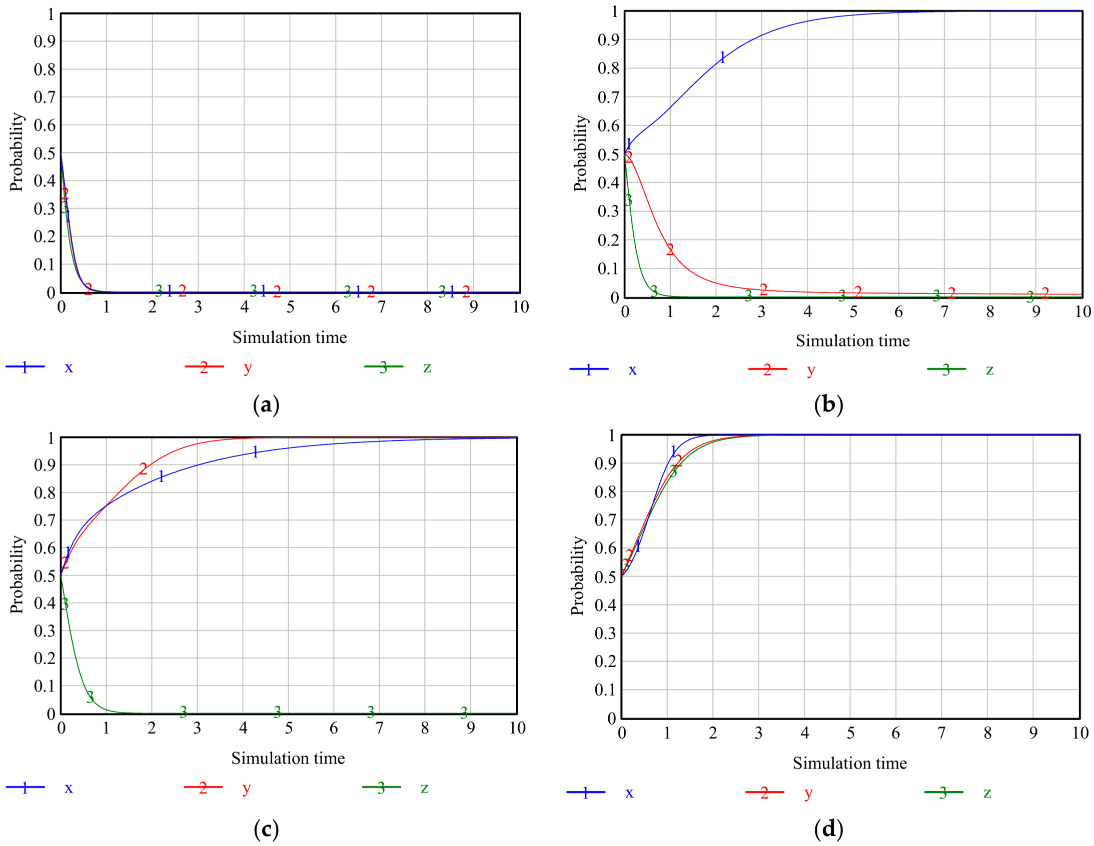


Figure 5. Evolutionary paths of strategies of the tripartite game in the four stages. (**a**) the initial stage; (**b**) the budding stage; (**c**) the growth stage; (**d**) the maturity stage.

Stage 2: The evolution of the strategy in the budding stage is shown in Figure 5b. x converges to 1, while y and z still converge to 0, reaching the stabilization point $e_4(1,0,0)$. It means that the ESS for owners, general contractors, and subcontractors is (require, not adopt, not adopt), verifying the previous theoretical stability analysis in Section 4.3.2. Specifically, in the budding stage, with the gradual embodiment of technical advantages and the government's encouragement of adopting BT, owners tend to choose the "require" strategy to obtain more benefits and establish a corporate image. The high cost of technological transformation and the high risk of revenue still hinder general contractors from adopting BT. Due to their limited ability to bear the cost of adoption and lack of external support, subcontractors also choose not to adopt BT out of their interests.

Stage 3: The evolution of the strategy in the growth stage is shown in Figure 5c. x and y, converge to 1, while z converges to 0, reaching the stabilization point $e_5(1,1,0)$. It means that the ESS for owners, general contractors, and subcontractors is (require, adopt, not adopt), which is consistent with the previous theoretical stability analysis in Section 4.3.2. Specifically, in the growth stage, with external incentives such as increased government subsidies and owners' continuous requirement for adoption, as well as the development of technology maturity, more general contractors begin to adopt BT for economic benefits. However, given a lack of sufficient financial and technological support to change their systems, subcontractors still choose not to adopt BT.

Stage 4: The evolution of the strategy in the maturity stage is shown in Figure 5d. x, y and z all converge to 1, reaching the stabilization point $e_8(1,1,1)$. It means that the ESS for owners, general contractors, and subcontractors is (require, adopt, adopt), corresponding to the previous theoretical stability analysis in Section 4.3.2. Specifically, in the maturity stage, as technology matures and continues to diffuse, the cost and risk of technology updates gradually decrease. It becomes crucial to collaborate on BT adoption to better utilize its technological advantages in PCSC. Therefore, as more and more general contractors adopt BT and the demand for collaboration increases, subcontractors will also gradually choose to adopt BT.

The multi-stage dynamic evolution simulation not only effectively validates and supports the theoretical analysis of the EG model but also serves as a scenario experiment for the behavioral validation of the SD model [97]. By setting parameter values that correspond to the conditions of the four stabilization stages of BT adoption, the outputs of the SD model under these specific scenarios were simulated. The results were consistent with the theoretical analyses of the evolutionary game model, demonstrating behavioral patterns that align with expectations. This consistency indicates that the SD model exhibits a high level of robustness across different strategy development stages.

To further enhance confidence in the SD model for practical applications, the study also tested the model under extreme conditions. Specifically, the technology maturity, a key factor affecting the expected benefits and costs for the three stakeholders, was adjusted to an extreme value of 0, and the resulting changes in the ultimate strategies of the stakeholders were observed. As shown in Figure 6, when technology maturity is 0, none of the three stakeholders adopt BT. This outcome aligns with real-world expectations, where stakeholders would not adopt a technology that is extremely immature and offers no tangible benefits.

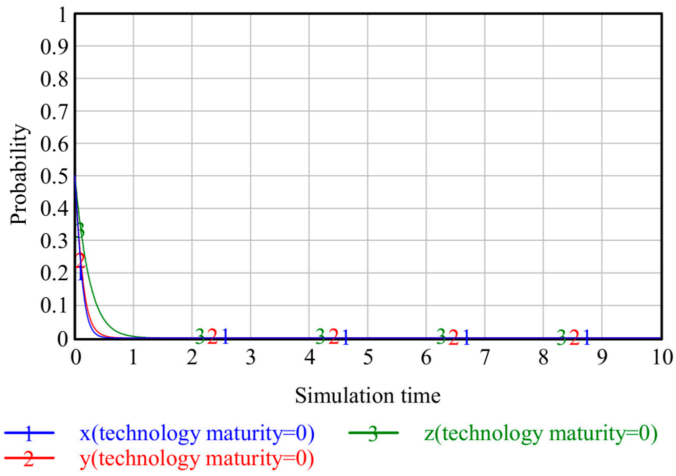


Figure 6. Extreme condition test of SD model.

In summary, the model successfully exhibits the expected behaviors under the scenarios outlined in the evolutionary game model and remains stable under extreme conditions, further validating the robustness and stability of the SD model and ensuring the accuracy of the evolutionary game model's validation.

5.3. Impact of Key Variables

According to the unilateral stabilization strategy analysis in Section 4.3.1, it can be seen that the final evolutionary stability point of each game player is affected by mutual initial strategy and key parameters in the model. However, the EG analysis only indicates whether a parameter's impact is positive or negative, without detailing the extent or specifics of that impact. Consequently, it does not provide direct guidance on how owners, general contractors, and subcontractors can effectively use key variables to promote blockchain technology adoption in PCSC. To address this, the study employs SD to simulate the effects of initial strategies and key parameters, offering a more concrete visualization of their impact on the adoption of stabilization strategies by the three stakeholders. This approach enables the provision of more detailed and precise recommendations.

Considering that the evolution result of the maturity stage is the ideal state of the system under realistic conditions, its evolution path is clearer and more intuitive. This clarity is conducive to analyzing and comparing the effects of parameter variations. Therefore, in the SD model, the situational parameters of the ideal state were simulated, and the initial strategy of owners, general contractors, and subcontractors was set as (0.5, 0.5, 0.5).

5.3.1. Impact of the Initial Strategies

To analyze the impact of initial strategies on the evolutionary results of the tripartite system, we changed the value of the initial strategy of one stakeholder each time and tested the evolution results in the SD model. Figure 7 shows the initial strategies of owners, general contractors, and subcontractors, with any one of them set to 0.1, 0.3, 0.5, 0.7, and 0.9 in turn, to observe the impact on the other two stakeholders' strategy evolution results.

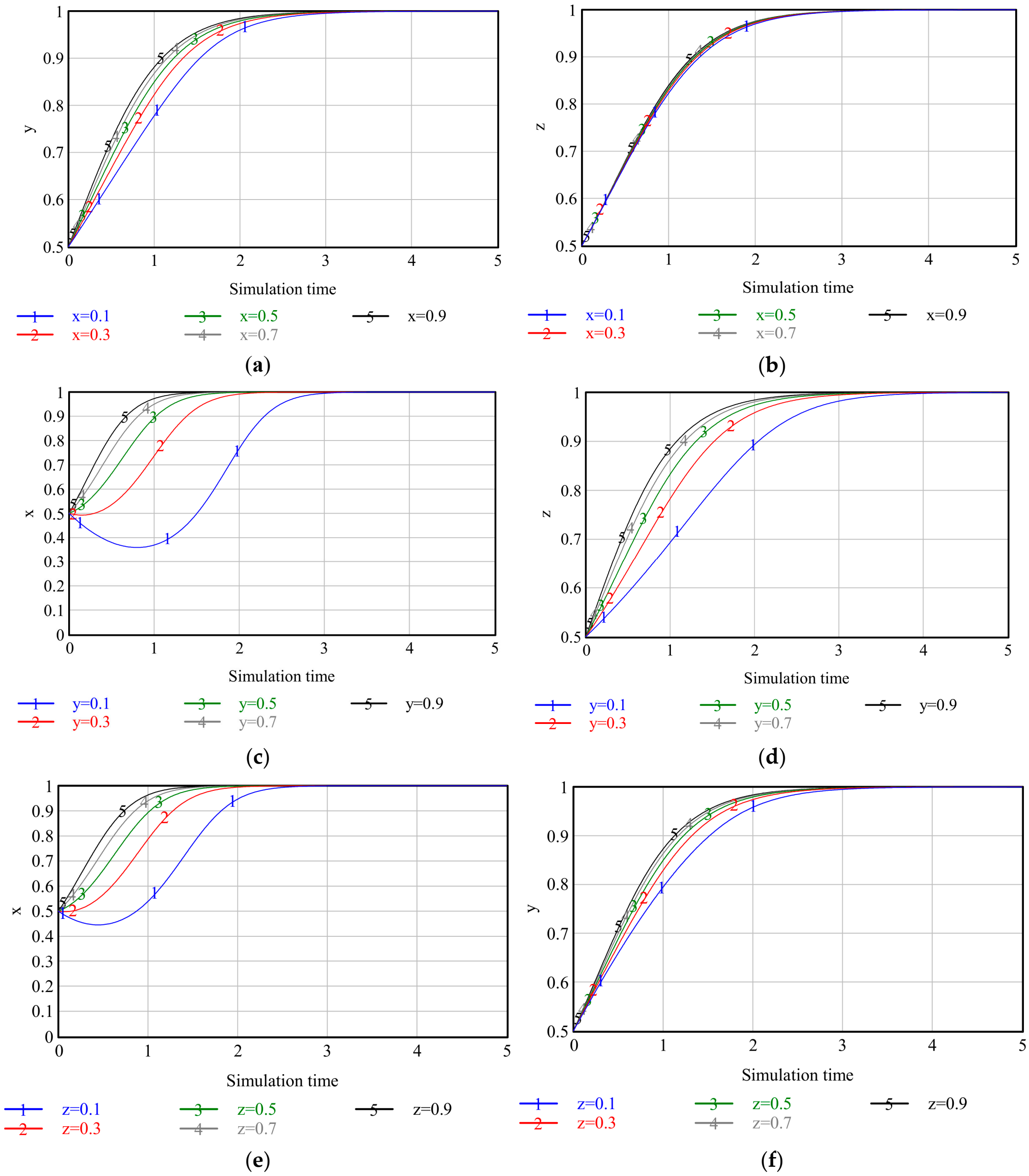


Figure 7. Effect of initial strategies changes on system evolution. (**a**) Effect of changes in x on y; (**b**) Effect of changes in x on z; (**c**) Effect of changes in y on x; (**d**) Effect of changes in y on z; (**e**) Effect of changes in z on x; (**f**) Effect of changes in z on y.

In Figure 7, it can be seen that by changing the initial strategy value of any party, the stable points x, y and z are all 1, that is, the stable state of the system is $e_8(1,1,1)$. As the initial strategy value of one stakeholder increases, the convergence rates to 1 of the other two stakeholders become faster. This indicates a mutual driving effect in BT adoption by the three-game parties. Moreover, by comparing Figure 7c with Figure 7e and comparing Figure 7b with Figure 7d, it can be observed that the initial strategy change of general contractors has a greater impact on the speed of owners' strategy convergence to the ideal stable strategy than the initial strategy change of subcontractors. Similarly, the initial strategy change of general contractors has a greater impact on subcontractors' strategy convergence to the ideal stable strategy than the initial strategy changes of owners. This implies that the general contractors play a more important driving role in BT adoption in PCSC.

5.3.2. Impact of Technology Maturity

To analyze the impact of technology maturity φ on the evolutionary results of the tripartite system, the technology maturity φ was set as 0.1, 0.3, 0.5, 0.7, and 0.9. The results of the impact of technology maturity φ are shown in Figure 8. It can be seen that as the technology maturity φ increases, the final stabilization point of the whole system evolves from $e_1(0,0,0)$ to $e_8(1,1,1)$, indicating that technology maturity is a key factor in determining the adoption of BT in PCSC. Specifically, there is a critical value φ_1 between 0.5 and 0.7. When $\varphi < \varphi_1$, owners do not require, and general contractors and subcontractors do not adopt BT. As technology maturity increases, the convergences of the three parties' strategies to 0 gradually slow down. When $\varphi > \varphi_1$, the strategies of all three parties begin to converge to 1. This indicates that only when the technology maturity φ reaches a certain level will three parties take action to adopt BT to obtain the benefits of the technology as soon as possible. Moreover, the more mature the technology, the quicker they evolve into optimal strategies.

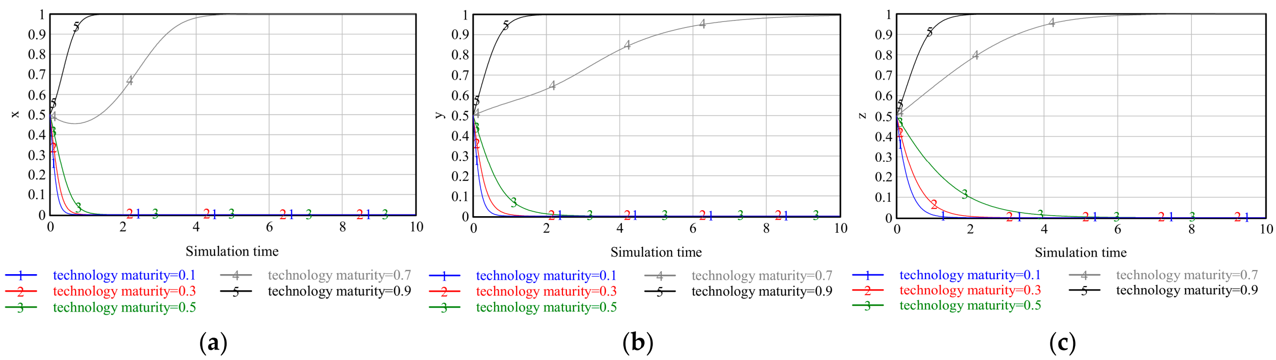
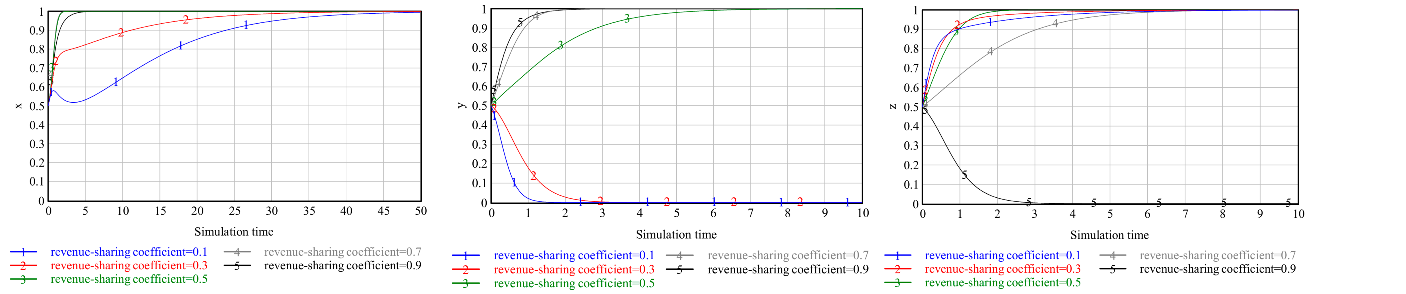


Figure 8. Effect of φ on system evolution. (**a**) Effect of φ on owners' strategy; (**b**) Effect of φ on general contractors' strategy; (**c**) Effect of φ on subcontractors' strategy.

5.3.3. Impact of Profit Sharing

(1) Impact of revenue-sharing coefficient α

To assess the impact of changes in the revenue-sharing coefficient α on the strategy evolution results of BT adoption, the simulation was conducted with α values of 0.1, 0.3, 0.5, 0.7, and 0.9. The results are shown in Figure 9. With the revenue-sharing coefficient α increasing, the stabilization point of the whole system evolves from $e_6(1,0,1)$ to $e_5(1,1,0)$. Specifically, there are two critical values for the revenue-sharing coefficient α_1 and α_2 ($\alpha_1 \in (0.3, 0.5)$, $\alpha_2 \in (0.7, 0.9)$). When $\alpha < \alpha_1$, y converges to 0 while x and z both converge to 1. As α increases, the convergence of general contractor to the "not adopt" strategy slows down and the convergence of the owner to the "require" strategy speeds up. In Figure 9c, for subcontractors, initially, z converges to 1 faster, but it slows down due to the disruption caused by the general contractors' non-adoption, which means subcontractors' inability to realize the benefits of collaborative adoption. When $\alpha_1 < \alpha < \alpha_2$, the strategies of all three parties begin to converge to 1 and the convergence rate of subcontractors to the "adopt" strategy obviously slows down. This indicates that the revenue-sharing coefficient affects the willingness of general contractors and subcontractors to adopt BT, with the effect being contrary. When $\alpha > \alpha_2$, x and y still converge to 1, with y converging faster and x converging slower, while z converges to 0. This result means general contractors obtain more benefits and have an increased incentive to adopt BT, while subcontractors receive too few benefits to cover the incremental costs and choose not to adopt BT. Consequently, owners gain fewer incremental benefits from subcontractors' non-adoption, slowing down their speed in choosing the "require" strategy.

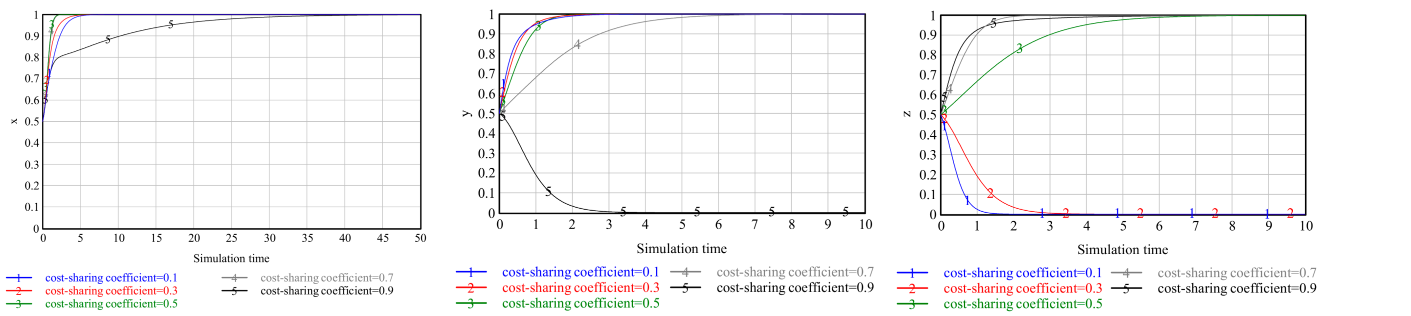


(**a**) (**b**) (**c**)

Figure 9. Effect of α on system evolution. (**a**) Effect of α on owners' strategy; (**b**) Effect of α on general contractors' strategy; (**c**) Effect of α on subcontractors' strategy.

(2) Impact of cost-sharing coefficient β

To assess the impact of changes in the cost-sharing coefficient β on the adoption of BT, the simulation was conducted with β values of 0.1, 0.3, 0.5, 0.7, and 0.9. The results are shown in Figure 10. As the cost-sharing coefficient β increases, the stabilization point of the whole system evolves from $e_5(1,1,0)$ *to* $e_6(1,0,1)$. There are two cost-sharing coefficient thresholds, β_1 and β_2 ($\beta_1 \in (0.3, 0.5)$, $\beta_2 \in (0.7, 0.9)$). When $\beta < \beta_1$, general contractors bear a small portion of the cost while subcontractors pay excessive adoption costs. This unfair cost-sharing system discourages subcontractors from adopting BT. When $\beta_1 < \beta < \beta_2$, owners require adoption and both general contractors and subcontractors adopt BT. The cost borne by general contractors increases while the cost paid by subcontractors falls with β increasing. Consequently, the convergence of general contractors to the adoption strategy slows down, while the convergence of subcontractors to the adoption strategy speeds up. When $\beta > \beta_2$, y converges to 0, while x decelerates its convergence to 1 and z accelerates its convergence to 1. This indicates that subcontractors only need to bear fewer adoption costs to obtain the technology strength, whereas general contractors face high adoption costs, prompting them to opt out of adopting BT. This results in a reduction in the incremental benefits that owners expect from the general contractors' adoption of BT, significantly slowing the rate of convergence to 1.



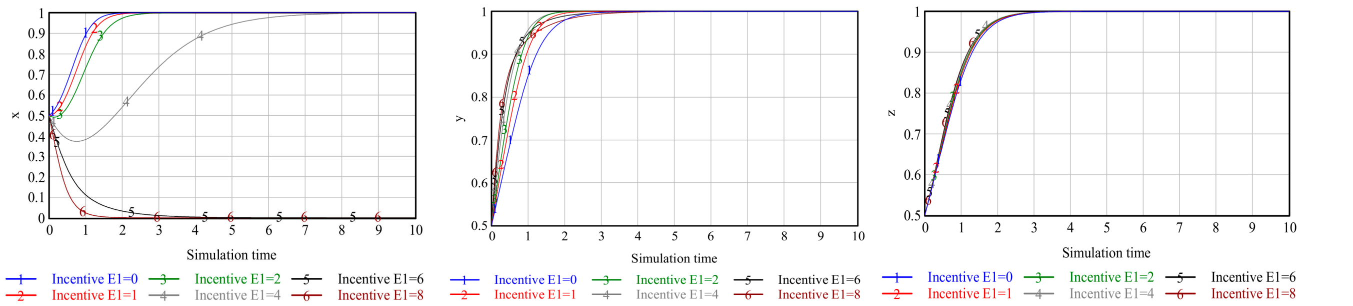
(**a**) (**b**) (**c**)

Figure 10. Effect of β on system evolution. (**a**) Effect of β on owners' strategy; (**b**) Effect of β on general contractors' strategy; (**c**) Effect of β on subcontractors' strategy.

5.3.4. Impact of Incentives and Compensation

(1) Impact of incentives E_1

To assess the impact of owners' incentives E_1 to general contractors on the evolutionary results, taking values of 0, 1, 2, 4, 6, and 8, the simulation results are shown in Figure 11. It can be seen in Figure 11a that the speed of owners' convergence to 1 decreases as owners' incentives to general contractors for adopting BT increase. When the value is too high, the owners' strategy converges to 0, shifting from "require" to "not require". This indicates that high incentives for general contractors' adoption increase owners' burden, weakening owners' motivation to "require" adoption until they choose "not require". Figure 11b shows that as E_1 increases, general contractors converge to the stable adoption strategy faster. However, when E_1 exceeds a critical value, the speed at which the general contractors' strategy converges to 1 decreases slightly under the influence of owners' "not require" strategy.

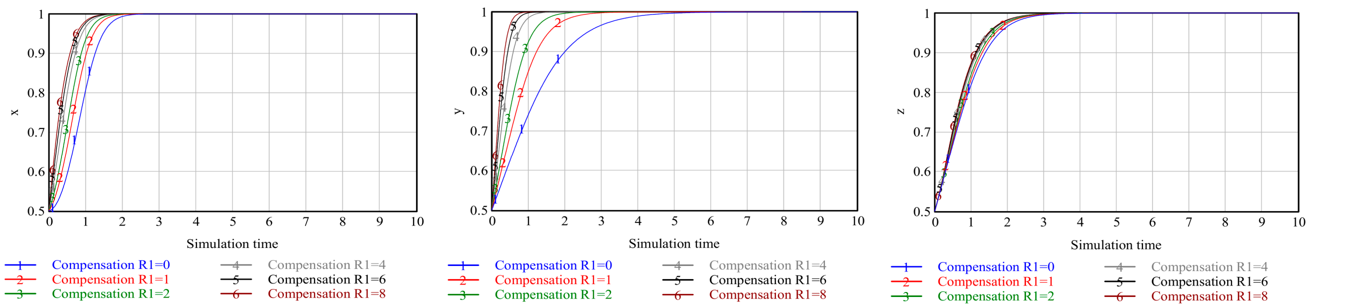


(**a**) (**b**) (**c**)

Figure 11. Effect of E_1 on system evolution. (**a**) Effect of E_1 on owners' strategy; (**b**) Effect of E_1 on general contractors' strategy; (**c**) Effect of E_1 on subcontractors' strategy.

(2) Impact of compensation R_i

The general contractors' compensation to owners R_1 and subcontractors' compensation to general contractors R_1 are both varied from 0 to 8. The simulation results, shown in Figures 12 and 13, assess the impact of changes in R_1 and R_2 on the strategy evolution results of the three participating subjects. The simulation results show that as R_1 increases, the rates of convergence of owners and general contractors' strategies to 1 increase. Similarly, as R_2 increases, the rate at which general contractors and subcontractors converge to 1 also increases. This means that the party required to pay default compensation is more likely to adopt BT due to the increased cost of not adopting it. Meanwhile, the party collecting the default compensation gains more potential benefits from requiring adoption, enhancing their willingness to demand adoption. This implies that using default compensation as a penalty for breach of contract facilitates the evolution of the gaming system to the (require, adopt, adopt) steady state more quickly.



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

Figure 12. Effect of R_1 on system evolution. (**a**) Effect of R_1 on owners' strategy; (**b**) Effect of R_1 on general contractors' strategy; (**c**) Effect of R_1 on subcontractors' strategy.

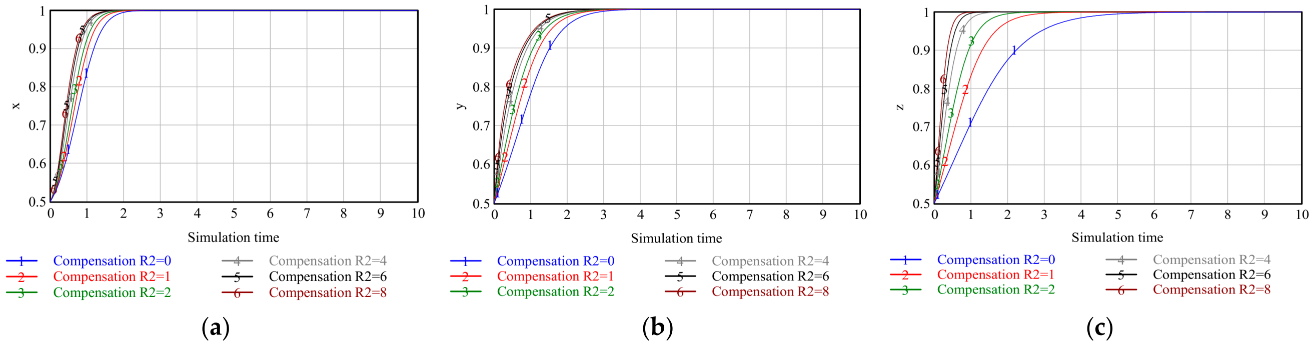


Figure 13. Effect of R_2 on system evolution. (**a**) Effect of R_2 on owners' strategy; (**b**) Effect of R_2 on general contractors' strategy; (**c**) Effect of R_2 on subcontractors' strategy.

5.3.5. Impact of Government Subsidy

The impact of changes in government subsidies on the strategies of owners, general contractors, and subcontractors is shown in Figure 14. As government subsidies increase, these stakeholders' strategies converge to 1 more rapidly. This suggests that appropriately increasing government subsidies enhances the benefits of adopting BT for critical stakeholders in PCSC, leading to a quicker evolution towards the steady state of (require, adopt, adopt). Additionally, in Figure 14a, it can be seen that for owners, when the government subsidy is too low, their willingness to require the adoption of the technology initially decreases, then increases until it converges to 1. In Figure 14b,c, it is shown that general contractors and subcontractors maintain a strong willingness to adopt the technology even if the government subsidy is low. Therefore, compared to general contractors and subcontractors, owners' strategies are more sensitive to government subsidies.

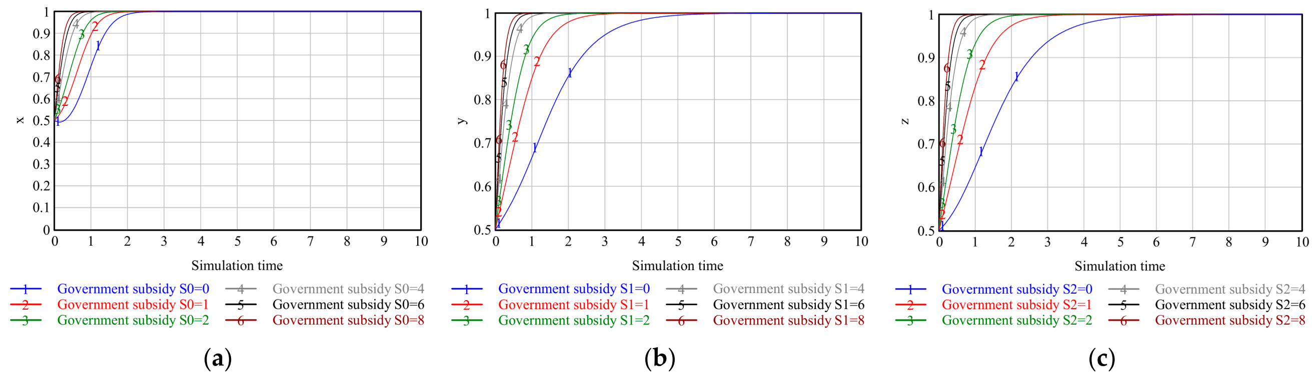


Figure 14. Effect of S_i on system evolution. (**a**) Effect of S_0 on owners' strategy; (**b**) Effect of S_1 on general contractors' strategy; (**c**) Effect of S_2 on subcontractors' strategy.

In summary, the simulation results of the SD model for the effects of key variables are consistent with the corollaries in the stability analysis of the evolutionary game model, which validates the evolutionary game model. Additionally, these simulation results offer more specific details about the impacts of key parameters, such as one threshold φ_1 for the technology maturity and the two thresholds α_1 and α_2 for revenue-sharing coefficient, providing more practical action recommendations for the owner, the general contractor, and the subcontractors.

6. Discussion and Implications

6.1. Discussion

From the perspective of strategic interaction of BT adoption by critical stakeholders in PCSC, this study explored the interaction mechanism of BT adoption and analyzed the impact of changes in initial strategies and related parameters on the evolutionary outcome by constructing an evolutionary game model and a system dynamics model. Five aspects are discussed below:

(1) Leverage the key driving role of the general contractor for BT adoption

General contractors play a crucial role in driving the adoption of BT in PCSC. This study found that the general contractors' initial strategy has a greater influence on owners than subcontractors do. Likewise, the general contractors' initial strategy impacts subcontractors more than the owners' strategy. This aligns with Ding et al.'s finding that BT diffusion in actual projects heavily relies on the general contractors' efforts [48]. As the central figure in coordinated supply chain management, general contractors closely collaborate with both owners and subcontractors to achieve supply chain goals [67]. Thus, general contractors have the potential to possess supply chain leadership in adopting BT in PCSC. Supply chain leadership refers to the ability of a core enterprise to influence the behavior and performance of supply chain members to achieve shared goals [98,99]. It requires supply chain influence, relationship building with other supply chain organizations, establishing a supply chain vision, and leading members toward common objectives. Given their pivotal role, the success of BT adoption in PCSC largely depends on the proactive actions of general contractors. By leveraging their leadership, they can drive BT adoption, set collaboration standards, and ensure all stakeholders work toward shared goals with a unified vision.

(2) Promote research and development of BT

The increase in technology maturity is essential in facilitating the evolution of the system to the ideal state. The research findings show that owners, general contractors, and subcontractors are highly sensitive to technology maturity. When technology maturity is low, they tend to avoid risks and adopt a wait-and-see attitude. However, as technology maturity increases and exceeds a certain threshold, these stakeholders immediately begin to strategize. Their strategies shift from (not require, not adopt, not adopt) to (require, adopt, adopt) due to the enhanced benefits and reduced costs brought about by technological development [47]. Economically, it lowers the cost of deploying and operating technology, as well as communication and coordination in the supply chain [49]. Socially, the higher technology maturity of BT enhances supply chain transparency and regulatory compliance, reducing opportunistic behavior and ensuring data privacy and security [5,56]. Environmentally, the advancement of BT enables accurate recording and non-tampering of carbon emission information in the construction industry [100] and improves construction waste management [101]. The maturation of BT enhances the economic, social, and environmental benefits of the supply chain, advancing it toward sustainability. This is highly attractive to critical stakeholders in PCSC.

(3) Establish a reasonable profit-sharing mechanism

An excessively high or low revenue-sharing and cost-sharing coefficient is not conducive to the evolution of the system to the ideal steady state. The results show that when these coefficients are too high or too low, either general contractors or subcontractors choose not to adopt BT because they are allocated too little benefit or bear too much cost. Only when the revenue-sharing and cost-sharing coefficients are within an appropriate range will general contractors and subcontractors collaborate to adopt BT. Ding et al. similarly find that there is an ideal revenue-sharing proportion for BT diffusion among collaborating enterprises [48]. Appropriate revenue-sharing and cost-sharing coefficients imply a sustainable, mutually beneficial supply chain collaborative relationship. Not only can more synergistic benefits be obtained compared to adoption alone, but the sharing of adoption costs and risks is also realized. This is especially important for financially disadvantaged subcontractors. Besides obtaining direct benefits, they also gain competitive advantages from the merits of BT [102]. The profit-sharing strategy skillfully combines the interests of general contractors and subcontractors, facilitating the achievement of BT adoption goals in PCSC [48,71].

(4) Strengthen incentives and compensation when appropriate

Incentives and compensation will contribute to BT adoption in PCSC. Owners' incentives for general contractors increase the benefits of technology adoption for general contractors, encouraging them to adopt BT [48]. The default compensation increases the cost of not adopting the technology [47], compelling general contractors to respond to owners' adoption requirements and ensuring subcontractors adhere to contract terms for BT adoption. This is consistent with the findings made by Xu et al. [26], which indicate that sufficient incentives and penalties given by owners are essential to promote new technologies. Additionally, incentives also increase the cost of owners' requirements for adoption. Owners might decide not to mandate BT adoption after evaluating the benefits against the high incentive costs. A similar result, that high incentives will increase the burden on incentive givers, is generally recognized by scholars.

(5) Enhance government subsidies

Government subsidies promote the adoption of BT in PCSC. These subsidies can increase the benefits of adoption by enterprises and help alleviate the high costs associated with technology adoption [49]. This is particularly crucial during the initial stage of technology adoption when the advantages of BT are not yet apparent, and the technical barriers are significant. Owners, as early adopters of BT within PCSC, bear greater cost risks. At this juncture, government subsidies are essential to compensate for these costs [48], making owners' strategies highly responsive to such subsidies. Additionally, government subsidies send positive signals to the market [103], alleviate concerns about the legitimacy of technology use, and create an environment conducive to BT adoption [49]. Wang et al. found that government support fosters a favorable policy environment for the research, development, and application of BT, significantly contributing to the rapid development of the BT industry in China [104].

6.2. Implications

Based on the analysis of the EG and SD models, along with the preceding discussion, this study offers practical implications for owners, general contractors, subcontractors, and the government. These guidelines aim to assist in developing effective strategies to promote the adoption of BT in PCSC.

For owners, who are the ultimate beneficiaries of improved supply chain efficiency, it is essential to leverage the role of general contractors as leaders in the PCSC's adoption of BT. This can be achieved by initially increasing incentives to boost the general contractors' willingness to adopt BT and promote active implementation. However, excessive incentives may increase the owner's financial burden, so the incentive mechanism must balance financial impact with BT adoption goals. Owners can incorporate performance-based clauses related to technology adoption and establish various incentive tiers based on cost savings, project duration reduction, and quality enhancement, thereby transferring some of the adoption pressure to general contractors. Moreover, a dynamic incentive and compensation mechanism can be implemented. In the initial stages, higher levels of compensation and incentives can encourage BT adoption. As the adoption progresses and the economic, social, and environmental benefits become more evident, owners can gradually reduce and eventually eliminate the incentives, fostering voluntary adoption by general contractors.

General contractors should recognize their leadership role in BT adoption within the PCSC, balancing their own interests with a sense of social responsibility to guide the supply chain toward successful BT implementation. In collaboration with subcontractors, general contractors must acknowledge that subcontractors are key users of blockchain technology in the PCSC. They should negotiate and dynamically adjust benefit distribution strategies to align their interests with the shared goal of BT adoption. While higher penalties can deter non-compliance, general contractors should avoid coercing subcontractors through increased compensation. Instead, they should focus on building long-term supply chain relationships that encourage reasonable compliance. It is essential that any default compensation strictly adheres to the legal provisions of construction project contracts to ensure fairness and legality.

Subcontractors play a crucial role in enhancing supply chain efficiency but often face limited financial resources. Although adopting blockchain technology can be costly, subcontractors can benefit from shared advantages through collaboration with general contractors. This partnership not only helps mitigate the costs and risks associated with BT adoption but also provides an opportunity for technological advancement, boosting subcontractors' competitiveness in the industry. Therefore, subcontractors should look beyond the short-term costs of BT adoption and consider the long-term benefits of increased market competitiveness. By negotiating a fair benefit-sharing mechanism with general contractors, subcontractors can contribute to a win-win situation for BT adoption.

Additionally, this study offers insights for shaping government policies. Given the positive impact of subsidies, the government should implement subsidy policies to alleviate cost pressures on PCSC members and incentivize their adoption of BT. Furthermore, the advancement of BT should not rely solely on enterprise investments; the government should actively support research and development to enhance BT's performance. Encouraging pilot projects that integrate BT with construction practices will further demonstrate its potential in improving PCSC performance, thereby increasing supply chain members' confidence in adopting the technology.

7. Conclusions

The decision-making practices of stakeholders in PCSC have a significant influence on the adoption of BT, which has enormous potential but a delayed adoption process. This study explored the interaction relationships of BT adoption and established a tripartite EG model of BT adoption by owners, general contractors, and subcontractors in PCSC to analyze the interaction mechanism of the adoption strategies of the three stakeholders. Moreover, this study employed the SD model based on the EG model to simulate the evolutionary paths and parameter sensitivities of the technology adoption system.

The main conclusions are drawn as follows: (1) Increasing technology maturity is crucial for BT adoption. For PCSC stakeholders to be more inclined to adopt BT, technology maturity should surpass a specific level. (2) General contractors play a key driving role in BT adoption in the supply chain, which can be utilized to promote BT adoption in PCSC. (3) General contractors should also negotiate with subcontractors to reach a reasonable profit-sharing coefficient because too high or too low a coefficient will lead to the non-adoption of BT by either general contractors or subcontractors. (4) The system of incentives and compensation promotes the adoption of BT by general contractors and subcontractors, but excessively high incentives increase the financial burden on owners. (5) Government subsidies facilitate BT adoption in the supply chain, especially in the early stages.

This study contributes to the body of knowledge by explaining the BT adoption strategy interaction mechanism based on a combination of evolutionary game theory and system dynamics. It is one of the preliminary investigations on BT adoption in PCSC, which has been rarely explored in previous research, providing the theoretical basis for further investigation in BT adoption. Practically, it illustrates the impact of relevant factors and stakeholder strategies, giving PCSC stakeholders valuable guidance to make well-informed decisions in various situations. Furthermore, some valuable enlightenments are drawn for the government to promote BT adoption in PCSC.

This study requires further investigation. Firstly, the conflicts of interest and considerations among stakeholders are derived from literature review and analysis, whereas the actual adoption process may involve more complex and dynamic factors, such as market competition and pre-existing supply chain relationships. Future research could integrate real-world BT implementation with in-depth consultations and studies to better capture these intricate interest dynamics. Secondly, this study focuses on three stakeholders; the owner, general contractor, and subcontractors. However, stakeholders such as different prefabricated component suppliers and transporters also play a role in BT adoption, which can influence the overall effectiveness of its implementation in the supply chain. Future research should explore the interactions between suppliers within the supply chain to more comprehensively analyze the interactive BT adoption strategies in PCSC. Additionally, due to the limited cases of BT adoption in PCSC, there is a degree of subjectivity in the parameter settings, and thus, only numerical simulations were conducted in this study. Future research should incorporate pilot cases and targeted data collection to enhance the practical relevance of the simulation results.

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Appendix A

The details of payoffs and replicator dynamic equations are derived as follows. Firstly, we calculated the expected payoffs if owners require or do not require adoption, denoted as E_x and E_{1-x}, respectively. The average expected payoff is denoted by $\overline{E_x}$.

$$E_x = y\left\{\begin{array}{c} z\left[P_0+\left(1-e^{-\varphi}\right)(D_1+D_2)-e^{-\varphi}C_0-E_1+S_0+G_0\right] \\ +(1-z)\left[P_0+\left(1-e^{-\varphi}\right)D_1-e^{-\varphi}C_0-E_1+S_0+G_0\right] \end{array}\right\} +(1-y)\left\{\begin{array}{c} z\left[P_0+\left(1-e^{-\varphi}\right)D_2-e^{-\varphi}C_0+R_1+S_0+G_0\right] \\ +(1-z)[P_0-e^{-\varphi}C_0+R_1+S_0+G_0] \end{array}\right\} \quad (A1)$$

$$E_{1-x} = y\left\{z\left[P_0+\left(1-e^{-\varphi}\right)(gD_1+hD_2)\right]+(1-z)\left(P_0+\left(1-e^{-\varphi}\right)gD_1\right)\right\} +(1-y)\left[z\left(P_0+\left(1-e^{-\varphi}\right)hD_2\right)+(1-z)P_0\right] \quad (A2)$$

$$\overline{E_x} = xE_x+(1-x)E_{1-x} \quad (A3)$$

Then, according to Equations (A1)–(A3), the replicator dynamics equation *F(x)* for owners choosing the "require" strategy is shown below:

$$F(x)=\frac{dx}{dt}=x\left(E_x-\overline{E_x}\right)=x(1-x)(E_x-E_{1-x})=x(1-x)\left[\begin{array}{c}(1-g)y\left(1-e^{-\varphi}\right)D_1+(1-h)z\left(1-e^{-\varphi}\right)D_2 \\ -e^{-\varphi}C_o+S_o+G_0+(1-y)R_1-yE_1\end{array}\right] \quad (A4)$$

Secondly, the expected payoffs that general contractors choose to adopt and not adopt are shown in E_y and E_{1-y}. The average expected payoff is denoted by $\overline{E_y}$.

$$E_y = x\left\{z\left[P_1+\left(1-e^{-\varphi}\right)\alpha\Delta B-e^{-\varphi}\beta\Delta C+E_1+S_1\right]+(1-z)\left[P_1+\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1+E_1+R_2+S_1\right]\right\} +(1-x)\left\{z\left[P_1+\left(1-e^{-\varphi}\right)\alpha\Delta B-e^{-\varphi}\beta\Delta C+S_1\right]+(1-z)\left[P_1+\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1+R_2+S_1\right]\right\} \quad (A5)$$

$$E_{1-y} = x[z(P_1-R_1)+(1-z)(P_1-R_1)]+(1-x)[zP_1+(1-z)P_1] \quad (A6)$$

$$\overline{E_y} = yE_y+(1-y)E_{1-y} \quad (A7)$$

Then, according to Equations (A5)–(A7), the replicator dynamics equation *F(y)* for general contractors choosing the "adopt" strategy is shown below:

$$F(y)=\mathrm{y}(1-\mathrm{y})\left\{z\left[\left(1-e^{-\varphi}\right)\alpha\Delta B-e^{-\varphi}\beta\Delta C\right]+(1-z)\left[\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1+R_2\right]+x(E_1+R_1)\right]+S_1\right\} \quad (A8)$$

Finally, the expected payoffs that subcontractors choose to adopt and not adopt are shown in E_z and E_{1-z}. The average expected payoff is denoted by $\overline{E_z}$

$$\begin{aligned} E_z = \quad & x\left\{\begin{array}{c} y\left[P_2+\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C+S_2\right] \\ +(1-y)\left[P_2+\left(1-e^{-\varphi}\right)B_2-e^{-\varphi}C_2+S_2\right] \end{array}\right\} \\ & +(1-x)\left\{\begin{array}{c} y\left[P_2+\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C+S_2\right] \\ +(1-y)\left[P_2+\left(1-e^{-\varphi}\right)B_2-e^{-\varphi}C_2+S_2\right] \end{array}\right\} \end{aligned} \tag{A9}$$

$$E_{1-z} = x[y(P_2-R_2)+(1-y)P_2]+(1-x)[y(P_2-R_2)+(1-y)P_2] \tag{A10}$$

$$\overline{E_z} = zE_z+(1-z)E_{1-z} \tag{A11}$$

Then, according to Equations (A9)–(A11), the replicator dynamics equation *F(y)* for subcontractors choosing the "adopt" strategy is shown below:

$$F(z) = \mathrm{z}(1-\mathrm{z})\left\{y\left[\left(1-e^{-\varphi}\right)(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C\right]+(1-y)\left[\left(1-e^{-\varphi}\right)B_2-e^{-\varphi}C_2\right]+yR_2+S_2\right\} \tag{A12}$$

Appendix B

Appendix B.1. Proof of Corollary 1

Based on $z^* = \frac{e^{-\varphi}C_o-y(1-g)\left(1-e^{-\varphi}\right)D_1-S_o-G_0-(1-y)R_1+yE_1}{(1-h)\left(1-e^{-\varphi}\right)D_2}$, $\frac{\partial z^*}{\partial y} = \frac{-(1-g)\left(1-e^{-\varphi}\right)D_1+R_1+E_1}{(1-h)\left(1-e^{-\varphi}\right)D_2}$. When $\left(1-e^{-\varphi}\right)(1-g)D_1 < R_1+E_1$, $\frac{\partial z^*}{\partial y} > 0$, the function z^* is an increasing function of y. Therefore, when y goes up, z^* increases, then $z^* > z > 0$. According to the analytic process of the influence of z on x, the owners will tend to choose the "not require" strategy.

Appendix B.2. Proof of Corollary 2

$\frac{\partial z^*}{\partial R_1} = \frac{-(1-y)}{(1-h)\left(1-e^{-\varphi}\right)D_2} < 0$, $\frac{\partial z^*}{\partial S_o} = \frac{-1}{(1-h)\left(1-e^{-\varphi}\right)D_2} < 0$, $\frac{\partial z^*}{\partial E_1} = \frac{y}{(1-h)\left(1-e^{-\varphi}\right)D_2} > 0$, the function z^* is a decreasing function of R_1 and S_o and an increasing function of E_1. when R_1 and S_o increase or E_1 decreases, z^* goes down, then $z^* < z < 1$. Based on the analytic process of the influence of z on x, the owners will tend to choose the "require" strategy.

Appendix B.3. Proof of Corollary 3

Based on $x = \frac{-z\left[\left(1-e^{-\varphi}\right)\alpha\Delta B-e^{-\varphi}\beta\Delta C\right]-(1-z)\left[\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1+R_2\right]-S_1}{E_1+R_1}$, $\frac{\partial x^*}{\partial z} = \frac{-\left[\left(1-e^{-\varphi}\right)\alpha\Delta B-e^{-\varphi}\beta\Delta C\right]+\left[\left(1-e^{-\varphi}\right)B_1-e^{-\varphi}C_1+R_2\right]}{E_1+R_1}$, when $(1-e^{-\varphi})\alpha\Delta B-e^{-\varphi}\beta\Delta C > (1-e^{-\varphi})B_1 - e^{-\varphi}C_1+R_2$, $\frac{\partial x^*}{\partial z} < 0$, the function x is a decreasing function of z. Therefore, when z goes up, x decreases, then $x < x < 1$. According to the analytic process of the influence of x on y, the general contractors will tend to choose the "adopt" strategy.

Appendix B.4. Proof of Corollary 4

$\frac{\partial x^*}{\partial \alpha} = \frac{-z\left(1-e^{-\varphi}\right)\Delta B}{E_1+R_1} < 0$, $\frac{\partial x^*}{\partial E_1} = \frac{-1}{(E_1+R_1)^2} < 0$, $\frac{\partial x^*}{\partial R_1} = \frac{-1}{(E_1+R_1)^2} < 0$, $\frac{\partial x^*}{\partial R_2} = \frac{-(1-z)}{E_1+R_1} < 0$, $\frac{\partial x^*}{\partial S_1} = \frac{-1}{E_1+R_1} < 0$; $\frac{\partial x^*}{\partial \beta} = \frac{ze^{-\varphi}\Delta C}{E_1+R_1} > 0$, the function x^* is a decreasing function of α, E_1, R_1, R_2 and S_1 and an increasing function of β. When α, E_1, R_1, R_2 and S_1 increase or β decreases, x^* goes down, then $x^* < x < 1$. Based on the analytic process of the influence of x on y, the general contractors will tend to choose the "adopt" strategy.

Appendix B.5. Proof of Corollary 5

Considering the actual situation, the cost often is higher than the benefit when subcontractors adopt alone even though there is a government subsidy, therefore, $\left(1-e^{-\varphi}\right)B_2-e^{-\varphi}C_2+S_2<0$.

The first order partial derivative of y^* with respect of α, β, R_2, and S_2 are calculated as follows.

$$\frac{\partial y^*}{\partial \beta}=\frac{-\left[-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]-S_2\right]e^{-\varphi}\Delta C}{\left[\left[(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C\right]-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]+R_2\right]^2}<0$$

$$\frac{\partial y^*}{\partial R_2}=\frac{-\left[-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]-S_2\right]}{\left[\left[(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C\right]-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]+R_2\right]^2}<0$$

$$\frac{\partial y^*}{\partial S_2}=\frac{-1}{\left[(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C\right]-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]+R_2}<0$$

$$\frac{\partial y^*}{\partial \alpha}=\frac{\left[-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]-S_2\right](1-e^{-\varphi})\Delta B}{\left[\left[(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C\right]-\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]+R_2\right]^2}>0$$

When $(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C>\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]-R_2$, the function y^* is a decreasing function of $\beta,\ R_2$ and S_2 and an increasing function of α. When $\beta,\ R_2$ and S_2 increase or α decreases, y^* goes down, then $y^*<y<1$. Based the analytic process of the influence of y on z, the subcontractors will tend to choose the "adopt" strategy.

Similarly, When $(1-e^{-\varphi})(1-\alpha)\Delta B-e^{-\varphi}(1-\beta)\Delta C<\left[(1-e^{-\varphi})B_2-e^{-\varphi}C_2\right]-R_2$, the function y^* is a decreasing function of $\beta,\ R_2$ and S_2 and an increasing function of α. When $\beta,\ R_2$ and S_2 decrease or α increases, y^* goes up, then $0<y<y^*$. Based on the analytic process of the influence of y on z, the subcontractors will tend to choose the "adopt" strategy.

Appendix C

Table A1. Parameter values.

Parameter Name	Parameter Value			
	$e_1(0,0,0)$	$e_4(1,0,0)$	$e_5(1,1,0)$	$e_8(1,1,1)$
P_0	5	5	5	5
D_1	15	15	15	15
D_2	10	10	10	10
G_0	1	1	1	1
g	0.3	0.3	0.3	0.3
h	0.3	0.3	0.3	0.3
C_0	15	15	15	15
E_1	0	1	1	0
R_1	0	4	4	1
R_2	0	0	0	1
S_0	1	6	4	1
S_1	0	1	1	1
S_2	0	0	0	1
P_1	4	4	4	4
B_1	6	6	6	6
C_1	15	12	12	10
ΔB	20	20	20	25
ΔC	30	25	25	30
α	0.8	0.8	0.8	0.6
β	0.4	0.4	0.5	0.6
P_2	3	3	3	3
B_2	2	3	3	4
C_2	10	8	8	6
φ	0.4	0.4	0.6	0.8

References

1. Han, Y.; Yan, X.; Piroozfar, P. An overall review of research on prefabricated construction supply chain management. *Eng. Constr. Archit. Manag.* **2023**, *30*, 5160–5195. [CrossRef]
2. Wang, Z.; Hu, H.; Gong, J.; Ma, X.; Xiong, W. Precast supply chain management in off-site construction: A critical literature review. *J. Clean. Prod.* **2019**, *232*, 1204–1217. [CrossRef]
3. Zhai, Y.; Zhong, R.Y.; Li, Z.; Huang, G. Production lead-time hedging and coordination in prefabricated construction supply chain management. *Int. J. Prod. Res.* **2017**, *55*, 3984–4002. [CrossRef]
4. Wu, H.; Zhong, B.; Li, H.; Guo, J.; Wang, Y. On-Site Construction Quality Inspection Using Blockchain and Smart Contracts. *J. Manag. Eng.* **2021**, *37*, 04021065. [CrossRef]
5. Wu, H.; Zhang, P.; Li, H.; Zhong, B.; Guo, S.; Fung, I.W.H.; Lee, Y.Y. Blockchain Impact on Construction Quality Management and Its Adoption Analysis: A Game Theory–Based Method. *J. Constr. Eng. Manag.* **2024**, *150*, 04024039. [CrossRef]
6. Wang, Z.; Wang, T.; Hu, H.; Gong, J.; Ren, X.; Xiao, Q. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Autom. Constr.* **2020**, *111*, 103063. [CrossRef]
7. Li, J.; Greenwood, D.; Kassem, M. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Autom. Constr.* **2019**, *102*, 288–307. [CrossRef]
8. Perera, S.; Nanayakkara, S.; Rodrigo, M.N.N.; Senaratne, S.; Weinand, R. Blockchain technology: Is it hype or real in the construction industry? *J. Ind. Inf. Integr.* **2020**, *17*, 100125. [CrossRef]
9. Badi, S. The role of blockchain in enabling inter-organisational supply chain alignment for value co-creation in the construction industry. *Constr. Manag. Econ.* **2024**, *42*, 266–288. [CrossRef]
10. Li, X.; Lu, W.; Xue, F.; Wu, L.; Zhao, R.; Lou, J.; Xu, J. Blockchain-Enabled IoT-BIM Platform for Supply Chain Management in Modular Construction. *J. Constr. Eng. Manag.* **2022**, *148*, 04021195. [CrossRef]
11. Janpan Cabinet Secretariat. Regulatory Sandbox System. Available online: https://www.cas.go.jp/jp/seisaku/s-portal/regulatorysandbox.html (accessed on 26 August 2024).
12. Monetary Authority of Singapore. Regulatory Sandbox. Available online: https://www.mas.gov.sg/development/fintech/regulatory-sandbox (accessed on 26 August 2024).
13. China Academy of Information and Communications Technology. Blockchain Whitepaper. 2023. Available online: http://www.caict.ac.cn/kxyj/qwfb/bps/202312/t20231207_467544.htm (accessed on 26 August 2024).
14. Celik, B.G.; Abraham, Y.S.; Attaran, M. Unlocking Blockchain in Construction: A Systematic Review of Applications and Barriers. *Buildings* **2024**, *14*, 1600. [CrossRef]
15. Xu, Y.; Chong, H.-Y.; Chi, M. Modelling the blockchain adoption barriers in the AEC industry. *Eng. Constr. Archit. Manag.* **2023**, *30*, 125–153. [CrossRef]
16. Sadeghi, M.; Mahmoudi, A.; Deng, X. Adopting distributed ledger technology for the sustainable construction industry: Evaluating the barriers using Ordinal Priority Approach. *Environ. Sci. Pollut. Res.* **2022**, *29*, 10495–10520. [CrossRef] [PubMed]
17. Wang, X.; Liu, L.; Liu, J.; Huang, X. Understanding the Determinants of Blockchain Technology Adoption in the Construction Industry. *Buildings* **2022**, *12*, 1709. [CrossRef]
18. Waqar, A.; Hannan Qureshi, A.; Othman, I.; Saad, N.; Azab, M. Exploration of challenges to deployment of blockchain in small construction projects. *Ain. Shams Eng. J.* **2024**, *15*, 102362. [CrossRef]
19. Li, C.; Zhang, Y.; Xu, Y. Factors Influencing the Adoption of Blockchain in the Construction Industry: A Hybrid Approach Using PLS-SEM and fsQCA. *Buildings* **2022**, *12*, 1349. [CrossRef]
20. Yuan, M.; Li, Z.; Li, X.; Li, L.; Zhang, S.; Luo, X. How to promote the sustainable development of prefabricated residential buildings in China: A tripartite evolutionary game analysis. *J. Clean. Prod.* **2022**, *349*, 131423. [CrossRef]
21. Sun, C.; Wang, M.; Man, Q.; Wan, D. Research on the BIM Application Mechanism of Engineering-Procurement-Construction Projects Based on a Tripartite Evolutionary Game. *J. Constr. Eng. Manag.* **2023**, *149*, 04022182. [CrossRef]
22. Hu, Q.; Xiong, F.; Shen, G.Q.; Liu, R.; Wu, H.; Xue, J. Promoting green buildings in China's multi-level governance system: A tripartite evolutionary game analysis. *Build. Environ.* **2023**, *242*, 110548. [CrossRef]
23. Xue, X.; Ji, A.; Luo, X.; Dou, Y.; Fan, H. Integrating Evolutionary Game and System Dynamics for Multi-Player Safety Regulation of Major Infrastructure Projects in China. *J. Civ. Eng. Manag.* **2024**, *30*, 307–325. [CrossRef]
24. Zuo, W.; Wang, Q.; Li, P. Rent-seeking decisions of the main participants in construction projects based on evolutionary-game and system dynamics. *J. Civ. Eng. Manag.* **2022**, *28*, 106–119. [CrossRef]
25. Laurence, T. *Blockchain for Dummies*, 3rd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2023; pp. 9–18.
26. Li, J.; Kassem, M. Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. *Autom. Constr.* **2021**, *132*, 103955. [CrossRef]
27. Qian, X.; Papadonikolaki, E. Shifting trust in construction supply chains through blockchain technology. *Eng. Constr. Archit. Manag.* **2021**, *28*, 584–602. [CrossRef]
28. Swan, M. *Blockchain: Blueprint for a New Economy*, 1st ed.; O'Reilly Media, Inc.: Sebastopol, CA, USA, 2015; pp. 27–52.
29. Moosavi, J.; Naeni, L.M.; Fathollahi-Fard, A.M.; Fiore, U. Blockchain in supply chain management: A review, bibliometric, and network analysis. *Environ. Sci. Pollut. Res.* **2021**, 1–15. [CrossRef]
30. Chakraborty, K.; Ghosh, A.; Pratap, S. Adoption of blockchain technology in supply chain operations: A comprehensive literature study analysis. *Oper. Manag. Res.* **2023**, *16*, 1989–2007. [CrossRef]

31. Han, Y.; Fang, X. Systematic review of adopting blockchain in supply chain management: Bibliometric analysis and theme discussion. *Int. J. Prod. Res.* **2024**, *62*, 991–1016. [CrossRef]
32. Akhavan, P.; Philsoophian, M. Improving of Supply Chain Collaboration and Performance by Using Block Chain Technology as a Mediating Role and Resilience as a Moderating Variable. *J. Knowl. Econ.* **2023**, *14*, 4561–4582. [CrossRef]
33. Friedman, N.; Ormiston, J. Blockchain as a sustainability-oriented innovation?: Opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains. *Technol. Forecast. Soc. Change* **2022**, *175*, 121403. [CrossRef]
34. Hong, L.; Hales, D.N. How blockchain manages supply chain risks: Evidence from Indian manufacturing companies. *Int. J. Logist. Manag.* **2024**, *35*, 1604–1627. [CrossRef]
35. Zhen, Z.; Yao, Y. The Confluence of Digital Twin and Blockchan Technologies in Industry 5.0: Transforming Supply Chain Management for Innovation and Sustainability. *J. Knowl. Econ.* **2024**, 1–17. [CrossRef]
36. Hong, Z.; Xiao, K. Digital economy structuring for sustainable development: The role of blockchain and artificial intelligence in improving supply chain and reducing negative environmental impacts. *Sci. Rep.* **2024**, *14*, 3912. [CrossRef]
37. Zhang, Z.; Yuan, Z.; Ni, G.; Lin, H.; Lu, Y. The quality traceability system for prefabricated buildings using blockchain: An integrated framework. *Front. Eng. Manag.* **2020**, *7*, 528–546. [CrossRef]
38. Jiang, Y.; Liu, X.; Kang, K.; Wang, Z.; Zhong, R.Y.; Huang, G.Q. Blockchain-enabled cyber-physical smart modular integrated construction. *Comput. Ind.* **2021**, *133*, 103553. [CrossRef]
39. Olawumi, T.O.; Chan, D.W.M.; Ojo, S.; Yam, M.C.H. Automating the modular construction process: A review of digital technologies and future directions with blockchain technology. *J. Build. Eng.* **2022**, *46*, 103720. [CrossRef]
40. Msawil, M.; Greenwood, D.; Kassem, M. A Systematic evaluation of blockchain-enabled contract administration in construction projects. *Autom. Constr.* **2022**, *143*, 104553. [CrossRef]
41. Lu, W.; Li, X.; Xue, F.; Zhao, R.; Wu, L.; Yeh, A.G.O. Exploring smart construction objects as blockchain oracles in construction supply chain management. *Autom. Constr.* **2021**, *129*, 103816. [CrossRef]
42. Zhao, R.; Chen, Z.; Xue, F. A blockchain 3.0 paradigm for digital twins in construction project management. *Autom. Constr.* **2023**, *145*, 104645. [CrossRef]
43. Yoon Jong, H.; Pishdad-Bozorgi, P. State-of-the-Art Review of Blockchain-Enabled Construction Supply Chain. *J. Constr. Eng. Manag.* **2022**, *148*, 03121008. [CrossRef]
44. Toufaily, E.; Zalan, T.; Dhaou, S.B. A framework of blockchain technology adoption: An investigation of challenges and expected value. *Inf. Manag.* **2021**, *58*, 103444. [CrossRef]
45. Bai, C.; Zhu, Q.; Sarkis, J. Joint blockchain service vendor-platform selection using social network relationships: A multi-provider multi-user decision perspective. *Int. J. Prod. Econ.* **2021**, *238*, 108165. [CrossRef]
46. Cheng, M.; Chong, H.Y. Understanding the Determinants of Blockchain Adoption in the Engineering-Construction Industry: Multi-Stakeholders' Analyses. *IEEE Access* **2022**, *10*, 108307–108319. [CrossRef]
47. Xu, S.; Zhou, L.; Zou, P.X.W. What influences stakeholders' decision in adopting blockchain-based quality tracking systems in prefabricated construction. *Eng. Constr. Archit. Manag.* **2024**, *31*, 2224–2247. [CrossRef]
48. Ding, S.; Hu, H.; Dai, L.; Wang, W. Blockchain Adoption among Multi-Stakeholders under Government Subsidy: From the Technology Diffusion Perspective. *J. Constr. Eng. Manag.* **2023**, *149*, 04023016. [CrossRef]
49. Zhang, P.; Wu, H.; Li, H.; Zhong, B.; Fung, I.W.H.; Lee, Y.Y.R. Exploring the adoption of blockchain in modular integrated construction projects: A game theory-based analysis. *J. Clean. Prod.* **2023**, *408*, 137115. [CrossRef]
50. Li, C.Z.; Chen, Z.; Xue, F.; Kong, X.T.R.; Xiao, B.; Lai, X.; Zhao, Y. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. *J. Clean. Prod.* **2021**, *286*, 125391. [CrossRef]
51. Bakhtiarizadeh, E.; Shahzad, W.M.; Poshdar, M.; Khalfan, M.; Rotimi, J.O. Blockchain and Information Integration: Applications in New Zealand's Prefabrication Supply Chain. *Buildings* **2021**, *11*, 608. [CrossRef]
52. Lee, D.; Wen, L.; Choi, J.O.; Lee, S. Sensor-Integrated Hybrid Blockchain System for Supply Chain Coordination in Volumetric Modular Construction. *J. Constr. Eng. Manag.* **2023**, *149*, 04022147. [CrossRef]
53. Kim, M.; Zhao, X.; Kim, Y.-W.; Rhee, B.-D. Blockchain-enabled supply chain coordination for off-site construction using Bayesian theory for plan reliability. *Autom. Constr.* **2023**, *155*, 105061. [CrossRef]
54. Eltoukhy, A.E.E.; Hussein, M.; Xu, M.; Chan, F.T.S. Data-driven Game-theoretic Model Based on Blockchain for Managing Resource Allocation and Vehicle Routing in Modular Integrated Construction. *Int. J. Prod. Res.* **2023**, *61*, 4472–4502. [CrossRef]
55. Jiang, Y.; Liu, X.; Wang, Z.; Li, M.; Zhong, R.Y.; Huang, G.Q. Blockchain-enabled digital twin collaboration platform for fit-out operations in modular integrated construction. *Autom. Constr.* **2023**, *148*, 104747. [CrossRef]
56. Wu, L.; Lu, W.; Chen, C. Resolving power imbalances in construction payment using blockchain smart contracts. *Eng. Constr. Archit. Manag.* **2023**. *ahead-of-print*. [CrossRef]
57. Li, X.; Wu, L.; Zhao, R.; Lu, W.; Xue, F. Two-layer Adaptive Blockchain-based Supervision model for off-site modular housing production. *Comput. Ind.* **2021**, *128*, 103437. [CrossRef]
58. Sheng, D.; Ding, L.; Zhong, B.; Love, P.E.D.; Luo, H.; Chen, J. Construction quality information management with blockchains. *Autom. Constr.* **2020**, *120*, 103373. [CrossRef]
59. Zhong, B.; Wu, H.; Ding, L.; Luo, H.; Luo, Y.; Pan, X. Hyperledger fabric-based consortium blockchain for construction quality information management. *Front. Eng. Manag.* **2020**, *7*, 512–527. [CrossRef]

60. Wang, Z.-J.; Chen, Z.-S.; Xiao, L.; Su, Q.; Govindan, K.; Skibniewski, M.J. Blockchain adoption in sustainable supply chains for Industry 5.0: A multistakeholder perspective. *J. Innov. Knowl.* **2023**, *8*, 100425. [CrossRef]
61. Fan, C.; Binchao, D.; Yin, Y. Hierarchical structure and transfer mechanism to assess the scheduling-related risk in construction of prefabricated buildings: An integrated ISM–MICMAC approach. *Eng. Constr. Archit. Manag.* **2023**, *30*, 2991–3013. [CrossRef]
62. Enshassi Mohammed, S.A.; Walbridge, S.; West Jeffrey, S.; Haas Carl, T. Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects. *J. Manag. Eng.* **2019**, *35*, 05019004. [CrossRef]
63. Liu, K.; Su, Y.; Zhang, S. Evaluating Supplier Management Maturity in Prefabricated Construction Project-Survey Analysis in China. *Sustainability* **2018**, *10*, 3046. [CrossRef]
64. Arashpour, M.; Heidarpour, A.; Akbar Nezhad, A.; Hosseinifard, Z.; Chileshe, N.; Hosseini, R. Performance-based control of variability and tolerance in off-site manufacture and assembly: Optimization of penalty on poor production quality. *Constr. Manag. Econ.* **2020**, *38*, 502–514. [CrossRef]
65. Luo, L.; Shen, G.Q.; Xu, G.; Liu, Y.; Wang, Y. Stakeholder-Associated Supply Chain Risks and Their Interactions in a Prefabricated Building Project in Hong Kong. *J. Manag. Eng.* **2019**, *35*, 05018015. [CrossRef]
66. Zhai, Y.; Fu, Y.; Xu, G.; Huang, G. Multi-period hedging and coordination in a prefabricated construction supply chain. *Int. J. Prod. Res.* **2019**, *57*, 1949–1971. [CrossRef]
67. Luo, L.; Jin, X.; Shen, G.Q.; Wang, Y.; Liang, X.; Li, X.; Li, C.Z. Supply Chain Management for Prefabricated Building Projects in Hong Kong. *J. Manag. Eng.* **2020**, *36*, 05020001. [CrossRef]
68. Wuni, I.Y.; Shen, G. Critical success factors for modular integrated construction projects: A review. *Build. Res. Inf.* **2019**, *48*, 763–784. [CrossRef]
69. Wang, Z.-J.; Sun, Y.; Su, Q.; Deveci, M.; Govindan, K.; Skibniewski, M.J.; Chen, Z.-S. Smart Contract Application in Resisting Extreme Weather Risks for the Prefabricated Construction Supply Chain: Prototype Exploration and Assessment. *Group Decis. Negot.* **2024**. *ahead-of-print*. [CrossRef]
70. Wu, L.; Lu, W.; Zhao, R.; Xu, J.; Li, X.; Xue, F. Using Blockchain to Improve Information Sharing Accuracy in the Onsite Assembly of Modular Construction. *J. Manag. Eng.* **2022**, *38*, 04022014. [CrossRef]
71. Ding, S.; Hu, H.; Chai, Z.; Wang, W. Secure and Formalized Blockchain-IPFS Information Sharing in Precast Construction from the Whole Supply Chain Perspective. *J. Constr. Eng. Manag.* **2024**, *150*, 04023150. [CrossRef]
72. Zheng, L.; Lu, W.; Chen, K.; Chau, K.W.; Niu, Y. Benefit sharing for BIM implementation: Tackling the moral hazard dilemma in inter-firm cooperation. *Int. J. Proj. Manag.* **2017**, *35*, 393–405. [CrossRef]
73. Wang, Y.; Singgih, M.; Wang, J.; Rit, M. Making sense of blockchain technology: How will it transform supply chains? *Int. J. Prod. Econ.* **2019**, *211*, 221–236. [CrossRef]
74. Chen, C.; Dong, C.; Ng, C.; Shi, X. Operations strategy for a construction supply chain: Modular integrated construction and blockchain adoption. *Int. Tran. Oper. Res.* **2023**, *31*, 3999–4024. [CrossRef]
75. Demiralp, G.; Guven, G.; Ergen, E. Analyzing the benefits of RFID technology for cost sharing in construction supply chains: A case study on prefabricated precast components. *Autom. Constr.* **2012**, *24*, 120–129. [CrossRef]
76. Nguyen, B.N.; London, K.; Zhang, P. Stakeholder relationships in off-site construction: A systematic literature review. *Smart Sustain. Built Environ.* **2022**, *11*, 765–791. [CrossRef]
77. Lee, D.; Lee, S.H.; Masoud, N.; Krishnan, M.S.; Li, V.C. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Autom. Constr.* **2021**, *127*, 103688. [CrossRef]
78. Lv, J.; Lin, M.; Zhou, W.; Xu, M. How PPP Renegotiation Behaviors Evolve with Traffic Changes: Evolutionary Game Approach. *J. Constr. Eng. Manag.* **2021**, *147*, 04021032. [CrossRef]
79. Patare, S.; Venkataraman, S.V. Strategies in supply chain competition: A game theoretic approach. *Comput. Ind. Eng.* **2023**, *180*, 109242. [CrossRef]
80. Ocampo, L.A.; Vasnani, N.N.; Chua, F.L.S.; Pacio, L.B.M.; Galli, B.J. A bi-level optimization for a make-to-order manufacturing supply chain planning: A case in the steel industry. *J. Manag. Anal.* **2021**, *8*, 598–621. [CrossRef]
81. Eissa, R.; Eid, M.S.; Elbeltagi, E. Current Applications of Game Theory in Construction Engineering and Management Research: A Social Network Analysis Approach. *J. Constr. Eng. Manag.* **2021**, *147*, 04021066. [CrossRef]
82. Li, L.; Yi, Z.; Zhang, S.; Shao, Z. Competitive threat or win-win cooperation? Evolutionary analysis of digital alliances in construction. *Dev. Built Environ.* **2023**, *15*, 100182. [CrossRef]
83. Zhang, Y.; Rehman, K.S.A. Evolutionary game analysis of green agricultural product supply chain financing system: COVID-19 pandemic. *Int. J. Logist. Res. Appl.* **2022**, *25*, 1115–1135.
84. Long, Q.; Tao, X.; Shi, Y.; Zhang, S. Evolutionary Game Analysis Among Three Green-Sensitive Parties in Green Supply Chains. *IEEE Trans. Evol. Comput.* **2021**, *25*, 508–523. [CrossRef]
85. Peña-Mora, F.; Han, S.; Lee, S.; Park, M. Strategic-Operational Construction Management: Hybrid System Dynamics and Discrete Event Approach. *J. Constr. Eng. Manag.* **2008**, *134*, 701–710. [CrossRef]
86. Sedarati, P.; Santos, S.; Pintassilgo, P. System Dynamics in Tourism Planning and Development. *Tour. Plan. Dev.* **2018**, *16*, 256–280. [CrossRef]
87. Martinez-Moyano, I.J.; Richardson, G.P. Best practices in system dynamics modeling. *Syst. Dyn. Rev.* **2013**, *29*, 102–123. [CrossRef]
88. Du, Q.; Yang, M.; Wang, Y.; Wang, X.; Dong, Y. Dynamic simulation for carbon emission reduction effects of the prefabricated building supply chain under environmental policies. *Sustain. Cities Soc.* **2024**, *100*, 105027. [CrossRef]

89. Liu, H.; Yu, Y.; Sun, Y.; Yan, X. A system dynamic approach for simulation of a knowledge transfer model of heterogeneous senders in mega project innovation. *Eng. Constr. Archit. Manag.* **2021**, *28*, 681–705. [CrossRef]
90. Guo, S.; Zhang, P.; Yang, J. System dynamics model based on evolutionary game theory for quality supervision among construction stakeholders. *J. Civ. Eng. Manag.* **2018**, *24*, 318–330. [CrossRef]
91. Lv, L.; Li, H.; Wang, Z.; Zhang, C.; Qiao, R. Evolutionary game analysis for rent-seeking behavior supervision of major infrastructure projects based on prospect theory. *J. Civ. Eng. Manag.* **2021**, *28*, 6–24. [CrossRef]
92. Coria, J. Taxes, permits, and the diffusion of a new technology. *Resour. Energy Econ.* **2009**, *31*, 249–271. [CrossRef]
93. Taylor, P.D.; Jonker, L.B. Evolutionary stable strategies and game dynamics. *Math. Biosci.* **1978**, *40*, 145–156. [CrossRef]
94. Friedman, D. On economic applications of evolutionary game theory. *J. Evol. Econ.* **1998**, *8*, 15–43. [CrossRef]
95. Lyapunov, A.M. The general problem of the stability of motion. *Int. J. Control* **1992**, *55*, 531–534. [CrossRef]
96. Rogers, E.; Singhal, A.; Quinlan, M. Diffusion of Innovations. In *An Integrated Approach to Communication Theory and Research*, 2nd ed.; Stacks, D.W., Salwen, M.B., Eds.; Routledge: New York, NY, USA, 2008; Volume 4, pp. 432–448.
97. Ford, A. Validation. In *Modeling the Environment: An Introduction to System Dynamics Models of Environmental System*, 1st ed.; Baldwin, T., Ed.; Island Press: Washington, DC, USA, 1999; Volume 1, pp. 283–289.
98. Defee, C.; Stank, T.; Esper, T. Performance implications of transformational supply chain leadership and followership. *Int. J. Phys. Distrib. Logist. Manag.* **2010**, *40*, 763–791. [CrossRef]
99. Gosling, J.; Jia, F.; Gong, Y.; Brown, S. The role of supply chain leadership in the learning of sustainable practice: Toward an integrated framework. *J. Clean. Prod.* **2016**, *137*, 1458–1469. [CrossRef]
100. Rodrigo, M.N.; Perera, S.; Senaratne, S.; Jin, X. Potential Application of Blockchain Technology for Embodied Carbon Estimating in Construction Supply Chains. *Buildings* **2020**, *10*, 140. [CrossRef]
101. Liu, Z.; Wu, T.; Wang, F.; Osmani, M.; Demian, P. Blockchain Enhanced Construction Waste Information Management: A Conceptual Framework. *Sustainability* **2022**, *14*, 12145. [CrossRef]
102. Dai, R.; Zhang, J.; Tang, W. Cartelization or Cost-sharing? Comparison of cooperation modes in a green supply chain. *J. Clean. Prod.* **2017**, *156*, 159–173. [CrossRef]
103. Yuan, H.; Yang, Y. BIM Adoption under Government Subsidy: Technology Diffusion Perspective. *J. Constr. Eng. Manag.* **2020**, *146*, 04019089. [CrossRef]
104. Wang, Q.; Su, M.; Li, R. Is China the world's blockchain leader? Evidence, evolution and outlook of China's blockchain research. *J. Clean. Prod.* **2020**, *264*, 121742. [CrossRef]