Blockchain Adoption among Multi-Stakeholders under Government Subsidy: From the Technology Diffusion Perspective

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Abstract: Despite the well-documented benefits and encouraging policy environment for blockchain technology (BT), its extensive adoption in the construction industry is still unsolved. The interorganizational diffusion of BT is not explored in existing studies, requiring a comprehensive investigation for better government policymaking. Thus, from the technology diffusion perspective, this paper proposes an evolutionary game-based system dynamics (EG-SD) model to describe the complicated relationships between government and construction enterprises in the process of BT adoption. Through theoretical analysis, the main stakeholders, influencing factors, and diffusion channels in the process of BT adoption are identified. Further, a simulation collecting data from China's construction industry is conducted to evaluate the diffusion performance under different scenarios. This study contributes to the body of knowledge by providing a quantitative perspective for understanding BT adoption behaviors among construction enterprises and revealing the diffusion mechanism of BT from a multilevel perspective. Also, this paper for the first time combines evolutionary game theory with system dynamics into explaining BT adoption, providing practical implications to both government and construction enterprises on policymaking and promoting BT adoption practices.
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Introduction and Literature Review

With the increasing pressure from the decline in labor and resources, the last decades witnessed a great transformation in the construction industry from labor-intensive to digital and automatic (Dou et al. 2020). Blockchain technology (BT), as an emerging technology holding the promise of transparent, traceable, and reliable information management (Yoon and Pishdad-Bozorgi 2022), has been viewed as an important booster for this global transformation. In the last few years, BT has been widely implemented in various fields of construction management such as information integration (Yang et al. 2020), quality management (Lee et al. 2021), and governmental supervision (Lu et al. 2021). The decentralized nature of BT prevents issues such as information asymmetry, falsification, and tampering, making it a desirable method to mitigate risks and uncertainty in construction management (Xu et al. 2022). It has been regarded as a breakthrough innovation which reforms mutual trust among different participants in the construction industry.

Consequently, considering the disruptive benefits of BT, countries worldwide have proposed specific programs to embrace its adoption. In 2016, the UK took the lead in issuing the white paper "Distributed Ledger Technology: Beyond Blockchain," raising the research and development of BT into the national strategic level (GOS 2016). The Industry and Technology Minister in Turkey issued "Turkey's 2023 Industry and Technology Strategy," targeting the year 2023 by when a national platform will be established to apply BT into the public administration and infrastructure management (ITMMV 2019). In 2021, the State Council of China issued the "National Standardization Development Outline" which clearly proposes to strengthen the research on standards of BT, applying it to improve quality governance (SCPRC 2021). Since then, local governments in China have launched numerous incentive policies and set up relevant supporting funds for promoting BT adoption.

However, despite the well-documented benefits of BT and the encouraging policy environment, the adoption process of BT in the construction industry is much slower than expected. In general, incorporating BT into the construction industry is a lasting process through which BT is adopted and developed among various stakeholders. Given the characteristics of BT, its adoption is a technology diffusion phenomenon, which is defined as "the process by which an innovation is communicated through certain channels over time among the members of a social system"(Rogers 1983). Technology diffusion has been a hot research topic in many fields such as diffusion of green technology (Tian et al. 2014) and manufacturing mode (Wang et al. 2020a). In the construction industry, diffusion of information technologies such as building information modeling (BIM) (Yuan and Yang 2020) and computer aided design (Kale and Ardit 2005) has also gained much attention.

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To comprehend BT diffusion, it is important to investigate how the innovation (BT) is adopted and developed through what channels among which members. Existing studies have investigated BT diffusion to some extent, mainly focusing on the identification of influencing factors such as opportunities, challenges, barriers, and drivers (Clohessy and Acton 2019; Teisserenc and Sepasgozar 2021; Wang et al. 2019). However, in those studies, BT diffusion was explained from a static and qualitative perspective, ignoring the changing and dynamic nature of technology diffusion. In practice, BT, as an emerging innovation, is mainly adopted among construction firms through the motivation of the economic benefits brought by BT implementation, including reduction in costs, additional profits, and government subsidy (Cao et al. 2015). Among those benefits, government subsidy plays the dominant role since the additional profits brought by BT implementation are relatively low in the early stage of development. Under this circumstance, qualitative descriptions of BT diffusion in existing studies without real-world data support failed to provide practical guidelines on policymaking.

Many prior studies have applied game theory in investigating the technology diffusion phenomenon across different fields (Cheng et al. 2020; Jia et al. 2021; Yuan and Yang 2020). These studies have provided the groundwork for quantitative analysis of BT diffusion while they mainly considered the interactions between limited participants. Literature indicates that BT diffusion is a complex process, involving multiple stakeholders such as local governments, project owners, general contractors, and subcontractors, whose decisions would be pivotal in influencing technology adoption (Yuan and Yang 2020). This paper argues that it is important to take more stakeholders into consideration when analyzing BT diffusion to provide more practical implications on policymaking. Meanwhile, literature reveals that besides government subsidy, market competition is also an important factor affecting technology adoption significantly (Zhu and Weyant 2003) which existing studies ignored. Those research gaps result in the inefficiency of incentive policies provided by the governments, which will further limit the BT adoption in the construction industry.

Regarding these insufficiencies, this paper aims to investigate how is BT diffused among various stakeholders in the construction industry under government subsidy. The primary objective of this paper is to describe the complicated relationships of BT adoption among multiple stakeholders to deepen their understandings of how to enhance BT adoption. Specifically, this paper proposes an EG-SD model to identify the relevant factors influencing stakeholders' decisions on BT adoption, and quantitatively analyze how different stakeholders' decisions influence with each other. This research contributes to the body of knowledge by providing a quantitative perspective for understanding BT adoption behaviors among construction enterprises and revealing the diffusion mechanism of BT from a multilevel perspective. Also, through the quantitative analysis, this paper will provide practical implications to both government and construction enterprises on how to promote BT adoption in a more efficient way.

The remainder of this study is organized as follows: The next section reviewed the current works of BT diffusion in the construction industry. Further, an analyzing model was proposed to describe the diffusion process comprehensively, followed by a numerical simulation of diffusion performance under different scenarios. Based on simulation results, both theoretical and practical implications were concluded. Finally, conclusions, limitations, and future research were discussed.

In recent years, upon practical needs, increasing studies have been conducted on BT adoption and diffusion. For instance, Wang et al. (2017) investigated the technical, business-related, and human-related challenges of BT adoption in the construction industry. Khan et al. (2021) identified ten critical factors influencing BT adoption through a systematic literature survey. Kar and Navin (2021) reviewed both academic literature and industrial practices to understand the actual levels of BT adoption. Vu et al. (2021) conducted a literature review to identify the drivers, barriers, and implementation stages of BT. In those studies, BT diffusion was mainly discussed based on qualitative descriptions. While in practice, despite these claimed factors, the main motivation for enterprises adopting emerging technologies is the visible economic benefits from government subsidies, cost savings, and additional profits (Cao et al. 2015).

To author's knowledge, there has been no research quantitatively studying the BT diffusion from the economic perspective which may be owing to the short time of BT development and adoption in the construction industry. Nevertheless, many prior studies have explored the technology diffusion phenomenon across different fields. Owing to cooperative and competitive characteristics of technology diffusion phenomenon, game theory has been widely applied to find a balance of interests between different parties (Eissa et al. 2021). In recent years, more and more studies have applied game theory into technology diffusion field with the rapid development of simulation methods (Yuan and Yang 2020). Especially, evolutionary game theory (EGT) has been widely used. Compared with classical statistic game theories, it takes the limited rationality of organizations into consideration and helps to explain behavioral relations between those parties in a more practical and realistic way (Lv et al. 2021). By combing game theory and dynamic evolution process analysis, it has been proven to be more suitable for investigating long-term dynamic game processes (Cheng et al. 2020). By proposing a tripartite game model using prospect theory and EGT, Jia et al. (2021) discussed the diffusion of BIM among various stakeholders in public-private-partnership (PPP) projects. Liu (2020) constructed an evolutionary game model to explore diffusion of BIM between government and developers in the construction industry. A numerical simulation was conducted to analyze the decision-making development under different scenarios. Zhang et al. (2019) studied how the low-carbon policies promote diffusion of related technologies among alliance-based firms in China based on EGT and complex networks. All those studies have proven the effectiveness of EGT for exploring technology diffusion across multiple industries.

Those aforementioned studies have provided the theoretical foundations for investigating BT diffusion in construction industry while they mainly focus on interactions between limited parties, generally government and general contractors. The literature indicates that BT diffusion is a complex process, involving multiple stakeholders such as local governments, project owners, general contractors, and subcontractors, whose decisions would be pivotal in influencing technology adoption (Yuan and Yang 2020). Meanwhile, the literature reveals that besides government subsidy, market competition is also an important factor affecting technology adoption significantly (Zhu and Weyant 2003). Thus, not only subsidizing & subsidized relations between government and contractors should be considered, but also cooperative & competitive relations between different contractors. However, the latter has rarely been explored in extant studies. Meanwhile, the analysis of BT diffusion based on EGT is relatively complicated, consisting of multiple participants and evolution phases (Guo et al. 2018). System dynamics (SD), as a structural modelling technique capable of understanding, simulating, and analyzing complex systems (Peña-Mora et al. 2008), has proven to be effective in performing stable analysis and identifying equilibrium solutions in simulating the evolutionary game process (Liu et al. 2015). For instance, Tian et al. (2014) applied SD to simulate the evolutionary game model of green supply chain diffusion in the Chinese manufacturing industry under government subsidy.

To sum up, despite the importance of BT diffusion, it has rarely been studied in extant studies owing to the complexity of interorganizational relationships and difficulty in data collection. This paper's literature study showed that limited studies have identified influencing factors of BT diffusion while no study quantitatively explains the dynamic interactions among stakeholders. When reviewing the literature on technology diffusion, it was discovered that most studies centered on the contacts between government and general contractors but ignored the inter-organizational interactions among different contractors, failing to provide comprehensive implications on BT diffusion and policy-making. The macromechanism and microfeatures of the interorganizational diffusion of BT are not clearly revealed, requiring further exploration.

Therefore, this study combines EGT with SD and constructs a comprehensive model to analyze the complicated relationships between government and construction enterprises. The proposed EG-SD model illustrates the holistic evolution process from the external to the internal, revealing both macromechanism and microcharacteristics among various stakeholders.

Development of the EG-SD Model

Analytical Framework

To better understand this study, the structure of the proposed model is presented in Fig. 1. In short, this study analyzed BT diffusion under different scenarios among local government (LG), general contractor enterprises (GCEs), and subcontractor enterprises (SEs). Through modeling, simulating, and discussing, both practical and theoretical implications were concluded.

First, multiple scenarios for analyzing BT diffusion were identified. In general, subsidy from the government has been indicated as a critical factor for promoting technology adoption in the construction industry (Eadie et al. 2013). Static subsidies, on the other hand, have been criticized for their low promotion efficiency and excessive financial burdens for local governments. Recently, some studies have claimed that dynamic subsidy may balance the diffusion performance and fiscal expenditure (Ji et al. 2019). However, it requires exploration in other fields for further validation. Thus, in this paper, scenarios of LG aimed to investigate the efficiency of static and dynamic subsidies on diffusion performance to analyze which is preferable. Also, within the project perspective, methods of supply chain collaboration such as revenue-sharing (Zhang and Ma 2020) cost-sharing (Wang et al. 2020a), and penalty for default (Zhang and Ma 2020) have attracted much attention in existing studies of technology diffusion. Specifically, scenarios of GCE aim to discuss the effects of those collaborative measures on diffusion performance.

Then, the EG-SD model was proposed. In the EG part, some important hypotheses were made according to characteristics of EGT, technology diffusion in construction industry, and BT implementation. The EG model aimed to illustrate the interorganizational interactions from the economic perspective. Also, it served as the input of the simulation in the SD model. Further, the SD model was constructed to reveal the diffusion mechanism comprehensively. The complicated relationship among tripartite stakeholders was revealed, including evolution between different groups in GCEs and SEs; competition and cooperation between GCEs and SEs, and subsidy from LG toward GCEs. Meanwhile, relevant factors influencing BT diffusion and their causal relations were also identified. Some factors have positive effects on BT diffusion while others have negative. Finally, based on inputs from the EG model and data collected from literature and industry references, a numerical simulation was conducted. Diffusion performance under each scenario was evaluated by conducting a sensitivity analysis regarding important variables. Based on the discussion of simulation results, both practical implications on policymaking and theoretical implications on technology diffusion were concluded.

Evolutionary Game Model

To comprehend the model for better analysis, some assumptions are made as follows:

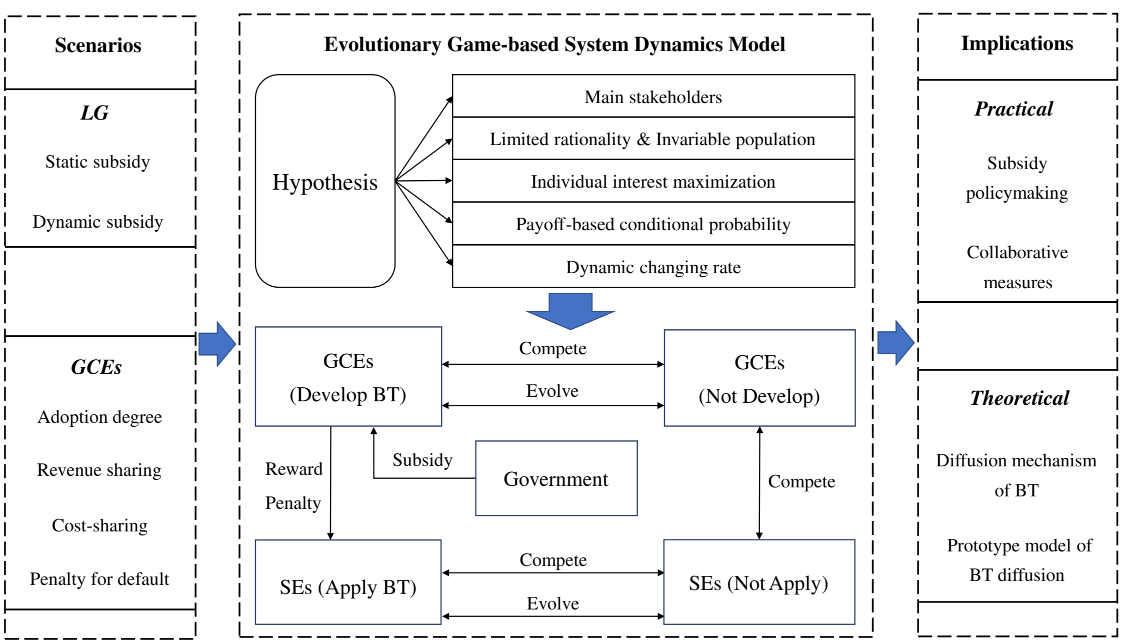

Fig. 1. Structure of the evolutionary game-based system dynamics model.

Assumption 1: In this model, the LG, GCEs, and SEs are selected as the main stakeholders in the construction industry. SEs refer to all other participants such as manufacturer and supervisor.

Assumption 2: In this model, the total number of GCEs and SEs are assumed to be invariable. Within every time period, each GCE or SE will stick to a certain strategy. In the condition of market competition, they are assumed to seek maximization of their interests.

*Assumption 3: Adoption of BT, as a market activity, is to maximize its economic benefits. Thus, the behaviors of the GCEs and SEs are determined by their payoffs (*Chen et al. 2017*). Suppose that each GCE or SE randomly samples an agent from the corresponding population with equal probability, observes the respective strategy, and compares its payoff with the sampled one.*

In the condition of market competition, they are assumed to seek maximization of their interests. The average expected payoff (***U***) of GCEs for choosing the "develop" strategy is U_{GAD}, and U_{GAN} for "not develop". Further adjustment parameters are supplemented to introduce randomness: $U_{GD} = U_{GAD} + \varepsilon_{GD}$ and $U_{GN} = U_{GAN} + \varepsilon_{GN}$, and ε_{GD}, ε_{GN} are normally distributed random variables. Similarly, the average expected payoffs of SEs for choosing "apply" and "not apply" strategies can be obtained as: $U_{SA} = U_{SAA} + \varepsilon_{SA}$ and $U_{SN} = U_{SAN} + \varepsilon_{SN}$ respectively, and ε_{SA}, ε_{SN} are normally distributed random variables. If an i-enterprise samples a j-enterprise, then the i-enterprise will possibly switch to j-enterprise's strategy if the observed payoff difference is positive (Tian et al. 2014). The conditional probability of GCEs deciding to switch from strategy i to j is $\emptyset(U_{Gi} - U_{Gj})$ calculated as

$$\emptyset(\mathrm{U}_{Gi} - \mathrm{U}_{Gj}) = \begin{cases} \dfrac{U_{Gj} - U_{Gi}}{U_{Gi}}, & if\, U_{Gi} - U_{Gj} \le 0 \\ 0 & if\, U_{Gi} - U_{Gj} \ge 0 \end{cases} \quad (i, j = D, N) \tag{1}$$

*Assumption 4: Assuming the probability of GCEs to choose the "develop" strategy is x, and $1 - x$ for choosing "not develop." Similarly, the probability of SEs to choose "apply" strategy is y, and $1 - y$ for "not apply"; and x and y are the functions of time t. The basic dynamic changing rate of x and y be expressed as replicator dynamics equations (*Weibull and Press 1997*):*

$$\dot{x} = x(1 - x)[\emptyset(U_{GN} - U_{GD}) - \emptyset(U_{GD} - U_{GN})] \tag{2}$$

$$\dot{y} = y(1 - y)[\emptyset(U_{SN} - U_{SA}) - \emptyset(U_{SA} - U_{SN})] \tag{3}$$

Assumption 5: Owing to the distributed nature of BT, its adoption requires fully cooperation from all participants involved. Thus, GCEs choosing the develop strategy are cooperating with SEs choosing apply while GCEs choosing not develop strategy can only cooperate with SEs choosing not apply.

*Assumption 6: Unlike the diffusion of other ICTs such as BIM, Barcode, and radio frequency identification (RFID) which have direct and visible effects in improving management performance, the main benefits brough by BT implemented come from the reinforcement of mutual trust among various stakeholders (*Qian and Papadonikolaki 2021*). Thus, the additional profits brought by BT in initial stage are low and increase quickly with BT diffusion, and finally slow down till the limitation.*

System Dynamics Model

The SD model describes the evolutionary path of BT diffusion with four modules: Macrodiffusion module, Microdiffusion module, GCEs' payoff module, and SEs' payoff module.

Macrodiffusion Module

In this module, the diffusion mechanism of BT among GCEs is modeled, with two level variables (GD and GN), one rate variable (DR_1), and other variables included. Those links represent the causal associations between variables where links with + mean that the increase of variable A (end of the arrow) will lead to the increase of variable B (head of the arrow) while − mean the decrease of B. Further, the implementation of BT is a lasting process and GCEs take different time owing to the difference in scale, resource, and culture. Thus, in this model, the implementation time is assumed to be a normally distributed variable. Based on some practical policies launched in China, the maximization of implementation time is set to be 2 years, and average to be 1 year. The main equations are presented as follows:

$$DR_1 = GT \times TR_1 \tag{4}$$

$$TR_1 = DELAY\ FIXED\ (BR_1, RANDOM\ NORMAL\ (0, 2, 1, 0.1, 0), BR_1) \tag{5}$$

$$BR_1 = x(1 - x)[\emptyset(U_{GD} - U_{GN}) - \emptyset(U_{GN} - U_{GD})] \tag{6}$$

$$GD_t = GD_{t-1} + DR_1 \tag{7}$$

$$GN_t = GN_{t-1} - DR_1 \tag{8}$$

where $\boldsymbol{DR_1}$ = the promoting rate of BT in the population of GCEs; $\boldsymbol{GT}$ = the total number of GCEs; $\boldsymbol{TR_1}$ = the dynamic changing rate after implementation time; $\boldsymbol{BR_1}$ = the basic changing rate of probability of GCEs for choosing *develop* strategy; $\boldsymbol{GD_t}$ = the number of GCEs choosing the *develop* strategy after time period t; and $\boldsymbol{GN_t}$ = the number of GCEs choosing the not develop strategy after time period t.

Microdiffusion Module

Compared with macro module, micro diffusion module illustrates the diffusion of BT among SEs from the project level. Implementation time is set to be 1 year (maximization), 0.5 years (average), while others are similar with those in the macrodiffusion module. It shares a similar structure with the macrodiffusion module because different stakeholders make decisions in the process of BT diffusion in a similar way, based on the principle of interest maximization. The main difference lies in the diffusion rate which is fundamentally determined by the SEs' payoff module

$$DR_2 = ST \times TR_2 \tag{9}$$

$$TR_2 = DELAY\ FIXED\ (BR_2, RANDOM\ NORMAL(0, 1, 0.5, 0.1, 0), BR_2) \tag{10}$$

$$BR_2 = y(1 - y)[\emptyset(U_{SA} - U_{SN}) - \emptyset(U_{SN} - U_{SA})] \tag{11}$$

$$SA_t = SA_{t-1} + DR_2 \tag{12}$$

$$SN_t = SN_{t-1} - DR_2 \tag{13}$$

where $\boldsymbol{DR_2}$ = the diffusion rate of blockchain in the population of SEs; $\boldsymbol{ST}$ = the total number of SEs; $\boldsymbol{TR_2}$ = the dynamic changing rate after implementation time; $\boldsymbol{BR_2}$ = the basic changing rate of probability of SEs for choosing the apply strategy; $\boldsymbol{SA_t}$ = the number of SEs choosing the apply strategy after time period t; and $\boldsymbol{SN_t}$ = the number of SEs choosing the not apply strategy after time period t.

Payoff Module of GCEs

In this module, the average expected payoff of GCEs choosing the develop strategy U_{GAD} and not develop strategy U_{GAN} are established. Payoffs of GCEs consist of two parts: the basic part and the BT part. Basic part refers to the basic profit of GCEs without BT adoption. BT part refers to the additional benefits and costs incurred by BT implementation. In general, initial investment cost, which may include procurement cost and training cost, decreases gradually with time passing and technology development (Yuan and Yang 2020). Conversely, given the information storage characteristics of BT, operation cost increases gradually with time. Additional profits brought by BT embody in enhancement in mutual trust among various stakeholders. It contains two main parts: (1) improvements in supply chain management efficiency. Owing to the automated characteristics of BT, labor cost, inventory cost, quality cost and delivery cost can be decreased significantly (Wang et al. 2020b); and (2) reduction in projects disputes. Owing to transparent and traceable characteristics of BT, each procedure in construction projects can be traced by each participant at any time. Under this circumstance, costs for dispute resolution can be reduced since BT provides a trustworthy platform (Li et al. 2018)

$$U_{GAN} = (B - B_S)\frac{SN}{GN} \tag{14}$$

$$U_{GAD} = [B - B_S + (1-\alpha)P_B - (1-\beta)C]\frac{SA}{GD} + S \tag{15}$$

$$C = C_0 e^{-qt} + C_1 e^{\frac{t}{q}} \tag{16}$$

$$P_B = \frac{P_1 + P_2}{1 + e^{-qt}} \tag{17}$$

$$U_{GN} = U_{GAN} + \varepsilon_{GN}; \qquad U_{GD} = U_{GAD} + \varepsilon_{GD} \tag{18}$$

$$\varepsilon_{GN}, \varepsilon_{GD} = \text{RANDOM NORMAL}(-100{,}100, 0, 50, 0) \tag{19}$$

where $\boldsymbol{B}$ = the total profit of project without BT implementation; $\boldsymbol{B_S}$ = the basic profit for SEs without BT implementation; $\boldsymbol{P_B}$ = the additional profit with implementation of BT, $\boldsymbol{P_1}$ = the improvements in supply chain management efficiency, $\boldsymbol{P_1}$ for the reduction in potential risks; $\boldsymbol{\alpha}, \boldsymbol{\beta}$ = the coefficient of profit-sharing and cost sharing between GCEs and SEs; $\boldsymbol{C}$ = the total cost of BT adoption, $\boldsymbol{C_0}$ = initial investment cost, and $\boldsymbol{C_1}$ = operation cost; and $\boldsymbol{q}$ = the degree of BT implementation.

Payoff Module of SEs

In this module, the average expected payoffs of SEs choosing apply U_{SAA} and not apply strategy U_{SAN} are constructed. Similarly, SEs choosing not apply can only obtain basic profit from project while SEs choosing apply share additional costs and benefits with GCEs

$$U_{SAN} = B_S * \frac{GN}{SN} \tag{20}$$

$$U_{SAA} = (B_S + \alpha P_B - \beta C)\frac{GD}{SA} \tag{21}$$

$$U_{SN} = U_{SAN} + \varepsilon_{SN}; \qquad U_{SA} = U_{SAA} + \varepsilon_{SA} \tag{22}$$

$$\varepsilon_{SA}, \varepsilon_{SN} = \text{RANDOM NORMAL}(-25, 25, 0, 10, 0) \tag{23}$$

Based on the previous analysis, the system dynamics model of BT diffusion among tripartite organizations is established and presented in Fig. 2, with 4 level variables, 2 rate variable, 8 constant variables, and 16 auxiliary variables.

Simulation Results and Discussions

The proposed EG-SD model is customarily designed for the BT diffusion in the construction industry. In this section, a numerical simulation collecting data from the China's construction industry was conducted. Since precast construction has been trending up rapidly in China owing to its technical, economic, and environmental advantages, incentive policies for promoting adoption of advanced technologies are highly related with the precast construction mode. Thus, this paper collected data from the China's precast construction market for further simulation. It is important to note, the simulation results in this paper are supposed to be applicable for analysis of

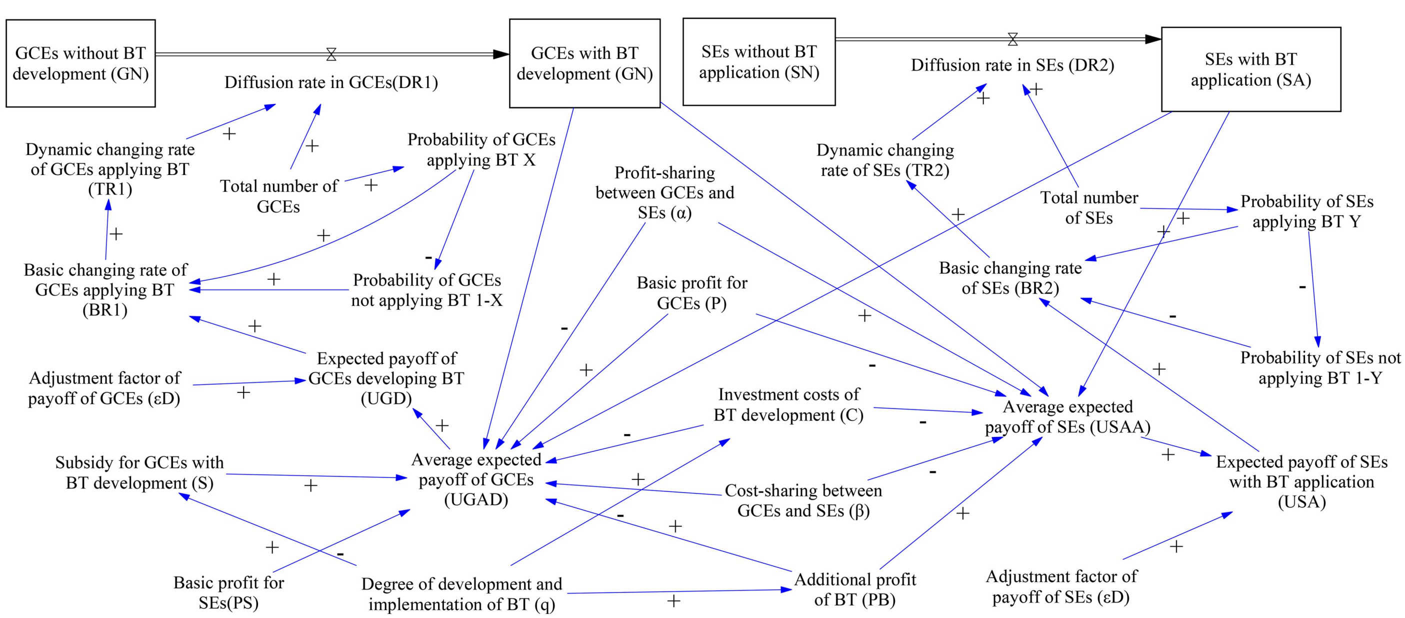

Fig. 2. BT diffusion modules of GCEs and SEs.

Table 1. Initial values of the simulation

Variables	Type	Value	Unit
GD	Level	35	1
SA	Level	70	1
GT	Constant	100	1
ST	Constant	330	1
P_B	Constant	1.2	Million RMB
S	Constant	1	Million RMB
B	Constant	1	Million RMB
B_S	Constant	3	Million RMB
C_0	Constant	0.7	Million RMB
C_1	Constant	0.2	Million RMB

BT diffusion in the construction industry, not limited for precast construction.

The initial values in this model were set up based on the situation of technology diffusion in Shanghai's AEC sector, with some specific modifications. In the model, the degree of BT adoption among multiple stakeholders was simplified as a variable owing to its immeasurability. The subsidy for GCEs with BT implementation was set up according to "***Policies for Promoting the Upgrading and Development of Blockchain Industry***" issued by Shanghai, China. According to statics published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China, there were 9834 GCEs qualified for First Grade in China, with 7061 in architectural engineering construction. For Shanghai, there were 152 GCEs, with approximately 104 in architectural engineering construction. For the sake of perspicuity in evaluation, there were assumed to be 100 GCEs and 330 SEs in Shanghai, and respectively 35 and 70 of them have already applied BT in their operations. It represented the initial values of $x(t)$ and $y(\mathrm{t})$ respectively. As for the additional profits of BT, as aforementioned, it contains two parts: improvements in performance and reduction in risks. Wang et al. (2020b) conducted a comprehensive simulation for analyzing the improvements of BT implementation in construction management such as reduction in operation times and lead times. Further by collecting data from industry practices, the economic benefits of BT implementation were quantified. Results in the study indicate that BT can decrease supply chain cost by 38%. The second part of additional profits brought by BT lies in the reduction in disputes in construction projects. Gebken and Gibson (2006) collected practical data from 46 construction projects to quantify the costs for disputes resolution in the construction industry. Results in the study indicate that costs for disputes take 1.75% of the total benefits. Combining the simulation results of existing studies with interviews with the related staff in Shanghai Jiangong construction company, this paper assumes the additional profits of BT account for 40% of the total profit of project. The rest of the values were collected based on the interviews also. The initial values of the simulation are shown in Table 1. Working with those values, the initial simulation results of BT diffusion among GCEs are presented in Fig. 3 ($q = 1$). It shows that GD (the number of GCEs choosing the develop strategy) increases gradually, and after approximately 30 years of diffusion, all GCEs will adopt BT eventually. Meanwhile, the diffusion performance of different strategies is evaluated from both time and cost perspectives. From the time perspective, diffusion performance is evaluated by the time it takes when the adoption of BT in the construction industry reaches the mature state. From the cost perspective, diffusion performance is evaluated by the total amount of subsidies provided by the local government when the adoption of BT reaches the mature state. Specifically, some criteria are selected in this paper, shown as follows:

$$T_{80}\text{:}diffusion\ time\ when\ 80\%\ of\ totoal\ GCEs\ choose\ to\ develop\ BT \tag{24}$$

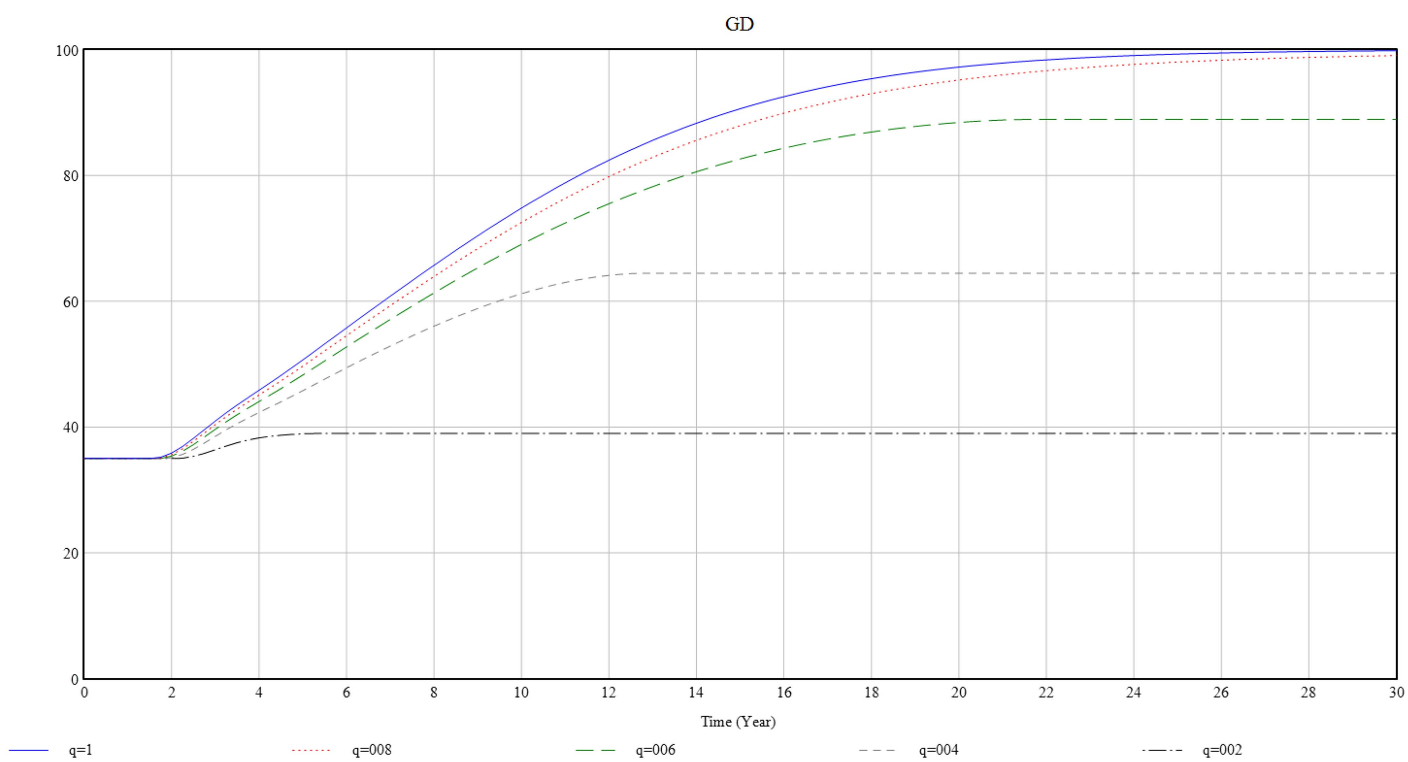

Fig. 3. Simulation of BT diffusion under different implementation degrees.

$$S_{80} = \int_{o}^{T_{80}} S_t * (GD_{t+1} - GD_t)dt \tag{25}$$

In this model, it was assumed that the diffusion of BT has tended to mature when 80% of total GCEs choose to adopt BT. The remained part was believed to be caused by inherent resistance to new technologies in construction industry and perceived lack of suitability of BT for all construction project management (Reza et al. 2018). Specifically, diffusion performance of some strategies was evaluated by the T_{80} criterion. The lower value of T_{80}, the more efficient the strategy is. For those subsidy-related strategies, another criterion S_{80}, the total amount of subsidies till T_{80}, was also used for evaluation. The lower value of S_{80}, the more efficient the strategy is.

Simulation under Different Scenarios

Impacts of Implementation Degree on BT Diffusion Performance

In this situation, the degree of BT implementation (q) was changed from 20%, 40%, 60%, 80%, and 100% to simulate its effects on diffusion performance. The curves of GD with time are shown in Fig. 3. In the initial scenario with q of 100%, it takes approximately 11 years to achieve mature diffusion in market and more than 30 years to fully diffused (fully diffusion is only for theoretical reference, not represents practical situations in reality). At implementation degrees of 20% and 40%, the number of GD will stabilize at 38 and 64 respectively after long-term diffusion process, failing to reach maturity. At degree of 60% and 80%, market maturity is achieved eventually while T_{80} are much higher than that in the initial scenario. According to the simulation results, degree of BT implementation which represents the level of cooperation among various stakeholders, positively influences the diffusion performance. These results are convergent with technical characteristics of blockchain: decentralization. In blockchain networks, all participants are bookkeepers, participating collaboratively to improve network security and efficiency.

Impacts of Static and Dynamic Subsidy on BT Diffusion Performance

In static scenario, government subsidy will not change with time. The curves of the number of GD are shown in Fig. 4. It clearly shows that the increase of subsidy amount will accelerate the diffusion process, which is convergent with previous experience. In dynamic scenario, the subsidy from government varies with the development and implementation of blockchain, presented as:

$$S = (1 - x)S_0 e^{-qt} \tag{26}$$

In the simulation, three pairs of comparisons between static and dynamic subsidy strategies were selected and compared: (1) $S = 100$ versus $S = (1 - x)300e^{-qt}$; (2) $S = 150$ versus $S = (1 - x)400e^{-qt}$; and (3) $S = 200$ versus $S = (1 - x)500e^{-qt}$. The curves of GD under different subsidy strategies were shown in Fig. 4. Apparently, all dynamic subsidy strategies have advantages over corresponding static strategies on diffusion time. Further, Fig. 5 illustrates the cumulative amount of subsidy with time under those strategies visually. Compared with static subsidy, expenditure under dynamic scenarios increase rapidly in initial stage but stabilize at a relatively lower level. Thus, it can be concluded dynamic subsidy is more appealing from the whole life cycle perspective of technology diffusion. Meanwhile, to evaluate the diffusion performance quantitatively, the exact data of evaluation criteria are collected and summarized in Table 2. Comparing the three sets of simulation, it can be observed that the time to reach market maturity (T_{80}) under the dynamic subsidy has been shortened by 1.80%, 2.17%, and 0.95% respectively. Meanwhile, S_{80} of

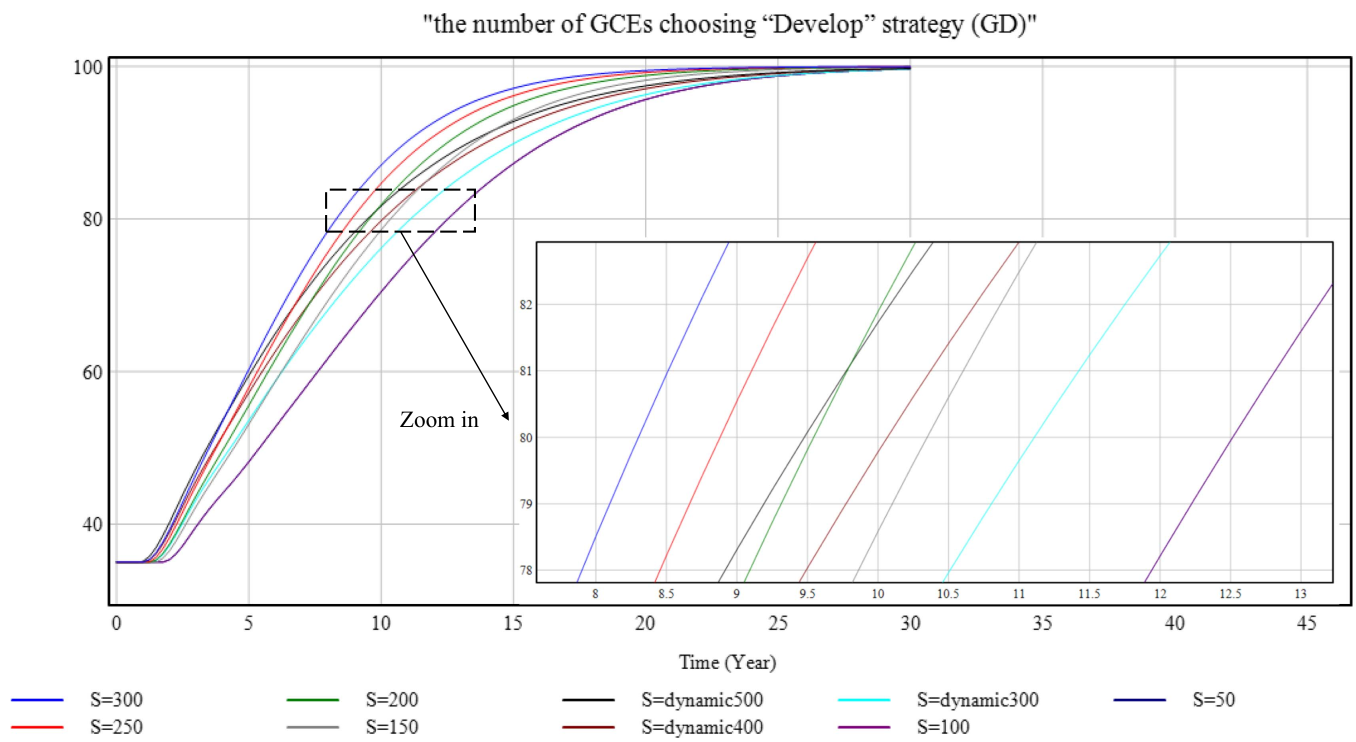

Fig. 4. Simulation of BT diffusion under different subsidy strategies.

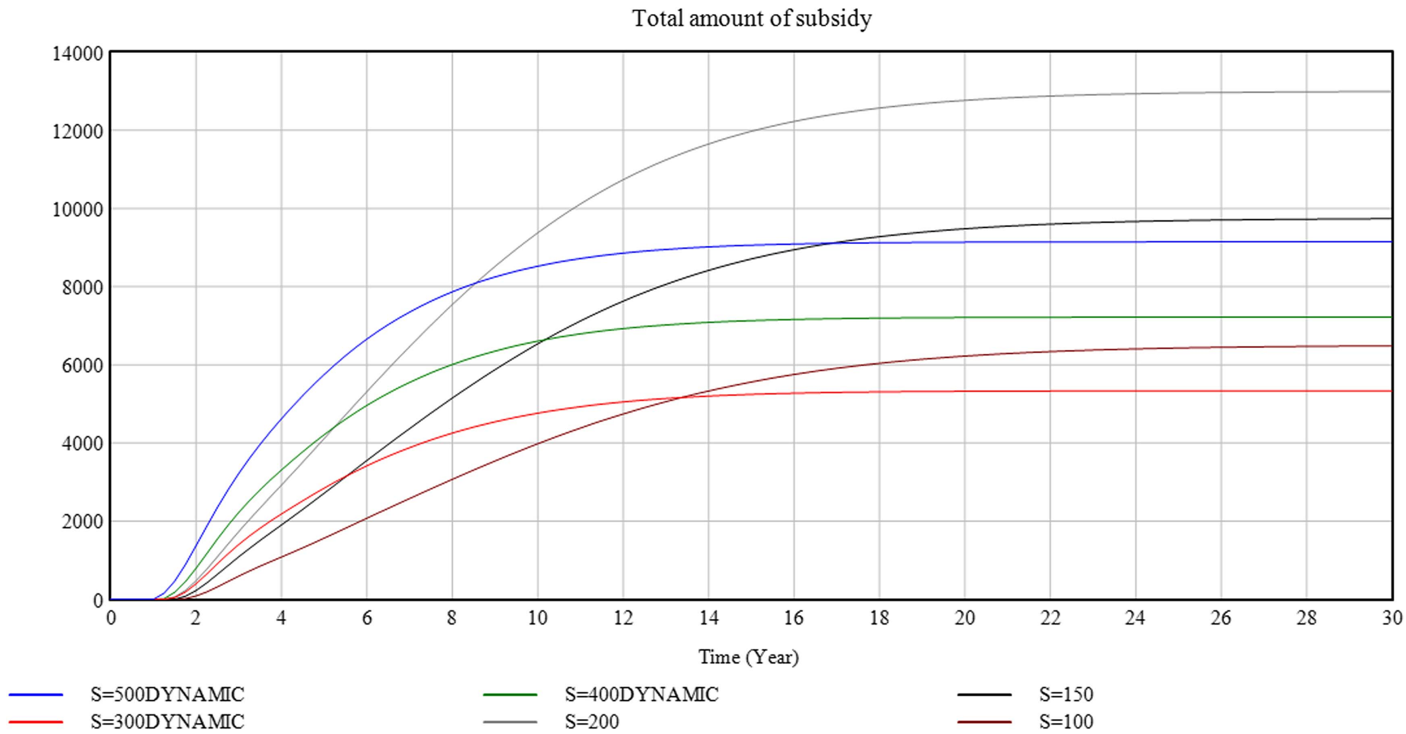

Fig. 5. Total subsidy amount under different subsidy strategies.

Table 2. Diffusion performance under different subsidy strategies

Subsidy	T_{80}	$\frac{T_{80}^s - T_{80}^d}{T_{80}^d}$	S_{80}	$\frac{S_{80}^s - S_{80}^d}{S_{80}^d}$
100	11.31	—	4,795.3	—
$(1-x)300e^{-t}$	11.11	1.80%	4,442.8	7.93%
150	10.35	—	6,750.7	—
$(1-x)400e^{-t}$	10.13	2.17%	6,688.0	0.94%
200	9.56	—	8,996.6	—
$(1-x)500e^{-t}$	9.47	0.95%	8,462.9	6.31%

dynamic subsidy strategies in each group are also less by respectively 7.93%, 0.94%, 6.31%. In other words, it takes less time and less financial expenditure for government to promote BT adoption under dynamic subsidy.

Impacts of Penalty-Settings on BT Diffusion Performance

In practice, some safeguards are always taken to secure the effectiveness of government subsidies. Besides deterrence from administrative measures, the penalty for breach of contract is always recognized as an effective method. In following simulation, effects of penalty-setting for GCEs were evaluated. GD obtain direct subsidy from government while a penalty will be imposed if breaching the contract (switching to the Not develop strategy). In this model, penalty-setting is directly associated with payoffs of GCEs, influencing the conditional probability function of switching from strategy j to i. The equations are represented in the followings:

$$\emptyset(U_{GD} - U_{GN}) = \begin{cases} \dfrac{U_{GN} - U_{GD} - P_G}{U_{GD}}, & if\, U_{GN} - U_{GD} - P_G \geq 0 \\ 0 & if\, U_{GN} - U_{GD} - P_G \leq 0 \end{cases} \tag{27}$$

In this simulation, the penalty was increased from 0 to 200 with the step of 20. The number of GD with time are presented in Fig. 6. However, T_{80} has never changed under different scenarios. It seems that penalty-settings have no influence on BT diffusion, inconsistent with previous studies.

Impacts of Revenue Sharing Strategies on BT Diffusion Performance

In this simulation, the coefficient of revenue-sharing (α) between GCEs and SEs was increased from 0% to 100% with the step of 10% to evaluate its influences. The curves of GD with time are shown in Fig. 7. It can be found T_{80} decreased remarkably with increase in α but rebounded slightly in the end. Similarly, exact data of evaluation criteria were collected and summarized in Table 3. When α is less than 70%, increase in α will shorten T_{80} prominently, from 11.31 to 8.54 years. It proves the positive effects on BT diffusion. But to mention, the marginal increase in diffusion performance brought by α is also decreasing, which means diffusion performance increases slower and slower with continuous increase in α. When exceeding more than 70%, an increase in α will cause longer time for market mature. It is natural to conclude that there exists an optimum proportion of revenue-sharing between GCEs and SEs for BT diffusion, between 60% to 80%. However, in practice, it is difficult to distribute such additional profits from GCEs to SEs to achieve the optimum diffusion of BT.

Impacts of Cost-Sharing Strategies on BT Diffusion Performance

In practice, cost-sharing has been viewed as an effective collaborative measure to bind the interests of different organizations up to foster common goals among upstream and downstream enterprises in the construction supply chains. In following simulation, the effects of cost-sharing strategies on diffusion performance were

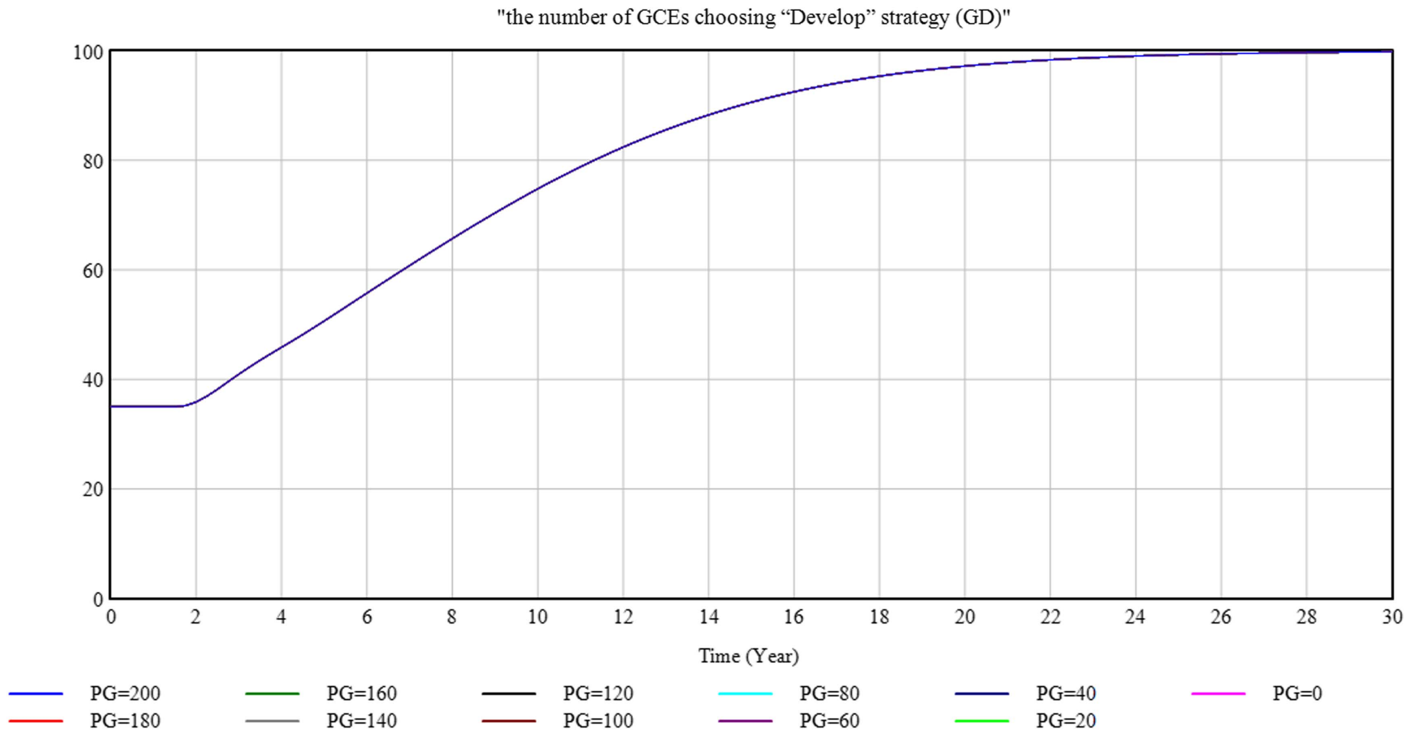

Fig. 6. Simulation of BT diffusion under different penalty-setting strategies.

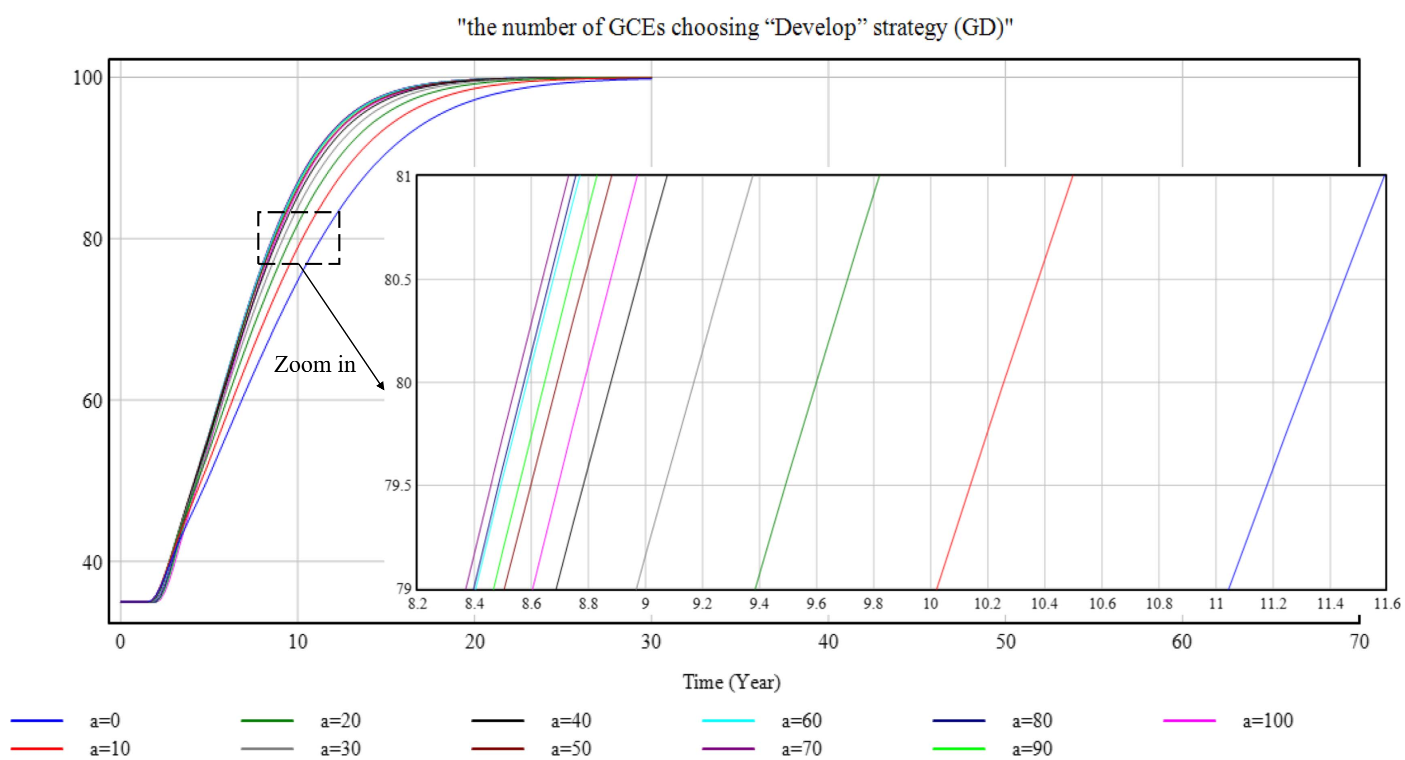

Fig. 7. Simulation of BT diffusion under different profit-sharing strategies.

analyzed. The coefficient of cost-sharing between GCEs and SEs (β) was increased from 0 to 0.5 with the step of 5% and the curves of GD under each scenario were shown in Fig. 8. It can be found that T_{80} increased continuously with increase in β, which indicates cost-sharing strategies hinder BT diffusion process. Compared with profit-sharing strategy, conversely, the marginal decrease in diffusion performance brought by β is increasing. In other words, diffusion performance decreases much faster with continuous increase in β.

Table 3. Diffusion performance under different profit-sharing strategies

a	T_{80}	Margin (%)
0	11.3	0
0.1	10.25	9.4
0.2	9.6	6.3
0.3	9.17	4.5
0.4	8.88	3.2
0.5	8.69	2.1
0.6	8.58	1.3
0.7	8.54	0.5
0.8	8.57	−0.4
0.9	8.64	−0.8
1	8.78	−1.6

Discussion

Based on the simulation results of the proposed model, some important conclusions regarding better diffusion of BT can be obtained as the follows:

1. Degree of BT implementation affects its diffusion performance significantly. The higher degree of BT implementation, which also means higher level of cooperation among stakeholders, could bring more additional profits, and accelerate the diffusion process prominently. This finding is also consistent with the technical characteristics of blockchain: decentralization, which requires fully coordination among participants.
2. Dynamic subsidies are proved to be more effective in promoting BT adoption and implementation than static subsidies. Static subsidies can be replaced with dynamic ones which provide higher subsidies when the potential benefits of BT implementation are not appealing and decrease gradually with the influx of adopters. This finding will provide practical suggestions for local governments as they issue relevant incentive policies to balance financial burdens and promotion performance.
3. Sharing of additional profits brought by BT adoption between GCEs and SEs promotes the diffusion performance while sharing of implementation and operation costs hinders it. Meanwhile, strategy of penalty will also not contribute to the BT diffusion.

However, there remained a question: Why did cost-sharing and penalty-setting strategies fail to contribute to BT diffusion? Driven by this doubt, we further investigated into the payoffs of GCEs and SEs and the reasons behind them were revealed. This is owing to the higher capacity of cost-bearing of GCEs compared with SEs. Compared with GCEs which obtained direct subsidy from government, SEs were more vulnerable to costs incurred by BT adoption. Any increase in costs will decrease SEs' enthusiasm for adopting BT. As for the invalidity of penalty-settings strategies, since the payoffs of GCEs choosing develop strategies were higher that of GCEs choosing not develop from the beginning of the simulation to the end, it is not rational for GCEs breaching the contract of subsidy. Thus, the conditional probability functions of GCEs were not influenced. Consequently, it failed to promote BT diffusion eventually.

Implications

Theoretical Implications

Based on the previous theoretical and numerical simulation analysis, this study provides theoretical implications to further research in the technology diffusion field from three aspects.

First, based on the combination of evolutionary game theory and system dynamics, this study has revealed the ***main stakeholders*** (LG, GCEs, SEs), the ***diffusion channels*** (industry-level diffusion channel: diffusion within GCEs' population; and project-level diffusion channel: diffusion within SEs' population), the ***related***

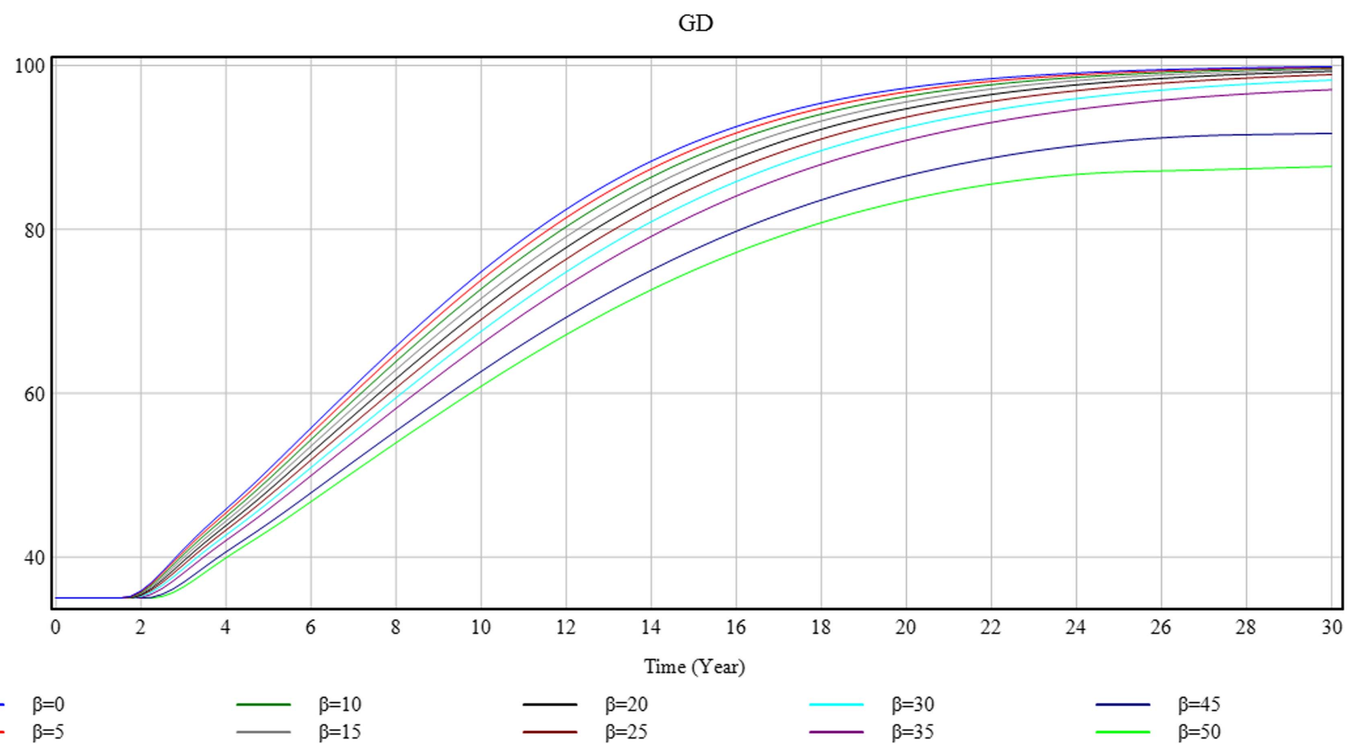

Fig. 8. Simulation of BT diffusion under different cost-sharing strategies.

influencing factors (additional profits, investment costs, government subsidy, profit-sharing coefficient, and cost-sharing coefficient), and the ***interorganizational interactions among main stakeholders*** (evolution within GCEs' and SEs' population; competition and cooperation between GCEs and SEs choosing different strategies; and subsidizing and subsidized relations between LG and GCEs) of BT diffusion. Such findings contribute to a new perspective for understanding BT diffusion process, serving as theoretical foundations for further research into the comprehensive diffusion mechanism.

Second, findings in this paper further validate the feasibility of dynamic government subsidy in promoting technology diffusion performance. On one hand, the conclusion echoes earlier studies emphasizing the government's significant role in promoting emerging technology adoption and implementation (Reza et al. 2018; Yuan and Yang 2020) and the efficiency of dynamic subsidy in balancing diffusion performance and financial burdens of local governments (Tian et al. 2014). On the other hand, this paper proposes a representation of dynamic government subsidy which varies with time and technology implementation. Further investigation into policy-making efficiency could be achieved based on modifications of this representation. Meanwhile, this study proposed some criteria for efficiency evaluation of government subsidy (e.g., T_{80}; S_{80}). More complicated cost-effectiveness analysis of government subsidy can be conducted by referring to the proposed criteria and simulation results.

Finally, the stakeholder identification, parameter and variable settings; simulation scenarios, data collection, and the analytical process in this paper could provide references for research of technology diffusion in other countries whose situations are similar to China.

Practical Implications

Meanwhile, analysis and findings in this study have significant implications for both local government and construction enterprises in industry practices.

For government, the simulation results prove that dynamic government subsidies are more effective in promoting BT diffusion than static subsidies. The findings are very inspiring for the local governments since it indicates the current paradigm of uniform subsidy policy for construction firms is not optimal from both time and monetary perspectives. Conversely, dynamic subsidy policy varies with time and technology development is more appealing. In practice, government should provide high fiscal subsidy to appeal GCEs for BT adoption in the initial stage, owing to the resistance caused by technology barriers and difficulty in development. With the rapid development of BT, technical and economic thresholds for new enterprises adopting BT decrease. Consequently, government may adjust its subsidy policy since more GCEs will adopt BT even less subsidies provided. When the market maturity is achieving, GCEs will adopt and implement BT spontaneously driven by competition from market. To conclude, the government is suggested to design appropriate policies according to BT diffusion characteristics to balance the effectiveness of incentive policies and technology promotion needs, and develop pilot projects to examine the efficiency of different dynamic subsidies (linear, polynomial, or exponential).

The industry-level diffusion of BT mainly relies on government subsidy, while the project-level diffusion requires efforts from general contractors. Thus, authors highly suggest local government to attach more deterrent clauses for diffusion performance when subsidizing construction enterprises, shifting part of pressure to them. Also, findings from this study may help local government issue guidelines for better BT diffusion to those subsidized enterprises.

For construction enterprises, the simulation results also show that the supply chain collaboration measures significantly influence BT technology diffusion. The profit-sharing strategy successfully binds the interests of GCEs with SEs to form a common goal in the BT diffusion process. Therefore, it is recommended that an appropriate division of additional profits between GCEs and SEs, generally not the optimum in practice, is needed to promote the diffusion performance. While how to balance the interests of different organizations in the technology promotion process requires further investigation. GCEs are also suggested to adjust the profit-sharing strategies dynamically to balance their profits and the social responsibility of technology promotion. Another noteworthy implication is that the degree of technology implementation plays an important role in promoting BT adoption. In real practice, the degree of implementation (q) would depend on various factors such as the information compatibility and interchangeability (Wang et al. 2020b), price volatility (Hamledari and Fischer 2021), organizational culture (Kar and Navin 2021; Khan et al. 2021), and stakeholders' involvement (Khan et al. 2021). Thus, construction firms are suggested to conduct explorative projects for blockchain research, development, and maintenance collaboratively to improve their BT adoption efficiency.

Conclusions

Owing to the revolutionary reform of mutual trust brought by blockchain technology, its diffusion mechanism, as a new-developing stream of research though, has attracted considerable attention from both practitioners and scholars worldwide. The primary objective of this paper was to explore the complicated relationships of BT diffusion among multiple stakeholders to deepen their understandings of how to enhance BT adoption. Through an in-depth investigation, some theoretical and practical contributions of this study can be concluded as follows:

1. This study for the first time introduces the evolutionary game theory and system dynamics into explaining the BT diffusion in the construction industry and further proposes an EG-SD model to identify and analyze the influencing factors, related stakeholders, spread channels, and interorganizational interactions in BT diffusion processes. It provides theoretical foundations for further investigation into BT adoption;
2. This study contributes to the body of knowledge by providing a quantitative perspective for understanding BT adoption behaviors among construction enterprises and revealing the diffusion mechanism of BT from a multilevel perspective; and
3. This study simulated the diffusion performance of BT under different strategies through data collection in China's construction industry. Based on simulation results, some important implications are drawn to provide practical help to governments for better policymaking and construction firms to promote BT adoption in practice. Also, this model can be modified and further applied in construction industries of countries similar to China.

Nevertheless, there are also some limitations in this study. For instance, the stakeholder network in this model is relatively simplified. Consideration of the upstream and downstream enterprises in a construction supply chain has not been involved. In practice, there are additional stakeholders who play important roles in the diffusion of BT, such as banks, insurance companies, and other financial institutions. Another limitation is the simplification of preference and unique characteristics of different subcontractors toward BT implementation. Different subcontractors hold different views toward adoption of advanced ICTs. Thus, in the future, a more complicated model will be needed to explore the path of BT diffusion more comprehensively, considering more stakeholders and their various preferences.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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