Risk-averse behavior and incentive policies: A new perspective on spatial-temporal traceability supervision in construction logistics supply chains

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ABSTRACT

Spatial-temporal decision support systems (STDS) serve as a crucial strategy for enhancing operational governance and mitigating risk within construction logistics. However, construction supply chains involve many opaque stakeholders, hindering whole industry compliance monitoring. This research formulates a tripartite evolutionary game model that scrutinizes the strategic interactions among government regulators, carriers, and contractors, thereby offering insights into the collaborative supervision outcomes shaped by these stakeholder engagements. Government regulators choose intelligent supervision incentives versus regular oversight. Carriers decide whether to invest in STDS or not. Contractors cooperate by enrolling or declining STDS. As key STDS investors, carriers’ decisions are investigated under varying risk preferences in an extension model. This examines how government incentives influence long-term intelligent supervision and risk aversion behavior emergence to improve safety and quality across construction supply chains. Our findings indicate that increased adverse events motivate government regulators to adopt STDS incentives for oversight, though carriers and contractors are not necessarily prompted to implement STDS themselves. Escalating risk aversion reduces carrier STDS adoption likelihood as they maintain basic services. Carriers perceiving contractor free riding as unfair competition also demotivates STDS rollout. Although larger subsidies initially raise STDS implementation probability, carriers become unwilling to adopt STDS over time even with greater subsidies. In summary, adverse events drive regulator but not necessarily carrier and contractor STDS adoption, while risk aversion, perceived fairness and changing subsidy effectiveness over time shape carrier decisions.

Keywords: Logistics, spatial-temporal traceability, risk-averse behavior, evolutionary game, construction supply chain

1. Introduction

Construction logistics supply chains comprise the network of organizations and the flow of materials, equipment, and labor that enable delivery to project sites (Irizarry, Karan, & Jalaei, 2013). However, significant challenges like delays, poor coordination, and lack of visibility plague construction logistics. As a high-risk, capital-intensive industry, construction faces sustainability issues including abandonment, quality deficits, and corruption. For instance, Country Garden, China’s largest private real estate developer, faces severe cash flow shortages in August 2023. An estimated 900,000 housing units are at risk of delayed completion or even forced suspension of projects1. Such abandonments underscore deficient oversight across fragmented construction supply chains. To avoid problems such as real estate cash flow disruptions and quality instability, intelligent governance measures regulating information, capital, and logistics across the entire construction supply chain are essential. These measures should mitigate abandonment risks, boost supply chain transparency, and enable thorough supervision of all construction logistics flows. It is well known that construction supply chains are intricate networks involving many stakeholders like suppliers, contractors, carriers, etc. Opaqueness in any part of the construction supply chain makes it difficult to monitor and control compliance and stability across

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1.  This preprint research paper has not been peer reviewed. Electronic copy available at: https://ssrn.com/abstract=4640460
the whole industry. Spatial-temporal decision support systems (STDS) offer a technological solution for improving operational governance and risk mitigation with real-time tracking, data analytics, and digital twin integration, enabling end-to-end visibility of information, capital, and logistics flows (Zhu, Cheng, Liu, Cheng, Zou, Xu, Wang, & Tao, 2023). The adoption of STDS can equip construction stakeholders with near real-time multidimensional insights, thereby enhancing planning, coordination, compliance, and reducing the risk of abandonment.

The efficacious advancement of STDS for holistic quality supervision in construction supply chains necessitates the active participation of a myriad of stakeholders. These include government regulators (GRs), carriers, and contractors. However, deciphering the intricate interdependencies and comprehending the impacts of the dynamic decisions made by these actors can pose significant challenges. The effective integration of STDS hinges on information sharing among three stakeholders, with government promotion measures playing a vital role by incentivizing STDS adoption. However, regulators are tasked with the delicate balancing act of weighing the costs of implementing such systems against the long-term benefits in terms of sustainability and oversight. Carriers often have to contend with risk aversion behaviors that may deter investment in STDS without adequate incentives. Nevertheless, their contribution is pivotal as they serve as key coordinators across multiple stages of construction projects. In order to successfully implement STDS, it is essential that contractors are willing to collaborate in the rollout led by carriers. They need to consider potential costs and the increased visibility across the supply chain that STDS offers. Understanding the complex tripartite dynamics between regulators, carriers and contractors is no mean feat. However, such exploration is critical to shed light on the optimal measures necessary for mainstreaming STDS. This will, in turn, contribute significantly towards improving quality control within construction supply chains, thereby ensuring more sustainable and efficient operations.

Recent literature has highlighted the significant influence of government incentives on the decision-making processes amongst various stakeholders in the green prefabricated building industry (Liu, Zuo, Pan, Ge, Chang, Feng, Fu, & Dong, 2022; Wang, Qin, & Zhou, 2021; Yuan, Li, Li, Li, Zhang, & Luo, 2022). This is particularly evident when viewed from a systemic perspective, where optimal decisions are not made in a vacuum. Instead, they are shaped by the interplay of interactions among different parties within the construction supply chain. In fact, it has been verified by Sluis and De Giovanni (2016) that carriers play an instrumental role in coordinating the construction supply chain. Despite these findings, there is a notable gap in the literature when it comes to characterizing and analyzing the new context where STDS-enabled intelligent supervision in construction logistics. The interactions among government regulators, carriers, and contractors in this novel scenario have yet to be adequately explored or understood. This framework facilitates a comprehensive understanding of the dynamics within the construction sector, enabling the development of strategies for enhanced safety and quality control. Another emerging trend in the literature has shed light on the fact that the risk aversion behavior of logistics service providers can significantly influence the optimal strategies of supply chain members (Heckmann, Comes, & Nickel, 2015). Given that logistics is a service industry often characterized by inherently minimal profit margins, the risk attitude towards investing in new
technologies becomes notably important. Interestingly, the impact of risk aversion has not been extensively studied in the context of construction logistics incentive policies, particularly through the lens of evolutionary game theory. To investigate how government incentive policies, carriers’ STDS investment, and contractors’ participation inclination influence decision-making to enhance intelligent supervision in construction supply chains, we need to answer the following research questions.

- What choices should be taken by carriers and contractors and is there an equilibrium point in the tripartite evolutionary game model with carriers’ risk neutrality where GRs boost STDS incentives?
- What effect does the risk aversion factor of carriers have on the game’s equilibrium?
- How can such a model explain changes in the three stakeholders’ strategic preferences, and what are the important impacting factors?

To provide comprehensive answers to these questions, we first propose a basic tripartite evolutionary game model (Model B) that incorporates GRs, risk-neutral carriers, and contractors. We then provide an extension model (Model R) that takes carriers’ risk aversion into account. The criteria for each evolutionary stable strategy (ESS) are determined, and sensitivity analyses are performed to elucidate the influence of key factors on strategic decision-making. In addition, we meticulously analyze optimal strategies, focusing on the dynamic interplay between these three critical stakeholders. As facilitators of STDS progression and public welfare advocates, GRs can implement incentive policies to encourage STDS adoption. Carriers, crucial actors overseeing transportation and warehousing, decide whether to invest in STDS. Contractors, accountable for execution, choose whether to participate in STDS rollout by carriers. Since carriers are key STDS investors, we examine tripartite decisions under varying risk preferences. Supply chain research has developed risk assessment methodologies including mean-variance, value-at-risk, and conditional value-at-risk models. This study primarily utilizes the mean-variance model to quantify risk (Chiu & Choi, 2016). To address these concerns, this study utilizes evolutionary game theory to model the time-dependent strategic progression of construction supply chain stakeholders adopting STDS. This theory, which employs a dynamic method, is well suited to multi-agent competitive and cooperative scenarios, such as supply chain analysis and transportation planning (Zhang, Yang, Zhao, Pratap, Wu, & Huang, 2023). Unlike classical game theory, evolutionary game theory does not assume perfect rationality or information. This more accurately simulates bounded rational decision-making in the real world. This theory is applied to examine long-term optimal STDS strategies for GRs, carriers, and contractors. These stakeholders interact within the construction supply chain, influencing individual payoffs. Over repeated games, they continuously refine strategies based on experience. We analyze this evolutionary learning process and emergent equilibrium strategies for STDS promotion.

We encapsulate our contributions in three key points. Firstly, we provide a theoretical analysis of a novel scenario examining the optimal strategies among decision-makers in construction logistics supply chains when STDS are employed to enhance building quality and reduce abandonment risks. Second, we incorporate risk preference behaviors of carriers into an evolutionary game model to assess the impacts of STDS adoption more comprehensively on construction stakeholder decisions. Third, we discuss three market development stages (i.e., initial, growth, and maturity) and key influencing factors for optimal decision-making among GRs,
carriers, and contractors. We also examine difficulties confronting long-term decision-making between these actors in achieving high-quality sustainable development of construction supply chains. Key findings reveal government regulators are motivated to employ spatial-temporal decision support systems (STDS) for intelligent supervision as adverse events like abandonment or poor-quality increase. However, carriers and contractors do not necessarily adopt STDS despite more frequent unfavorable events, due to elevated costs, minimal perceived short-term order effects, and uncertainty about benefits. Results also indicate punitive measures typically outperform rewards, and carrier perception of contractor free-riding as unfair competition also dampens STDS adoption. Increased risk aversion leads carriers to maintain basic services, thereby reducing STDS likelihood. However, regulators charged with public welfare will actively enhance supply chain transparency through STDS for oversight, regardless of carrier risk aversion.

The remainder of this paper is organized as follows. Section 2 reviews the most relevant prior research that forms the foundation for our study. In Section 3, we detail the model formulation and underlying assumptions. Section 4 presents the derivation of our baseline evolutionary game model without risk considerations. Section 5 extends this by incorporating a risk aversion factor into an enhanced model. Section 6 provides numerical analysis using the proposed models along with sensitivity analysis to offer key insights. Finally, we summarize the contributions of our work and propose potential avenues for future research based on the limitations and findings in Section 7.

2. Literature review

2.1. Construction logistics and supply chain

Construction projects are inherently complex undertakings (Amaral & Peças, 2021). As noted by Zhang, Kang and Zhong (2021), the construction supply chain involves the intricate flow of materials, equipment, and labor from various suppliers to the construction site. Effective management of these complex logistics flows is critical for ensuring on-time and on-budget delivery of construction projects (Said & El-Rayes, 2014). As discussed by Han, Yan and Piroozfar (2022), the high fragmentation of construction supply chains frequently impedes coordination efforts, which can subsequently lead to costly project delays and budget overruns. Balancing cost and quality in construction supply chains is complex. Certain studies utilize diverse algorithms to navigate this balance. Son and Khoi (2023) the mutation-crossover slime mold algorithm, aiming to equalize time, cost, quality, and work continuity in a particular construction project. Heo and Yang (2014) applies the adaptive boosting model to assess the financial risk associated with regional construction firms. Ekeskär and Rudberg (2022) propose an innovative coordinated logistics model, featuring enhanced collaboration between supply chain stakeholders. Indeed, as Wu, Yang, Xue, Zuo and Li (2022) in construction logistics and supply chain management argue, coordinated construction logistics can enhance productivity, cut costs, and foster safety and environmental sustainability. Various studies have advanced knowledge of coordinated logistics innovations in construction supply chains. Bortolini, Formoso and Viana (2019) introduce a logistics planning and control model integrating lean principles and building information modeling (BIM) to optimize site assembly logistics for prefabricated buildings. Yi, Zhen and Jin (2021) develop a Stackelberg game model to optimize government subsidies aimed at promoting sustainable construction logistics, accounting for decisions...
by government, suppliers, and customers. Hussein, Karam, Eltoukhy, Darko and Zayed (2023) investigate a holistic decision support system that integrates simulation, analysis, and optimization to boost modular construction logistics performance, identifying key decisions and generating near-optimal solutions. Greif, Stein and Flath (2020) present a digital twin concept focused on monitoring and decision support to enhance visibility and efficiency in construction logistics processes. Ding, Wang and Chan (2023) systematically review the literature on construction forward and reverse logistics flows, synthesizing opportunities to integrate bi-directional operations to enable circularity. In summary, current literature focuses on construction logistics management rather than leveraging intelligent monitoring to improve supply chain transparency and traceability. However, intelligent systems can enable real-time tracking of material flows for quality control. Research on construction logistics oversight using new technologies to enhance building quality and reduce abandonment risks is highly valuable. This requires supply chain-focused intelligent monitoring schemes to increase construction project transparency and controllability.

2.2. Spatial-temporal traceability

In recent years, spatial-temporal traceability technologies and digital twin technologies have gained increasing adoption in supply chain management. It is verified that by collecting and analyzing real-time data throughout the supply chain, these technologies can enable traceability and visibility of products across all stages from raw materials to final delivery (Zhu et al., 2023). RFID tags, GPS, sensors, and other Internet of Things (IoT) technologies provide the foundation for tracking the location and condition of physical items. Zhao, Shen, Yang, Wu, Zhang and Huang (2021) initially present a tracking solution framework for safety management, underpinned by IoT and digital twin technologies. They introduce an indoor safety tracking mechanism, designed to detect motionless behavior, and employ self-learning genetic positioning. Wang, Wang, Hu, Gong, Ren and Xiao (2020) adopt RFID and blockchain technology to achieve traceability and monitoring of concrete quality across the precast construction supply chain. Vilas-Boas, Rodrigues and Alberti (2022) suggest that distributed ledger technology is employed to foster transparency and trust among supply chain participants, while it contributes to security and facilitates the provision of logistics resources and services. Zhao, Zhong, Kuo, Fu and Huang (2021) indicate that through the implementation of physical hardware and spatial-temporal analytics, encompassing mobility and traceability analytics, high spatial-temporal correlation, albeit indirect tracing, can be achieved. Ivanov (2021) identifies the pivotal support that end-to-end visibility can provide in decision-making processes with the aid of various digital technologies. By leveraging these technologies, a comprehensive view of the supply chain can be obtained. Yan, Wang and Wu (2022) address a digital-twin enabled integrated optimization problem in flexible job shop scheduling and preventive maintenance, considering both machine and worker resources. Wang, Hu and Wan (2022) develop a digital twin system of ship construction processes to optimize pipeline arrangement and construction sequence. The existing body of research attests to the capacity of spatial-temporal traceability technologies to bolster transparency and responsiveness within supply chains. Despite their widespread integration in manufacturing supply chains, their utilization within the realm of construction logistics and supply chains remains comparatively sparse.
2.3. Evolutionary game

Evolutionary game theory operates under the premise that participants are not entirely rational and do not necessarily possess exhaustive market knowledge (Sandholm & Staudigl, 2018). This shift in perspective aligns more closely with real-world scenarios, providing a more nuanced understanding of strategic interactions. Numerous studies have shown the efficacy of evolutionary game theory in modeling various complex scenarios. Sun, Chen, Long and Yang (2023) construct a two-party evolutionary game model that integrates extended producer responsibility and green tax, structured around the parameters of government oversight and corporate recycling strategies. Johari and Hosseini-Motlagh (2022) employ a two-party evolutionary game theory model to examine a supply chain, comprising a single pharmaceutical manufacturer and a population of pharmaceutical distributors. These distributors have the option to either propose a credit time scheme or implement a pricing strategy, aimed at improving customer convenience. Peng and Wang (2023) integrates evolutionary game theory into a pricing framework, examining the dynamism of channel selection interactions between shipping entities and freight forwarders. Gu, Yu, Zhang, Yan and Wang (2023) expand upon the two-party evolutionary game model, incorporating three strategies for each player. This approach is utilized to investigate the strategic choices of bike-sharing companies regarding rebalancing strategies and third-party service providers’ cooperation strategies. The findings indicate that penalty mechanisms might not serve as effective deterrents against service quality deviations by logistics service providers. Mahmoodi (2020) explores the unified approach to pricing and inventory control for perishable products within competing supply chains, applying a nested evolutionary algorithm. Jamali, Rasti-Barzoki, Khosroshahi and Altmann (2022) use a one-population evolutionary game approach to demonstrate that cement and paper industries are more sensitive to subsidy allocation concerning electricity procurement strategies than the steel industry. Hosseini-Motlagh, Choi, Johari and Nouri-Harzvili (2022) analyze the instability of short-term coordination strategies, studying supply chain members’ evolutionary behaviors, and find that the share of coordination profit surplus significantly influences their evolutionary preference. da Silva Rocha and Salomão (2019) use a two-party evolutionary game model to study the interaction between corporate environmental compliance and policymaker enforcement in a pollution-trapped country, finding that excessive inspection costs can cause ineffective auditing and potentially force the few compliant firms to leave the country. Yuan et al. (2022) utilize a tripartite evolutionary game model to probe decision-making behaviors of key stakeholders in the prefabricated residential building industry, discovering that increased supervision costs can reduce the government’s regulatory enthusiasm. Despite prevalent research on evolutionary games, there remains a gap in studies examining the tripartite dynamic decision-making in construction supply chains with consideration of behavior-oriented carriers.

2.4. Risk averse behavior

As supply chain management becomes increasingly reliant on information technology, the costs and risks associated with new technology investments have become a major consideration for logistics supply chains (Kusi-Sarpong, Orji, Gupta, & Kunc, 2021). Logistics is a service industry with inherently low profit margins. Cohen and Kouvelis (2021) determine that supply chains with service operations expose firms to increased
bankruptcy risks, with decision-makers’ risk attitudes significantly affecting supply chain management outcomes. According to prospect theory, risk-averse individuals tend to overweigh losses compared to gains (Chai & Ngai, 2020). In logistics supply chains, this could lead to over-emphasis on risk mitigation at the expense of innovative investment opportunities (Hartwell, Macmillan, & Overend, 2021). Grubbström (2021) introduces a novel concept, termed ‘risk aversion leverage’, which assesses the dependence of absolute risk aversion on wealth. Zheng, Li and Song (2017) examine the contrasting pricing strategies of two competitive ocean carriers under demand uncertainty, specifically comparing a risk-neutral, high-capacity carrier with a risk-averse, limited-capacity one using the conditional value at risk (CVaR). Benioudakis, Burnetas and Ioannou (2021) present a model for Markovian make-to-order service system, specifically tailored for strategic, risk-averse customers. Zhang, Chen and Lin (2022) explore market targeting within a co-branding alliance, considering the impact of social influences and risk aversion. Bonzelet (2022) investigates how risk aversion affects retailer order quantities under buyback and real-option contracts, finding that risk averse retailers order more than under buyback contracts. Song, Tang, Zhao and Zhang (2021) study the decisions and strategies of a risk-averse supplier and an overconfident manufacturer, revealing that supplier risk aversion consistently reduces product supply and participant profit under the pull strategy. Despite the extensive consideration of decision-makers’ risk preferences in supply chain risk management research, literature specifically probing the risk attitudes of decision-makers within construction logistics firms remains relatively limited. Given the temporary and distinct nature of construction projects versus manufacturing supply chains, carriers may lean towards heightened risk aversion. Thus, quantifying risk preferences of decision-makers in construction logistics firms can yield crucial insights for crafting risk models.

In summary, previous studies confirm the applicability of spatial-temporal technology in improving logistics and supply chain transparency, and game theory in introducing incentive policies for the construction industry. However, existing literature does not analyze the optimal strategies among decision-makers in construction logistics supply chains when STDS are employed using game theoretic methods. Moreover, comprehensive consideration of carriers’ risk preference behaviors in an evolutionary game model is lacking, which limits holistic assessment of the impacts of STDS adoption on construction stakeholder decisions. Key influencing factors for optimal decision-making among government regulators, carriers, and contractors are not discussed considering different market development stages. To address this research gap, this study utilizes an evolutionary game model to analyze the dynamic decisions of the three stakeholders in adopting STDS under various scenarios. We consider not only government regulators’ incentive policies but also incorporate carriers’ risk aversion to reflect real-world situations. The results provide policymakers with suggested optimal strategies to incentivize STDS adoption under different market development levels. This research lays the foundation for the future expansion of intelligent supervision decisions in construction supply chains based on spatial-temporal technology.
3. The model

3.1. Model description

This study aims to examine the impacts of government incentive policies, carriers’ investment in STDS, and contractors’ willingness to join the STDS program on the decision-making process of improving intelligent supervision in the construction supply chain. Additionally, optimal strategies are meticulously examined with a specific emphasis on the dynamic decision-making processes among three critical stakeholders: GRs, carriers, and contractors. GRs are involved in the intelligent supervision in construction industry through making plans, issuing regulations, and formulating subsidy policies. Intelligent supervision utilizing advanced technologies such as IoT sensors and data analytics can help the construction industry actively identify and manage risks during the building process. As a result, intelligent supervision systems empower construction companies to avert issues before they occur and evade expensive mistakes later on. GRs intrinsically perceive that subsidy policies are crucial to encourage carriers to integrate advanced traceability technology into their projects. Despite this, GRs express uncertainty regarding the lack of willingness among carriers to invest in the development of comprehensive information traceability within the construction supply chain. Moreover, incorporating the STDS program is intuitively sensible, as contractors would shoulder all financial burdens in case of a construction defect. However, in reality, contractors may not be willing to fully disclose their building order information (Pan & Zhang, 2021). The alternative strategies for each player are shown in Fig. 1.

![Game relationships among the stakeholders.](https://ssrn.com/abstract=4640460)

To identify optimal policies and incentives for improving safety and quality management in engineering constructions, the analytical framework is developed to analyse the interactions and collective choices of three parties. Meanwhile, as carriers are the main investors in STDS, we also explore the tripartite decision-making under different risk preference scenarios of the carriers. Exclusively, this research addresses two focal points:
firstly, the development of the STDS for construction supply chain management (denoted as Model B), and second, the influences of risk aversion from carriers on optimal decisions (denoted as Model R). This section first introduces the baseline model, where the carrier is assumed to be risk neutral. As one of the major stakeholders in the entire game system, GRs facilitate the progression of STDS and uphold public welfare. They hold the discretion to either implement or forgo STDS incentive policies. Hence, the strategic decision space for GRs can be denoted as \( S_1 = \{\text{intelligent supervision, regular supervision}\} \). The adoption probability of STDS incentives for intelligent supervision by GRs is symbolized by \( x \) (where \( 0 \leq x \leq 1 \)), and the probability of regular supervision without STDS incentives is given as \((1 - x)\). Carriers, serving as the second participant in this system, bear responsibilities like warehousing and goods transportation. They have the choice to decide whether to execute STDS strategies. Thus, the carriers’ strategic decision space is illustrated as \( S_2 = \{\text{STDS, NSTDS}\} \). The chance of executing STDS policy is given by \( y \) (where \( 0 \leq y \leq 1 \)), while the likelihood of STDS policy not being executed is represented by \((1 - y)\). Contractors, on the other hand, are the primary parties responsible for completing engineering work and can choose whether or not to participate in the STDS plan. Therefore, contractors’ strategic decision space can be written as \( S_3 = \{\text{STDS enrolment, STDS declination}\} \). The likelihood of joining the STDS plan is given by \( z \) (where \( 0 \leq z \leq 1 \)), while the probability of declining the STDS plan is noted as \((1 - z)\). The alternative strategies available to each player are summarized in Table 1.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Strategies</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRs</td>
<td>Intelligent supervision</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Regular supervision</td>
<td>2</td>
</tr>
<tr>
<td>Carriers</td>
<td>STDS</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>NSTDS</td>
<td>2</td>
</tr>
<tr>
<td>Contractors</td>
<td>STDS enrolment</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>STDS declination</td>
<td>2</td>
</tr>
</tbody>
</table>

3.2. Model setup

This study assumes the three parties have bounded rationality and make decisions independently, given the information asymmetry. The mode posits the game system evolves dynamically, with players selecting singular strategies to optimize individual utility over time until equilibrium. The objective of stakeholders is utility maximization throughout the strategic process. Given information constraints, players’ initial strategy selections may be suboptimal. Despite this, through iterative gameplay, strategies evolve dynamically towards equilibrium as decisions are optimized over time. Besides, we assume that carriers hold two different risk preference attitudes when it comes to investing in STDS. The first is risk neutrality, where carriers have sufficient funds to bear the possibility of investment failure. The second is risk aversion, where carriers prefer guaranteed returns over the probabilities of higher rewards that involve potential losses. In other words, carriers may be hesitant to invest heavily in unproven technologies where the benefits are still uncertain.

To implement intelligent supervision in construction supply chain and prevent issues like abandoned projects and unsafe buildings, GRs highly value the implementation of the STDS program. When GRs provide
subsidies $A$ for carriers to implement STDS, they will gain benefits like reputation and benefits $B$ in terms of reputation or social credit. Undoubtedly, the subsidies alleviate carriers’ costs to better optimize their cost structure, so implementing STDS also brings the government incremental gains $\Delta B$ for better planning, and improved relationships. Clearly, only when all parties facilitate STDS can project risks be minimized. Therefore, if contractors choose to join the STDS plan, GRs will give contractors a certain reward, which denote as $R$. Notably, if carriers accept subsidies but do not implement STDS or misuse the funds, they must repay a proportion $\omega (0 \leq \omega \leq 1)$ of the subsidies. If issues like abandoned projects, delays, or poor quality occur, the government will suffer reputation loss $L_g$ plus governance cost $C_1$, and impose a fine $F_0$ on contractors. Moreover, we assume the probability of undesirable events occurring is $\gamma (0 \leq \gamma \leq 1)$.

The base operational cost for carriers without implementing the STDS strategy is denoted as $C_2$, and the additional cost (such as coordination, technology investment, and personnel training) for executing the STDS plan is set as $C_e$. The contractor incurs a base cost $C_3$ for purchasing basic services from the carrier, obtaining a base utility $U$. Additionally, if contractors adopt STDS by procuring the carriers’ STDS service and sharing its information, they bear additional costs of $C_a$ for the service and information sharing cost $C_e$. However, due to supply chain efficiency improvements and risk reduction from the technology upgrade, contractors gain incremental utility $\Delta U$. If issues like abandoned projects, delayed delivery, or poor quality occur, contractors suffer revenue loss $L_c$.

In the initial stage of implementing the STDS program, due to time effects, we assume the GRs’ subsidy costs for incentives exceed the value created, i.e., $A > B$. Plus, we assume the carriers’ extra costs of executing the STDS strategy are greater than contractors’ extra cost of procuring STDS services, i.e., $C_a > C_2$. Another hypothesis is that in the mid and late stages of STDS implementation, to increase the contractors’ enthusiasm for joining in STDS plan, GRs’ rewards for the contractor exceed the information sharing cost, $R > C_2$. Furthermore, when carriers execute the STDS strategy, the active promotion of STDS services can improve supply chain transparency and traceability. It is worth noting that contractors still gain some benefits even if they do not pay additional service upgrade fees or share information with carriers (Jamali et al., 2022). This free riding behavior of benefiting from others’ investments without contributing is defined as the free riding rate $\varphi$. This phenomenon occurs as enhanced traceability creates positive externalities, offering benefits even to those who are not directly participating in the system. Meanwhile, information asymmetry enables contractors to attain advantages without having to make substantial investments. For easy reference, we summarize all the notation in Table A.1 of online Appendix A.

### Table 2

The payoff matrix.

<table>
<thead>
<tr>
<th>Carriers</th>
<th>Contractors</th>
<th>GRs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intelligent supervision ($x$)</td>
<td>Regular supervision ($1 - x$)</td>
</tr>
<tr>
<td>STDS strategy ($y$)</td>
<td>STDS enrolment ($z$)</td>
<td>$f^{GR}_C; f^{GR}_C; f^{CO}_C$</td>
</tr>
<tr>
<td></td>
<td>STDS declination ($1 - z$)</td>
<td>$f^{GR}_C; f^{CO}_C; f^{IND}_C$</td>
</tr>
<tr>
<td>NSTDS strategy ($1 - y$)</td>
<td>STDS enrolment ($z$)</td>
<td>$f^{INE}_C; f^{INE}_C; f^{INE}_C$</td>
</tr>
<tr>
<td></td>
<td>STDS declination ($1 - z$)</td>
<td>$f^{IND}_C; f^{IND}_C; f^{IND}_C$</td>
</tr>
</tbody>
</table>
3.3. Model formulation

Based on the descriptions, a mixed strategy game matrix according to the interactions among GRs, carriers, and contractors, is shown in Table 2. Given that GRs have two possible strategies, we deliberate two distinct scenarios: one encompassing intelligent supervision, the other pertaining regular supervision.

3.3.1. Scenario with STDS incentives

In this scenario, GRs employ intelligent supervision to enhance the operational efficiency of the construction logistics sector. Such supervision is executed through the strategic application of STDS incentives for carriers. This approach is designed to encourage carriers to foster greater transparency in information dissemination within the industry.

(i) Upon carriers’ selection of the STDS strategy, contractors concurrently enrol in the STDS plan. The payoff functions of GRs, carriers, and contractors are expressed as follows, respectively:

\[ f^{ISE}_{GR} = B + \Delta B - A - \gamma C_1 + \gamma F_0 - \gamma L_g - R \]  
\[ f^{ISE}_{CA} = A - C_2 - C_e + C_3 + C_a \]  
\[ f^{ISE}_{CO} = U + \Delta U - \gamma F_0 - \gamma L_c - C_3 - C_a + R - C_s. \]

(ii) In situations where carriers adopt the STDS strategy, contractors refuse the STDS plan. The payoff functions of GRs, carriers, and contractors are obtained as follows, respectively:

\[ f^{ISE}_{GR} = B + \Delta B - A - C_1 + F_0 - L_g \]  
\[ f^{ISE}_{CA} = A - C_2 - C_e + C_3 \]  
\[ f^{ISE}_{CO} = U - F_0 - L_c - C_3 + \phi \Delta U. \]

(iii) When carriers employ the NSTDS strategy, and contractors decide to enrol in STDS plan. The payoff functions of GRs, carriers, and contractors are provided as follows, respectively:

\[ f^{INE}_{GR} = B - A - C_1 + F_0 - L_g + \omega A - R \]  
\[ f^{INE}_{CA} = A + C_3 - C_2 - \omega A \]  
\[ f^{INE}_{CO} = U - F_0 - L_c + R - C_3 - C_s. \]

(iv) When carriers choose the NSTDS strategy, and contractors choose to decline the STDS plan. The payoff functions of GRs, carriers, and contractors are given as follows, respectively:

\[ f^{INE}_{GR} = B - A - C_1 + F_0 - L_g + \omega A \]  
\[ f^{INE}_{CA} = A + C_3 - C_2 - \omega A \]  
\[ f^{INE}_{CO} = U - F_0 - L_c - C_3. \]

3.3.2. Scenario without STDS incentives

In this scenario, GRs institute a system of regular supervision, eschewing the use of STDS incentives typically employed to maintain the status quo among carriers. Such a methodology is implemented with the strategic intent of encouraging carriers to adhere to the current operational status, rather than motivating them through the prospect of STDS benefits. This tactic could potentially foster an environment where the carriers are motivated more by their inherent responsibility and roles, rather than external incentives.

(i) When carriers embracing the STDS strategy, contractors simultaneously enrol in the STDS plan. The payoff functions of GRs, carriers, and contractors are delineated as follows, respectively:

\[ f^{RSE}_{GR} = B + \Delta B - \gamma C_1 + \gamma F_0 - \gamma L_g \] 

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The first derivatives of

\[ f^{RSE}_{CA} = C_3 + C_a - C_2 - C_e \]  \hspace{1cm} (14)  
\[ f^{RSE}_{CD} = U + ΔU - γV_0 - γL_c - C_3 - C_a - C_e. \]  \hspace{1cm} (15) 

(ii) When carriers adopt the STDS strategy, and contractors decide to decline the STDS plan. The payoff functions of GRs, carriers, and contractors are defined as follows, respectively:

\[ f^{RSE}_{GR} = ΔB - C_1 + F_0 - L_g \]  \hspace{1cm} (16)  
\[ f^{RSE}_{CA} = C_3 - C_2 - C_e \]  \hspace{1cm} (17)  
\[ f^{RSE}_{CD} = U - F_0 - L_c - C_3 + φΔU. \]  \hspace{1cm} (18) 

(iii) When carriers apply the NSTDS strategy, and contractors simultaneously enrol in STDS plan. The payoff functions of GRs, carriers, and contractors are expressed as follows, respectively:

\[ f^{RNE}_{GR} = F_0 - C_1 - L_g \]  \hspace{1cm} (19)  
\[ f^{RNE}_{CA} = C_3 - C_2 \]  \hspace{1cm} (20)  
\[ f^{RNE}_{CD} = U - F_0 - L_c - C_3 - C_e. \]  \hspace{1cm} (21) 

(iv) When carriers follow the NSTDS strategy, contractors simultaneously reject the STDS plan. The payoff functions of GRs, carriers, and contractors are referred as follows, respectively:

\[ f^{RND}_{GR} = F_0 - C_1 - L_g \]  \hspace{1cm} (22)  
\[ f^{RND}_{CA} = C_3 - C_2 \]  \hspace{1cm} (23)  
\[ f^{RND}_{CD} = U - F_0 - L_c - C_3. \]  \hspace{1cm} (24) 

4. Model analysis

In this framework, the variables x, y, and z represent the likelihood of GRs, carriers, and contractors opting for differing strategies. Within the scope of the evolutionary game model, the expected payoffs of the participants, combined with the replicator dynamic equations, establish the basis for equilibrium points throughout the strategic evolution process. We label the anticipated payoffs of diverse players choosing different strategies as \( E_{ij} \). Additionally, \( E_i \) signifies the mean expected payoff for each player. The proofs of propositions can be found in online Appendix B.

4.1. Equilibrium analysis of evolutionary game model

The GRs’ expected payoff functions for selecting either the intelligent supervision strategy or the regular supervision strategy are designated as \( E_{11} \) and \( E_{12} \), respectively. Meanwhile, the function representing the average expected payoff is defined as \( \bar{E}_1 \). The functions are shown as follows:

\[ E_{11} = \frac{8(1 - \omega)A + (\Delta B - \omega A)y - Rz + (C_1 - F_0 + L_g)[(1 - γ)yz - 1]}{15} \]  \hspace{1cm} (25)  
\[ E_{12} = \frac{(C_1 - F_0 + L_g)[(1 - γ)yz - 1] + ΔBy}{16} \]  \hspace{1cm} (26)  
\[ \bar{E}_1 = \frac{[B - Rz - (1 - \omega)A]x - \omega Axy + (C_1 - F_0 + L_g)[(1 - γ)yz - 1] + ΔBy}{17}. \]  \hspace{1cm} (27) 

The corresponding replicator dynamics equation for GRs is articulated as:

\[ F(x) = \frac{dx}{dt} = x(x - 1)[(1 - \omega)A - B + \omega Ay + Rz]. \]  \hspace{1cm} (28)  

The first derivatives of x and G(y) can be derived as outlined below:

\[ \frac{dx}{dt} = (2x - 1)[(1 - \omega)A - B + \omega Ay + Rz]. \]  \hspace{1cm} (29)  
\[ G(y) = (1 - \omega)A - B + \omega Ay + Rz. \]  \hspace{1cm} (30)
Proposition 1. Through the course of strategic evolution, the possibility that GRs will choose intelligent supervision with STDS incentives inversely relates to the rewards destined for contractors inclined towards the STDS plan. On the contrary, the benefits accrued by GRs in advocating STDS incentives exhibit a positive correlation with the probability of GRs selecting the implementation of intelligent supervision strategy.

Proposition 1 elucidates the process through which GRs evaluate the adoption of incentive measures, typically incorporating elements such as costs and benefits into their decision-making calculus. In scenarios where the expenses associated with the implementation of intelligent regulation incentives become prohibitive, GRs, after a thorough cost-benefit analysis, might exhibit reluctance towards their execution. This is primarily because excessive costs would necessitate a surge in GRs’ expenditure. When the perceived reward costs linked to an intelligent regulation incentive surpass the projected benefits, GRs may conclude that the elevated financial outlay is unjustifiable. Conversely, if the deployment of the intelligent regulation incentive is expected to yield an abundance of economic, social, or environmental dividends, the propensity of GRs to operationalize the incentive measure amplifies. Specific examples of such benefits could include enhanced operational efficiency, improved stakeholder relations, or reduced environmental impact, thereby not only fostering a more sustainable operations model but also potentially leading to a more favorable public image and stronger regulatory compliance. Thus, the decision to implement incentive measures is a complex interplay of multiple factors, underscoring the need for GRs to navigate this balance carefully.

The expected payoff functions for carriers performing STDS strategy and NSTDS strategy are denoted as $E_{21}$ and $E_{22}$, respectively. Furthermore, the average expected payoff function is characterized as $E_2$. The functions are shown as follows:

\[
E_{21} = C_3 - C_2 - C_e + Ax + C_0z \\
E_{22} = C_3 - C_2 + (1 - \omega)Ax \\
E_2 = (y - 1)(C_3 - C_2 - Ax + \omega Ax) + y(C_3 - C_2 - C_e + Ax + C_0z). 
\]

The corresponding replicator dynamics equation for carriers is described as follows:

\[
F(y) = \frac{dy}{dt} = y(y - 1)(C_e - \omega Ax - C_0z). 
\]

The first derivative of $y$ and $J(z)$ are expressed respectively as follows:

\[
\frac{dy}{dt} = (2y - 1)(C_e - \omega Ax - C_0z) \\
J(z) = (C_e - \omega Ax - C_0z). 
\]

Proposition 2. As GRs augment subsidies for carriers implementing the STDS strategy, and as contractors incur additional costs when procuring the STDS service from carriers, there is a corresponding increase in the likelihood of carriers choosing the STDS strategy. On the other hand, an increase in carriers’ supplementary operational and supervisory costs associated with the execution of the STDS strategy results in a decreased probability of carriers opting for the STDS strategy.

Proposition 2 underscores the role of governmental subsidies in aiding carriers to mitigate the costs associated with the adoption of STDS strategies, thereby fostering a more proactive outlook towards their implementation. Further, carriers, propelled by the pursuit of profits, are incentivized to enhance service quality, thus attracting a broader customer base and augmenting revenue streams. Nonetheless, in instances
where the capital outlay for STDS services is exorbitant and challenging to recoup, carriers might opt to
preserve the existing situation. This could involve relying predominantly on their fundamental services to yield
profits, implying the adoption of NSTDS strategies, particularly if the projected future returns harbour
ambiguity. This dynamic elucidates the critical balance carriers must strike between pursuing innovative
strategies and managing operational costs. Governmental subsidies can tip this balance in favour of more
sustainable and forward-thinking strategies, highlighting the essential role of policy interventions in shaping
business strategies.

The expected payoff functions of contractors adopting STDS enrolment strategy and STDS declination
strategy are shown as $E_{31}$ and $E_{32}$, respectively. Besides, the average expected payoff function is described as
$E_3$. The functions are shown as follows:

$$E_{31} = U - F_0 - L_c - C_3 - C_s + [(1 - \gamma)(F_0 + L_c) + \Delta U - C_a]y + Rx$$  (37)
$$E_{32} = U - F_0 - L_c - C_3 + \phi \Delta Uy$$  (38)
$$E_3 = [(1 - \gamma)(F_0 + L_c) + (1 - \phi)\Delta U - C_a - C_s + Rx]z + U - F_0 - L_c - C_3 + \phi \Delta Uy.$$  (39)

The corresponding replicator dynamics equation for contractors is derived as follows:

$$F(z) = \frac{dz}{dt} = z(z - 1)[C_s - Rx + (C_a - F_0 - L_c - \Delta U + \phi \Delta U + \gamma F_0 + \gamma L_c) y].$$  (40)

The first derivative of $z$ is calculated as follows:

$$\frac{dF(z)}{dz} = (2z - 1)[C_s - Rx + (C_a - F_0 - L_c - \Delta U + \phi \Delta U + \gamma F_0 + \gamma L_c) y]$$  (41)

where $H(x) = C_s - Rx + (C_a - F_0 - L_c - \Delta U + \phi \Delta U + \gamma F_0 + \gamma L_c) y$.

**Proposition 3.** During evolution, the probability of contractors enlisting in the STDS initiative is
positively correlated with the incentives provided by GRs for participation, the punitive measures enforced by
the GRs upon contractors during unforeseen occurrences, and the potential profit losses contractors might
endure due to these events. Additionally, contractors’ propensity to engage in the STDS initiative increases if
the procurement of STDS services from carriers brings about supplementary benefits. However, the likelihood
of contractors enlisting in the STDS initiative exhibits an inverse relationship with the supplementary expenses
incurred when acquiring STDS services from carriers and the costs associated with data-sharing necessitated
for their participation in the program.

Proposition 3 underscores the importance of incentives and deterrents in influencing contractors’
participation in the STDS program. On one hand, rewards serve as an effective motivator, encouraging
contractors to actively join the STDS program by offsetting the associated participation costs. This could
include rebates, subsidies, or other forms of financial incentives that make enrolment in the program more
economically attractive. On the other hand, punitive measures act as a powerful deterrent, adding an additional
layer of risk for contractors who choose not to participate in the STDS program. In the event of an accident,
non-participating contractors could face penalties from GRs, and would be required to bear the full economic
loss resulting from the accident. This risk of financial loss makes participation in the STDS program a more
appealing option, as it can help to mitigate the cost of risk borne by contractors. Moreover, contractors might
be prepared to bear higher costs that come with procuring STDS services and sharing information if they
perceive that the benefits gained from the STDS program outweigh these costs. Participation in the program
can lead to increased utility in the form of enhanced safety protocols, better operational efficiency, or improved
reputation. However, there is a tipping point when costs related to the STDS services acquisition or information
sharing become excessively high, which could negatively impact contractors’ willingness to participate in the
program. If these costs become burdensome, they could inflate the contractors’ operational expenses, thereby
negatively impacting their financial stability. Therefore, it is crucial for contractors to thoroughly evaluate the
cost-effectiveness and potential return on investment before deciding to join the STDS program.

4.2. Analysis of evolutionary stable strategy (ESS)

The establishment of a three-party replicator dynamic system is shown as

\[ F(x) = \frac{dx}{dt} = x(x - 1)(1 - \omega)A - B + \omega Ay + Rx \]  (42)

\[ F(y) = \frac{dy}{dt} = y(y - 1)(C_e - \omega Ax - C_a) \]  (43)

\[ F(z) = \frac{dz}{dt} = z(z - 1)[C_s - Rz + (C_a - \gamma_0 - L_c - \Delta U + \varphi \Delta U + \gamma \gamma_0 + \gamma L_c)] \]  (44)

By setting the three equations to zero, an indication that the system has ceased to exist and has reached
equilibrium, solutions to this equation set yield eight distinct pure strategy equilibrium points, namely \( E_1 \)
\((0,0,0), E_2(1,0,0), E_3(0,1,0), E_4(0,0,1), E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), E_8(1,1,1) \). Additionally, our
analysis leads to the discovery of some mixed strategy points. Nonetheless, given that ESS are only present in
pure strategy points, the mixed strategy points are disregarded. The Jacobian matrix \( J_{ModelB} \) is illustrated below.

\[ J_{ModelB} = \begin{bmatrix} f_1 & f_2 & f_3 \\ f_4 & f_5 & f_6 \\ f_7 & f_8 & f_9 \end{bmatrix} \]  (45)

\[ \frac{\partial F(x)}{\partial x} = 2x - 1); \frac{\partial F(y)}{\partial y} = \omega Ax(1 - 1); \frac{\partial F(z)}{\partial z} = x(x - 1)R; \]
\[ \frac{\partial F(x)}{\partial x} = (1 - \omega)A - B + Rz + \omega Ay \); \frac{\partial F(y)}{\partial y} = \omega Ax(1 - 1); \frac{\partial F(z)}{\partial z} = x(x - 1)R; \]
\[ \frac{\partial F(y)}{\partial y} = (1 - 2\gamma)(C_a z - C_e + \omega Ax) \); \frac{\partial F(z)}{\partial z} = x(z - 1) \]
\[ \frac{\partial F(x)}{\partial x} = 2z - 1); \frac{\partial F(y)}{\partial y} = \gamma(1 - y)C_a; \frac{\partial F(z)}{\partial z} = \gamma(z - 1) \]
\[ \frac{\partial F(x)}{\partial x} = \gamma(1 - y)C_a; \frac{\partial F(y)}{\partial y} = \gamma(z - 1) \]
\[ \frac{\partial F(z)}{\partial z} = x(x - 1)R; \]

The Jacobi matrix’s eigenvalues corresponding to varying equilibrium points are computed as per
equation (45). Invoking Lyapunov’s indirect theorem, an equilibrium point is deemed asymptotically stable if
the real parts of all eigenvalues in its Jacobian matrix are negative (Wei, Cao, Chen, & Wei, 2022). On the
contrary, if the Jacobian matrix of an equilibrium point has at least one eigenvalue with a positive real part,
the equilibrium point is characterized as unstable. In instances where all the eigenvalues of the Jacobian matrix
possess negative real parts, barring those with zero real parts, the equilibrium point is deemed critical, with its
stability being indeterminable merely through the inspection of eigenvalue signs. The eigenvalues linked to
each pure strategy equilibrium point are encapsulated in Table 3.

**Table 3**
Local stability analysis of equilibrium points of Model B.

<table>
<thead>
<tr>
<th>Equilibrium points $E_i$</th>
<th>$\lambda_1$</th>
<th>$\lambda_2$</th>
<th>$\lambda_3$</th>
<th>Local stability results</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1(0,0,0)$</td>
<td>$-C_e$</td>
<td>$-C_S$</td>
<td>$B - (1 - \omega)A$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>$E_2(1,0,0)$</td>
<td>$\omega A - C_e$</td>
<td>$R - C_S$</td>
<td>$(1 - \omega)A - B$</td>
<td>Conditional ESS</td>
</tr>
<tr>
<td>$E_3(0,1,0)$</td>
<td>$C_e$</td>
<td>$B - A$</td>
<td>$(1 - \gamma)(F_0 + L_c) - C_S - C_a + (1 - \varphi)\Delta U$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>$E_4(0,0,1)$</td>
<td>$C_S$</td>
<td>$C_a - C_e$</td>
<td>$B - (1 - \omega)A - R$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>$E_5(1,1,0)$</td>
<td>$A - B$</td>
<td>$C_e - \omega A$</td>
<td>$(1 - \gamma)(F_0 + L_c) - C_S - C_a + R + (1 - \varphi)\Delta U$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>$E_6(1,0,1)$</td>
<td>$C_S - R$</td>
<td>$C_a - C_e + \omega A$</td>
<td>$(1 - \omega)A - B + R$</td>
<td>Unstable point</td>
</tr>
<tr>
<td>$E_7(0,1,1)$</td>
<td>$C_e - C_a$</td>
<td>$B - A - R$</td>
<td>$C_a + C_S - (1 - \varphi)\Delta U - (1 - \gamma)(F_0 + L_c)$</td>
<td>Conditional ESS</td>
</tr>
<tr>
<td>$E_8(1,1,1)$</td>
<td>$A - B + R$</td>
<td>$C_e - C_a - \omega A$</td>
<td>$C_a + C_S - R - (1 - \varphi)\Delta U - (1 - \gamma)(F_0 + L_c)$</td>
<td>Conditional ESS</td>
</tr>
</tbody>
</table>

**Proposition 4.** In the initial phase of the market, particularly under the conditions $A - B < \omega A < C_e$ and $R < C_S$, the sole ESS point is $E_2(1,0,0)$. At this point, GRs employ intelligent supervision incentives, but carriers adopt NSTDS strategies, and contractors abstain from participating in STDS plans.

Proposition 4 illustrates that for the strategic combination to remain stable at $E_2(1,0,0)$, two conditions must be met: (1) the funds that carriers are required to reimburse owing to either non-implementation of the STDS strategy or misuse of government subsidies need to be greater than the net benefits gained by GRs from promoting STDS incentives and the government subsidies for carriers, but less than the additional operational expenses borne by carriers due to the implementation of the STDS strategy; (2) the incentives offered by GRs to contractors for participating in the STDS program must be less than the costs that contractors incur for sharing information in the context of the STDS program. From a management perspective, this highlights the importance of ensuring that the potential losses carriers face from non-compliance or misuse of subsidies are perfectly balanced with the operational costs and benefits of the STDS strategy. Moreover, GRs must carefully evaluate the incentives offered to contractors, ensuring they do not exceed the contractors’ cost of information sharing within the STDS program. This intricate balancing act is critical to maintain strategic stability and encourage participation in STDS initiatives.

**Proposition 5.** During the middle phase of market evolution, particularly when the conditions $B > A + R$, $C_e < C_a + \omega A$ and $C_a + C_S < R + (1 - \varphi)\Delta U + (1 - \gamma)(F_0 + L_c)$ are met, the singular ESS point is $E_8(1,1,1)$.

At this juncture, GRs apply intelligent supervision strategy, carriers adopt STDS strategies, and contractors decide on enrolling in STDS plans.

Proposition 5 indicates that the strategy combination ESS becomes $E_8(1,1,1)$ when three conditions are simultaneously satisfied: (1) the advantages realized from GRs’ incentives exceed the combined value of subsidies to carriers and rewards to contractors; (2) the extra expense associated with carriers employing the STDS strategy is less than the aggregate of the supplementary cost of contractors buying the STDS service and the capital return; (3) the total additional cost for contractors to participate in the STDS program, including purchasing the STDS service and sharing information, is less than the sum of GRs’ rewards, benefits from free riding use of the STDS service, and the costs linked to undesirable events such as government fines and income losses. These conditions underscore the need for a careful balancing of incentives and costs across all players in the market. GRs’ incentives must outweigh the combination of subsidies and rewards, while carriers’ additional costs of implementing STDS should be lower than the combined additional costs and returns for...
contractors. Finally, contractors’ total extra costs should be less than the sum of GRs’ rewards, free riding benefits, and costs from undesirable incidents. This equilibrium is vital to maintain strategic stability and ensure active participation in the STDS initiatives.

Proposition 6. During the final stages of market progression, particularly when the conditions $C_e < C_a$, $B < A + R$ and $C_a + C_s < (1 - \varphi)\Delta U + (1 - \gamma)(F_0 + L_c)$ are met, the exclusive ESS point is $E_7(0,1,1)$. At this stage, GRs implement regular supervision without any STDS incentives, carriers enact STDS strategies, and contractors actively engage in STDS plans.

Proposition 6 establishes that the strategy profiles’ evolution towards $E_7(0,1,1)$ remains stable if and only if three conditions are concurrently met: (1) the marginal cost for carriers to adopt the STDS strategy is less than the additional cost for contractors to procure the STDS service; (2) the benefits derived from GRs’ incentives are less than the combined total of subsidies to carriers and rewards to contractors from GRs; (3) the aggregate incremental expense for contractors to participate in the STDS program, inclusive of the cost of purchasing STDS service and the cost of information sharing, is less than the sum of the benefits from free riding the STDS services and the cost savings from evading negative events such as government fines and income losses. This proposition underscores the critical need for cost-benefit analysis across the various stakeholders in the STDS ecosystem. Carriers should ensure their adoption costs are lower than the contractors’ procurement costs. Meanwhile, GRs should balance their incentives against the sum of carriers’ subsidies and contractors’ rewards. Contractors, on the other hand, should ensure their total incremental costs to join the STDS program are less than the sum of free riding benefits and cost savings from avoiding adverse effects.

These strategic considerations are not only vital for maintaining market stability, but also crucial for optimizing the operational efficiency of the STDS program, enhancing market competitiveness, and ultimately driving sustainable growth.

5. Model extension

For carriers, the adoption of the STDS strategy necessitates considerable investments in both human capital and material resources, which inherently introduces a degree of risk. Despite the notable benefits of STDS, the future profitability of this strategy remains uncertain, exacerbating the risks related to its implementation. In this section, we will delve into the carriers’ risk-averse behaviors and accordingly address the model. From the management science perspective, understanding these risks and how they influence carrier behavior is crucial. This insight can help shape strategic decisions, optimize investments, and potentially mitigate the uncertainties associated with STDS adoption. By examining these risk-averse behaviors, we can gain a deeper understanding of the dynamics at play and identify potential strategies to incentivize STDS adoption among carriers despite these challenges. This might involve balancing the risks and rewards more effectively or finding ways to reduce the investment required for STDS implementation. Ultimately, this could enhance the overall effectiveness and profitability of the STDS strategy in the carrier sector.

Within the domain of supply chain management research, various risk assessment methodologies are employed, as mentioned before, the well-established mean-variance model is employed for risk quantification.
The formulation of the mean-variance model is $U(\pi_i) = E(\pi_i) - \frac{\varepsilon}{2}(\pi_i) - \frac{\varepsilon}{2}(\pi_i)$, $V(\pi_i)$ signifies the anticipated return or advantage of the decision or portfolio. $V(\pi_i)$ is the variance of the decision, embodying the uncertainty of the decision outcome. $\varepsilon$ exemplifies the decision maker’s risk aversion coefficient, reflecting their risk preference. A larger $\varepsilon$ indicates a higher risk aversion, meaning the decision maker is inclined to relinquishing some expected return to diminish risk; a smaller $\varepsilon$ exhibits a stronger risk tolerance, implying that despite encountering higher risks, the decision maker prioritizes the pursuit of elevated expected returns. Incorporating carriers’ risk aversion behavior into consideration, the expected payoffs and average expected payoffs are formulated as

$$E_{21}^B = C - C_e + Ax + C_dz - \frac{\varepsilon}{2}(C - C_e)^2\sigma^2$$

$$E_{22}^B = C - C_e + (1 - \omega)Ax$$

$$E_{22}^R = (\gamma - 1)(C - C_e) - \omega Ax + y[C - C_e + Ax + C_dz - \frac{\varepsilon}{2}(C - C_e)^2\sigma^2].$$

Like Model B, we initiate the process by resolving the Jacobian matrix $J^R$. The solutions are given in the online Appendix C.

**Proposition 7.** Under the conditions where $A - B < \omega A < C_e + \frac{\varepsilon}{2}(C - C_e)^2\sigma^2$ and $R < C$, the sole ESS point $E_2(1, 0, 0)$. In this circumstance, GRs adopt the intelligent supervision, while carriers implement the NSTDS strategies, and contractors decline to participate in STDS programs.

Proposition 7 states that when the following two conditions are simultaneously satisfied, $E_2(1, 0, 0)$ will be the ESS point: (1) the amount of subsidy refund caused by the carriers’ failure to implement the STDS strategy or improper use of government subsidies is greater than the difference between the government subsidies and incentives obtained for promoting STDS, but less than the additional operating or regulatory costs incurred by the carrier in implementing the STDS strategy plus the gain from risk avoidance; (2) the reward for contractors joining the STDS program is less than the information sharing costs incurred by contractors for program participation. Compared to Proposition 4, Proposition 7 incorporates carriers’ risk aversion, which amplifies the additional operating costs of the STDS strategy. Proposition 7 validates that the conclusion from Proposition 4 still holds when risk aversion is considered, i.e., the extra operating costs of STDS persist even after accounting for risk aversion factors. This enhances the robustness of the conclusion from Proposition 4. Since risk aversion exacerbates carriers’ distaste for uncertainty in investment payback period, GRs should ramp up support for carriers as early as possible to reduce the cost burden of implementing the STDS strategy.

**Proposition 8.** In circumstances where $A + R < B$, $C_e + \frac{\varepsilon}{2}(C - C_e)^2\sigma^2 - \omega A < C_d$, and $C_a + C_s < R + (1 - \varphi)\Delta U + (1 - \gamma)(F_0 + L_c)$, the only ESS point converges to $E_0(1, 1, 1)$. It indicates that GRs implement intelligent supervision, carriers implement STDS strategies, and contractors participate in STDS plans.

Proposition 8 demonstrates that when the following three conditions are satisfied, $E_0(1, 1, 1)$ will be the ESS point: (1) GRs’ implementation of incentives yields benefits that surpass the costs incurred, which encompass subsidies provided to carriers and rewards offered to contractors; (2) the sum of the carriers’ additional costs of implementing the STDS strategy, gain from risk aversion, and amount of subsidy refund is
less than the contractors’ expense of purchasing STDS services; (3) the overall additional costs for contractors to join the STDS program are lower than the rewards for contractors, the utility derived from free riding, and the losses incurred due to undesirable events. Contrasting with Proposition 5, Proposition 8 introduces risk aversion components, leading to a contraction in the carriers’ profit margin. Despite the inclusion of risk aversion parameters, the outcome derived from Proposition 5 remains valid, as confirmed by Proposition 8. This solidifies the resilience of the findings from Proposition 5. Understanding that risk aversion dampens carriers’ willingness to implement STDS, it seems prudent for policymakers to consider a reduced subsidy return rate as a potential incentive for carriers to adopt the STDS strategy during the market expansion phase.

**Proposition 9.** When \( C_a + \frac{\varepsilon}{2}(C_3 - C_a)^2 \sigma^2 < C_a, B < A + R, \) and \( C_a + C_s < (1 - \varphi)\Delta U + (1 - \gamma)(F_0 + L_c) \), the sole ESS point is \( E_7(0,1,1) \) where GRs implement regular supervision, carriers execute STDS strategies, and contractors participate in STDS plans.

Proposition 9 indicates that \( E_7(0,1,1) \) will be the ESS point when the following three conditions are met:
(1) the sum of carriers’ additional costs of implementing the STDS strategy and gain from risk aversion is less than the contractors’ expense of purchasing STDS services; (2) the GRs’ gain from providing incentives is less than the cost they pay out; (3) contractors’ total additional costs of joining the STDS program are less than the sum of the free riding utility and losses caused by adverse events. In contrast to Proposition 6, Proposition 9 integrates elements of risk aversion, subsequently leading to an increase in the supplemental operational costs associated with the STDS strategy. The veracity of Proposition 6 is further consolidated by Proposition 9, even when the risk aversion parameters are accounted for. This strengthens the resilience of the initial conclusion. Recognizing the fact that risk aversion curtails the carriers’ propensity to employ STDS, it becomes imperative for GRs to implement alternative incentives for the carriers, especially in the absence of subsidies during the established market phase.

6. **Numerical study**

This section employs numerical simulation experiments to elucidate the dynamic evolution pathways of the system and investigate the impacts of various factors on the dynamic decision-making of game players. Specifically, utilizing MATLAB R2020a, we simulate the evolutionary trajectories under equilibrium based on the replicated dynamic equations of Model B and Model R we have established. The simulation results demonstrate that the system eventually stabilizes at a certain equilibrium point. In addition, by varying the values of individual factors, we analyze the changes in game players’ strategy selections under different parameter settings. The results indicate that properly adjusting certain critical parameters can facilitate game players in choosing cooperative strategies. This study provides quantitative analysis support for related policymaking and offers behavioral decision-making basis for achieving system optimization. Future studies could expand the parameter settings to examine evolutionary patterns under different scenarios and incorporate more model constraints to increase the practical significance of decision advice.

6.1. **Evolutionary convergence trajectory to ESS**
To validate the effectiveness of evolutionary stability analysis, this study specifies the parameter values of Model B at different developmental stages to meet corresponding equilibrium conditions. Specifically, the parameter values at the initial stage satisfy the conditions given in Proposition 4, those at the growth stage meet the conditions in Proposition 5, and the values at the mature stage fulfil the conditions in Proposition 6. Table 4 presents the detailed parameter settings of Model B at three stages.

Table 4
The parameter settings for each stage in Model B.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A</th>
<th>B</th>
<th>R</th>
<th>C_e</th>
<th>C_a</th>
<th>C_S</th>
<th>f_0</th>
<th>Delta U</th>
<th>L_C</th>
<th>gamma</th>
<th>phi</th>
<th>omega</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial stage</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>30</td>
<td>2</td>
<td>20</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Development stage</td>
<td>30</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Mature stage</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>10</td>
<td>30</td>
<td>10</td>
<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

As shown in Fig. 2, it is evident that over the course of temporal progression, the evolutionary trajectory of the initial stage gradually transitions towards ESS (1,0,0). Likewise, the evolutionary path of the developmental stage tends to converge towards ESS (1,1,1). Furthermore, the evolutionary trajectory of the mature stage progressively gravitates towards ESS (0,1,1).

![Fig. 2. Tripartite strategy evolutionary trajectories at ESS (1,0,0), ESS (1,1,1), ESS (0,1,1).](image)

Table 5 presents the values for different stages of Model R. The values in the initial stage satisfy the conditions in Proposition 7, the values in the development stage satisfy the conditions in Proposition 8, and the values in the mature stage satisfy the conditions in Proposition 9.

Table 5
The parameter settings for each stage in Model R.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A</th>
<th>B</th>
<th>R</th>
<th>C_e</th>
<th>C_a</th>
<th>C_S</th>
<th>f_0</th>
<th>Delta U</th>
<th>L_C</th>
<th>gamma</th>
<th>phi</th>
<th>omega</th>
<th>C_3</th>
<th>epsilon</th>
<th>sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial stage</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>30</td>
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<td>20</td>
<td>10</td>
<td>30</td>
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<td>0.2</td>
<td>0.2</td>
<td>0.8</td>
<td>5</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Development stage</td>
<td>30</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>5</td>
<td>10</td>
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<td>Mature stage</td>
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<td>5</td>
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<td>0.2</td>
<td>0.8</td>
<td>5</td>
<td>0.1</td>
<td>1</td>
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</tbody>
</table>

As delineated in Fig. 3, a distinct parallel can be drawn between Model R and Model B, particularly in the initial or nascent phase of the market where both models evolve towards the ESS (1,0,0). With the market’s transition into the developmental stage, the evolutionary trajectory incrementally converges towards the ESS (1,1,1). In the mature phase of the market, the evolutionary pathway invariably veers towards the ESS (0,1,1).
Drawing upon the evolutionary trajectories discerned in both Model B and Model R, it becomes apparent that fluctuations in specific variables possess the capacity to precipitate shifts in the course of evolution, thereby exerting an influence on the decision-making process of the involved actors. As a result, the ensuing section will undertake an exhaustive exploration of the ramifications that these variable fluctuations may have on the strategic choices made by stakeholders.

6.2. Sensitivity analysis of Model B and Model R

This section examines how different values of the same factors affect the decisions of the three stakeholders. Unless otherwise specified, it implies that the influence of the factors on the decision-making of the three stakeholders is consistent in both Model B and Model R.

6.2.1. The impact of the probability of undesirable events on tripartite game strategies

To illustrate the impact of the probability of undesirable events (γ factor) on the strategic choices of the three parties under ESS (0,1,1), we consider γ = (0.2,0.3,0.4). Fig. 4 presents the simulation results with varying values of γ. In Fig. 4 (a), as γ increases, the convergence rate of x towards 0 becomes slower, suggesting an increased likelihood of GRs implementing intelligent. Fig. 4 (b) and Fig. 4 (c) demonstrate that with higher γ values, both y and z converge towards 1 at a slower pace during the evolutionary process, particularly for z. This indicates a reduced willingness among carriers to execute STDS strategies and contractors to join the STDS plan, with contractors’ reluctance being more pronounced.

The given observations suggest that the increased likelihood of adverse events such as abandoned projects, late deliveries, and substandard construction quality motivates GRs to adopt intelligent supervision using STDS incentives. This aligns with intuitive understanding, given that such events have detrimental effects on the construction industry and the broader economy, leading to resource wastage, economic losses, and eroding
trust. Besides, STDS strategies offer a comprehensive, scientific approach to monitor and manage construction projects. They enable risk identification and enhance transparency, fostering collaboration and coordination among stakeholders. Therefore, with an aim to safeguard public interests, maintain market order, and ensure stability, GRs are more likely to employ STDS incentives as the risk of undesirable events escalates. However, an increased probability of adverse events does not necessarily prompt carriers and contractors to take proactive measures, such as the implementation of STDS strategies or participation in STDS programs.

This conclusion is counterintuitive and can be attributed to several factors. First, the additional costs tied to the implementation or participation in STDS strategies, such as technology investments and information sharing expenses, increase the operational burden on stakeholders, consequently reducing their profitability.

Second, stakeholders might believe that adverse events like late deliveries have a minimal impact on their short to medium-term order volume. Third, significant benefits are not perceived from adopting or participating in STDS strategies, leading to skepticism and a preference for persisting with their existing operational methods.

Thus, to enhance the confidence and participation of contractors and carriers in the STDS program, a multi-pronged approach by the government is essential. This could involve launching extensive promotional campaigns that elucidate the program’s objectives, rationale, and benefits, coupled with the establishment of dedicated support organizations or resource centers. These centers would offer services ranging from consultations to training and technical assistance, thereby helping contractors and carriers navigate potential challenges during the initial implementation phase of the STDS program.

6.2.2. The impact of free riding rate on tripartite game strategies

We conducted simulations to show how the probability of contractors’ free riding ($\varphi$ factor) affects the strategic decisions of the three stakeholders under ESS $(0,1,1)$. Fig. 5 depicts the simulation results with varied values of $\varphi = (0.2, 0.3, 0.4)$. In Fig. 5 (a), as the $\varphi$ value increases, the rate at which $x$ converges towards 0 over time slows down. This indicates that there is a higher likelihood of GRs implementing STDS incentive strategies. In Fig. 5 (b), as $\varphi$ value increases, the rate of $y$ convergence towards 1 during the evolutionary process decreases. This suggests a lower probability of carriers adopting STDS strategies. Fig. 5 (c) shows that as $\varphi$ increases, $z$ gradually decreases over time, indicating a declining probability of contractors participating in the STDS plan. It is worth noting that the acceleration of $z$ towards 1 is also slowed down with an increase in $\varphi$.

![Fig. 5. The impact of $\varphi$ on ESS $(0,1,1)$.](image)

The results suggest that carriers perceive contractor free riding as inequitable competition, given that contractors exploit the carriers’ services and benefits without assuming requisite obligations. A high incidence
of contractor free riding, exploiting carriers’ STDS services at no cost, erodes carriers’ economic incentive for
STDS implementation. This overextension of resources and ensuing resentment among carriers diminish their
willingness to deploy the STDS strategy. Participation in the STDS program escalates contractors’ operational
costs, including information sharing fees and purchasing STDS services. However, if a high likelihood of free
riding exists, contractors may perceive these costs as unjustifiable, since they can gain similar advantages
without program participation. The ability to access STDS services freely diminishes contractors’ motivation
to join the program, as they can reap benefits without any financial or obligatory commitments. This
phenomenon also elucidates why increased free riding probability correlates with contractors’ reluctance to
join the STDS program.

Overall, free riding in the construction industry has adverse impacts on suppliers, the market, and the
entire industry chain, because they undermine fair competition, reduce resource utilization efficiency, and
hinder innovation and development of the construction sector. Specifically, free riding enables some
construction companies to gain the same benefits without making equal efforts, which goes against the
principle of fair market competition. Also, such behaviors discourage industry players from investing in
innovations, slowing down the technological advancement of the whole industry. In addition, free riding leads
to inefficient allocation of resources like construction materials and equipment, wasting social resources to
some extent.

6.2.3. The impact of the subsidy return rate for carriers on tripartite game strategies

Let $\omega = (0.8, 0.9, 1)$ to show how the subsidy return rate ($\omega$ factor) of carriers affects the three parties’
ability to make strategic decisions under ESS $(0, 1, 1)$. Fig. 6 signifies the simulation results with varying
settings of $\omega$. Fig. 6 (a) depicts that as $\omega$ increases, the rate at which $x$ converges to 1 accelerates during the
initial phase. However, as time progresses, a larger $\omega$ accelerates the rate at which $x$ tends towards 0. In other
words, in the initial stages, a higher $\omega$ increases the likelihood of the government implementing STDS
incentives, but over time, this probability decreases. Fig. 6 (b) and Fig. 6 (c) reveal that an increasing of $\omega$
leads to an expedited convergence of $y$ and $z$ towards 1. This indicates a heightened probability of carriers
adhering to STDS strategies and contractors participating in the STDS program.

![Fig. 6. The impact of $\omega$ on ESS $(0,1,1)$.](image)

GRs will only mandate this refund of granted subsidies (in the proportion $\omega$) if the carrier misuses or
deceitfully acquires these subsidies. In essence, a larger $\omega$ implies a greater deviation by carriers from GRs’
expectations and objectives. Carriers’ misconduct dampens GRs’ motivation to provide incentives. This also
sheds light on why even though the government always intends to provide incentives, it still reduces the
probability of providing incentives in later periods. Because a relatively high $\omega$ is an effective restraint and penalty mechanism. When providing incentives, the government can force the carrier to implement the STDS strategy by setting a higher $\omega$, to ensure that the subsidy funds are used correctly. This setting increases the reputation or credibility loss for carriers if they do not implement the STDS strategy or improperly use the government subsidies, thereby avoiding carriers’ behavior of taking money without doing work or doing the wrong thing. This also explains why the higher $\omega$ is, the higher the probability that the carrier will implement the STDS strategy. Under this circumstance, the contractors’ tendency to join the STDS program is likely caused by GRs’ deterrence.

The behavior of taking money without doing the work not only seriously dampens the government’s enthusiasm but is also a waste of societal resources. Therefore, the government should implement reasonable measures to stop businesses from behaving opportunistically, such as setting a reasonable subsidy repayment rate or imposing strict penalty mechanisms for corporate breaches of contract. Simply obtaining subsidies without fulfilling one’s duties is detrimental to public trust in both enterprise and government. The government has a responsibility to allocate subsidies judiciously and ensure accountability from recipients. Rather than being an open invitation for exploitation, subsidies should catalyze societal goods through fair rigor.

6.2.4. The impact of the subsidies supported by GRs on tripartite game strategies

To depict the impact of the subsidies supported by GRs to carriers with STDS strategy ($A$ factor) on the choice of strategy for the three parties under ESS (0,1,1), let $A = (30,40,50)$. Fig. 7 signifies the simulation results with varying settings of $A$. In the case of Fig. 7 (a), as $A$ increases, the convergence rate of $x$ to 1 is initially very slow during the evolutionary process, indicating a decrease in the probability of government incentive implementation. However, over time, the rate of convergence of $x$ to 0 gradually slows down, suggesting that GRs are willing to implement incentives, even if it requires high subsidies, to prevent unexpected events from occurring. Fig. 7 (b) shows that as $A$ increases, the convergence rate of $y$ to 1 initially increases, but over time, $y$ instead converges to 0. The same trend is observed for $z$, as shown in Fig. 7 (c).

Fig. 7. The impact of $A$ on ESS (0,1,1).

From a cost perspective, providing subsidies means GRs need to allocate funds from fiscal budgets to support specific activities, industries, or entities. This increases government spending and stresses fiscal conditions, potentially leading to budget deficits or increased debt. Moreover, such economic outlays may limit GRs’ investment and spending in other areas, thus impacting their ability to fulfill other responsibilities. Furthermore, government subsidies are investments with uncertain returns, so the larger the subsidy amounts, the lower the probability GRs will provide incentives. Intuitively, GRs’ subsidies alleviate carriers’ burden of
implementing STDS strategies. Interestingly though, in the earliest stages, the larger the subsidies, the higher the probability carriers implement STDS strategies. However, over time, even with greater subsidies, carriers become unwilling to implement STDS strategies. This is because long-term STDS implementation requires undertaking continuous expenses, such as developing new technologies, purchasing new equipment, training new employees, etc. Although GRs provide substantial subsidies, they are negligible compared to implementation costs. Additionally, government subsidies do not adjust with market changes, and many are one-time. Therefore, facing multiple risks and uncertainties, even with greater subsidies, carriers do not favor implementing STDS strategies.

The analysis indicates that governments need to strike a balance between subsidies and costs to ensure fiscal sustainability and evaluate the effectiveness of subsidies in achieving intended goals. In addition, governments need to recognize that subsidies alone cannot motivate businesses, and other actions are needed, such as developing policies and regulations that facilitate business growth, providing training and technical support, etc. In other words, to incentivize businesses, comprehensive policies and actions should be taken so that subsidies work in conjunction with other measures. Rather than relying solely on subsidies, a combination of incentives, regulatory frameworks, and capacity building initiatives is required. This allows subsidies to be one component in a larger strategy to align business interests with public interests. With a more systems-based approach, governments can foster sustainable and socially conscious business practices.

6.2.5. The impact of penalties on contractors on tripartite game strategies

Let $F_0 = (20, 50, 80)$ represents the effect of government penalties on contractors in the event of accidents on the strategic decision-making of the three stakeholders under ESS $(0,1,1)$. Fig. 8 illustrates the simulation results for different settings of $F_0$. Fig. 8 (a) shows that as $F_0$ increases, the convergence rate of $x$ to 0 becomes faster, indicating a decrease in the probability of GRs implementing incentives. Fig. 8 (b) and Fig. 8 (c) demonstrate that as $F_0$ increases, the convergence rate of $y$ and $z$ to 1 accelerates. This effect is particularly pronounced for variable $z$, indicating that both carriers and contractors are more inclined to take proactive actions, with contractors exhibiting a more noticeable proactive attitude.

![Fig. 8. The impact of $F_0$ on ESS $(0,1,1)$.](image)

When delays, abandoned projects or quality issues arise, GRs impose fines on contractors. In a sense, the increase in penalty amounts implies more frequent occurrences or greater severity of accidents. GRs’ original intention is to encourage contractors to take proactive actions to ensure project safety and prevent accidents through incentives. However, the inevitability or uncontrollability of accidents makes GRs feel their expectations and trust have been betrayed. Therefore, in such cases, the GRs may hold negative views towards
contractors and adopt a reserved attitude towards incentives, which explains why more penalties lead to lower probability of GRs providing incentives. Once accidents in the construction industry occur, huge economic losses are bound to happen. If contractors also face government punishments like hefty fines or disqualification from future projects, they will bear tremendous economic burden. Carriers’ income will also be directly impacted. Thus, fines can cause economic damage to stakeholders, thereby serving as deterrence and education. This explains why stricter punishments lead to more positive attitudes from contractors and carriers.

The analysis above suggests that punishment is often more effective than rewards as a measure. Strict punitive measures can, to some extent, compel stakeholders to take positive actions. Therefore, governments should make reasonable use of punitive measures. However, relying too heavily on punishment risks creating an adversarial dynamic between regulators and the industry. Fines are a stick, not a carrot. While consequences for negligence are appropriate, they should be balanced with incentives for progress. The goal should be promoting real safety outcomes through a collaborative spirit of continuous improvement, not just penalizing failures after they occur. Governments must strike a nuanced balance, neither allowing impunity through overly lax oversight, nor stifling progress through draconian regulations. Open communication channels can help align interests and foster a proactive culture of safety rooted in shared accountability.

6.2.6. The impact of the risk averse coefficient on tripartite game strategies in Model R

To illustrate the impact of carriers’ risk aversion ($\epsilon$ factor) on the strategic choices of the three parties under ESS (0,1,1), we consider $\epsilon = (0.1, 0.2, 0.3)$. Fig. 9 shows the simulation results as $\epsilon$ varies. In Fig. 9 (a), as the risk aversion coefficient $\epsilon$ increases, the speed at which $x$ converges to 0 slows down, indicating that GRs’ likelihood of implementing STDS incentives increases. Fig. 9 (b) and 9 (c) show that during the evolution, as the risk aversion coefficient $\epsilon$ increases, the convergence speed of $y$ and $z$ to 1 slows down. This indicates that carriers’ willingness to implement STDS strategies weakens, and contractors’ willingness to join STDS programs decreases.

The magnitude of the risk aversion coefficient represents the degree of risk aversion exhibited by the decision maker. A larger risk aversion coefficient indicates greater risk aversion, meaning carriers are more cautious and prone to minimize potential losses under possible profit forfeiture. Conversely, a smaller risk aversion coefficient indicates lower risk aversion, suggesting carriers are more inclined to accept higher uncertainty and potential losses in pursuit of greater potential returns. From a short-term perspective, executing STDS strategies represents a risky decision for carriers when returns are uncertain. Therefore, when the risk aversion coefficient increases, i.e., carriers are unwilling to undertake substantial risks, they become more
inclined to maintain operations by selling basic services. This explains the observed decrease in the probability of carriers implementing STDS strategies. However, as institutions tasked with protecting public safety and promoting social welfare, GRs have the authority and responsibility to maximize societal interests. Hence, even if carriers are risk averse and thus reluctant to implement STDS strategies, GRs will still take proactive measures to enhance transparency in construction logistics supply chain for effective oversight.

The analysis above shows that carriers’ risk aversion psychology influences their strategy choices and has spillover effects on other stakeholders. Therefore, the government should build carriers’ confidence in STDS strategies through appropriate measures and reduce the risks of implementing STDS through relevant policies. However, risk is inherent to innovation. Rather than eliminate risk entirely, the goal should be developing collaborative frameworks that prudently calibrate and share risk. For instance, GRs can provide technical assistance and temporary subsidies to ease the STDS transition, while emphasizing long-term efficiency and competitiveness gains. Additionally, partial adoption of STDS components can serve as incremental steps to validate benefits and build trust. With constructive cooperation between regulators and enterprises, risk-taking can become an opportunity.

7. Conclusion

SDTS strategy can be instrumental in empowering construction logistics to monitor real-time logistics dynamics, preempt risks, and guarantee the quality and safety of construction. The behavioral choices of supply chain members can have an effect on the deployment of STDS based intelligent supervision in construction logistics. Yet, the decision to adopt STDS strategy and its long-term impact on the strategic decisions among construction logistics members have not been thoroughly investigated. In this study, we construct an evolutionary game-theoretic model to explore the dynamic strategic interactions among GRs, carriers, and contractors within the construction logistics industry. We scrutinize a scenario where long-term STDS strategies are responsive to the optimal decision generated from the tripartite interaction. Subsequently, we investigate the new equilibrium points of the dynamic evolutionary system under circumstances characterized by the risk-averse behavior of carriers. More precisely, we start with Model B, a basic tripartite evolutionary game model premised on carriers’ neutrality towards investment risk. Following that, we create Model R, an extended tripartite evolutionary game model that incorporates customers’ risk aversion. We then identify the equilibrium points for both models and derive the conditions under which ESS exists. Numerical simulations are conducted to examine the impact of various factors on the tripartite strategy employed by the stakeholders in the construction logistics supply chain. Drawing upon the equilibrium points and the sensitivity analysis conducted for both models, several substantive conclusions are derived as follows.

We find that, the increased likelihood of adverse events, such as project abandonment, late deliveries, and subpar construction quality, propels GRs to adopt intelligent supervision through STDS incentives. However, paradoxically, the escalation of such adverse events does not necessarily incite the adoption of STDS strategies from carriers and contractors. This reluctance can be traced back to factors including increased operational costs, perceived minimal impact on short-to-medium term order volume, and scepticism regarding the benefits of STDS strategies. In addition, the higher the subsidy return rate, the more likely carriers will properly...
implement the STDS strategy. This increases reputation and credibility costs for misusing funds, avoiding behaviors like taking subsidies without implementing STDS or improperly using the fund. Furthermore, the results show that punishment is often more effective than rewards. However, early on, larger subsidies increase the likelihood of carriers implementing STDS strategies. Over time, though, carriers become unwilling to implement STDS even with greater subsidies. Imposing punishments like fines or disqualification from future projects creates economic burden for contractors. With severe penalties in place, both carriers and contractors would implement STDS strategies.

The results also reveal that carriers regard contractor free riding, which involves exploiting carrier services without assuming necessary obligations, as unfair competition. This demotivates carriers from implementing the STDS strategy. For contractors, the ability to freely access STDS services without financial or obligatory commitments reduces their motivation to participate in the program. GRs, in their role of safeguarding public interests, typically advocate for market autonomy as the industry matures, explaining the initial increase and subsequent decrease in the likelihood of introducing STDS incentives. Finally, the risk aversion coefficient represents the degree of risk aversion among carriers, with a higher coefficient indicating greater caution and a lower one suggesting more risk tolerance. Increased risk aversion leads carriers to maintain basic services, reducing the likelihood of adopting STDS strategies. Yet government regulators, tasked with protecting public safety and welfare, will proactively enhance transparency in the construction logistics supply chain for effective oversight, regardless of carriers’ risk aversion.

Our findings provide useful managerial insights. First, promoting contractors and carriers’ trust and participation in STDS necessitates a multi-faceted governance approach, potentially involving promotional campaigns and support structures. Additionally, opportunistic behaviors like obtaining subsidies without fulfilling obligations not only dampen government enthusiasm but also waste societal resources. Thus, the government should implement accountability measures like reasonable subsidy repayment rates or strict penalties to maintain public trust, using subsidies to catalyze societal good rather than exploitation. Further, the construction industry should curb free-riding to maintain fair market competition, with the government establishing laws clearly defining and penalizing such activities to increase violation costs. Encouraging industry associations and public participation in supervision, establishing reporting channels, and intensifying exposure efforts are also pivotal. Moreover, carriers’ risk aversion affects strategy choices and other stakeholders. Governments should build carriers’ confidence in STDS through appropriate measures and risk reduction policies, calibrated not to eliminate but share risk via collaboration. Measures could include technical assistance, temporary subsidies, and incremental STDS adoption to facilitate risk-taking through regulator-enterprise cooperation.

To conclude this paper, some potential future research directions are discussed. First, we assume three major stakeholders in the building business in our scenario. However, sometimes the attitude and decision of the end consumer is also significant. Consumers should be considered for a more detailed behavioral analysis of stakeholders in building quality safety and risk early warning. Future research into four-party evolutionary game models and equilibrium point analysis would be more extensive, though mathematically more difficult.
Furthermore, in the construction supply chain, the economic activities of carriers and contractors, as well as the acquisition of information, are inextricably linked. Future studies might be interesting in examining collusive behaviors between carriers and contractors when obtaining government subsidies. Furthermore, an extensive theoretical study such as competition and coordination in construction logistics is also another promising research direction.

References


Notes