Emergency response strategy and simulation analysis considering inter-government coordination and information sharing

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Abstract

This paper investigates the application of game-theoretic approaches to engineering management problems, focusing on multi-agent optimization in complex systems. We develop a mathematical framework that combines Nash equilibrium concepts with optimization theory to model decision-making processes in distributed engineering environments. Our computational experiments demonstrate significant improvements in system efficiency and resource allocation. The proposed methodology provides both theoretical foundations and practical implementation strategies for modern engineering management challenges.

Keywords: Game theory, Multi-agent systems, Engineering management, Optimization, Nash equilibrium

1. Introduction

Construction enterprises, characterized by project-based production, capital intensity, and geographical dispersion(A.S B et al. 2021), recently face three aspects of pressures that threaten their long-term viability. First, traditional operational challenges have intensified, including escalating material costs and acute skilled labor shortages (ref). Second, digital transformation imperatives require fundamental shifts from conventional project management to integrated digital ecosystems, demanding substantial investments in BIM, AI, and IoT technologies across fragmented project networks(Z. -S. Chen et al. 2024). Third, sustainability mandates pressure enterprises to adopt sustainable operations while maintaining strict project timelines and budget constraints(İbrahim

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Yitmen 2007). These challenges exhibit compounding effects: labor shortages accelerate automation needs(Zijun Z et al. 2025), sustainability requirements demand both technological upgrades and workforce retraining, while digital transformation costs strain already tight project margins.

In this context, developing sustainable competitive advantages becomes critical for construction enterprises' survival and growth. Sustainable competitive advantage denotes an enterprise's capacity to sustain superior performance relative to competitors through the deployment of unique resources and capabilities that exhibit temporal persistence and inimitability(6). Characterized by deep embeddedness in organizational capabilities, path dependency, and resistance to imitation(7), sustainable competitive advantages have become core strategic resources enabling construction enterprises to navigate structural industry transformations (e.g. XX) and cyclical market shocks (e.g. XX) (REF). Consequently, construction enterprises must construct sustainable competitive advantages; failure to do so will expose them to severe risk of marginalization amid intensifying market competition.

Existing Architecture, Engineering, and Construction (AEC) literature has examined construction enterprises' competitive strategies from perspectives including political relationships, social responsibility, Enterprise Resource Planning (ERP), digital transformation, and blockchain(H. Li, Y. Chang et al. 2024; Ram , J. et al. 2014S. Wang et al. 2025A. Kumar et al. 2025). However, existing research exhibits two significant limitations.

First, the majority of AEC literature focuses predominantly on traditional competitive advantages rather than sustainable competitive advantages, yet these concepts differ fundamentally. Traditional competitive advantages typically stem from external market opportunities(ref) or temporary resource allocations (ref). This exhibits replicability and temporal constraints that render them susceptible to displacement through competitor imitation or technological catch-up. They primarily emphasize static resource allocation efficiency. Rather, sustainable competitive advantages originate from enterprises' internal unique resource bundles and capability systems, possessing VRIN characteristics—valuable, rare, inimitable, and non-substitutable—enabling enterprises to generate superior profits over extended periods while resisting competitive pressures(ref). Moreover, sustainable competitive advantages emphasize the construction and evolution of dynamic capabilities—enterprises' capacity to sense environmental changes, seize market opportunities, and reconfigure resources. This fundamental distinction means that insights from traditional competitive advantage research may inadequately guide construction enterprises seeking long-term resilience and performance.

Second, previous studies have predominantly analyzed the impact of individual factors on competitive advantage This literature fails to capture the complex, systemic nature of success in the construction industry. Competitive advantage in this sector rarely stems from a single "silver bullet"; rather, it emerges from the synergistic interplay among an enterprise's strategy, its environment, and its internal resources (Ref). This reality exposes the limitations of traditional linear models and necessitates a theoretical lens that can explain how different combinations of conditions lead to superior performance. The configurational school of strategic management provides such a lens, positing that an enterprise's advantage derives from the holistic fit of these multidimensional elements(DESS G G et al. 1993MILLER D 1996SHORT J C et al. 2008). By examining these combinations, or configurations, it becomes possible to understand why enterprises with similar resources in the same environment can exhibit vastly different outcomes. Therefore, this study adopts a configurational perspective to ask its first key question: From the multi-dimensional perspective of strategy, environment, and resources, what are the effective configurations for building a sustainable competitive advantage in the construction industry?

While sustainable competitive advantage determines construction enterprises' market position and profitability, organizational resilience ensures their survival and stability in turbulent environments. Organizational resilience refers to an enterprise's potential ability to anticipate, avoid, and respond to environmental shocks (especially crisis events)(SAJKO M et al. 2021), with its core characteristic being the stability and reliability of maintaining competitive advantage and business performance under crisis impacts. Unlike competitive advantage which focuses on exceptional operational performance, organizational resilience focuses on stable operational performance. Existing research demonstrates that organizationally resilient construction enterprises can better absorb shocks, maintain operational continuity, and recover more quickly from disruptions. For example, during the COVID-19 pandemic, construction enterprises with strong organizational resilience maintained project continuity through flexible resource reallocation and adaptive management practices, while less resilient competitors faced project suspensions and financial distress(Rufaidah A ,Amani Q B 2023). This divergence in crisis responses underscores the critical importance of organizational resilience in sustaining competitive advantage over time.

Existing research largely focuses separately on the singular dimensions of either organizational resilience or competitive advantage. For instance, Diamantopoulos et al. (2006) concentrated on functional resilience rather than systemic resilience(Diamantopoulos A et al. 2006); Burnard and Bhamra (2011), Williams et al. (2017) and other scholars provided organizational resilience frameworks(Burnard K et al. 2017), However, existing research largely focuses on either organizational resilience or competitive advantage as separate dimensions. The crucial interplay between them, particularly how resilience contributes to the sustainability of an advantage, remains underexplored. A truly sustainable advantage must be a resilient one; otherwise, it is merely a temporary high-performance state vulnerable to the next crisis.

The Resource-Based View (RBV) provides a theoretical foundation for understanding this relationship, positing that enterprises' sustained competitive advantage stems primarily from internal rather than external factors. From this perspective, organizational resilience capability can be viewed as a strategic internal resource that enhances sustainable competitive advantage. Organizational resilience enables enterprises to withstand pressure, continuously innovate, and rapidly adapt to changes, thereby protecting and reinforcing their competitive advantages during environmental turbulence. In the context of construction enterprises facing increasingly complex and volatile market environments characterized by supply chain disruptions, regulatory changes, and economic fluctuations, the interplay between organizational resilience and competitive advantage becomes particularly critical. Solely pursuing high competitive advantage without resilience leaves enterprises vulnerable to crisis-induced performance collapse, while focusing exclusively on resilience without competitive advantage results in stable mediocrity. Construction enterprises must therefore develop strategic configurations that simultaneously cultivate both organizational resilience and sustainable competitive advantage—enabling them to not only excel in stable periods but also maintain stability during crisis events and capitalize on post-crisis opportunities. Therefore, this study presents its second research question: How can enterprises simultaneously maintain organizational resilience while achieving high competitive advantage?

To address these two research questions, this study employs Time-Series Qualitative Comparative Analysis (TSQCA)(SAETRE A S et al. 2021). This configurational method was selected because traditional regression analysis, which focuses on the net effects of isolated variables, is ill-suited to explain how competitive advantage and resilience emerge from the complex, synergistic interplay of an enterprise's strategy, environment, and resources. TSQCA, in contrast, is designed to identify the multiple, distinct combinations of conditions that produce an outcome. By embracing the principles of conjunctural causation (outcomes stem from combinations of factors) and equifinality (multiple pathways lead to success), this approach provides a powerful tool for uncovering the different "recipes for success." In this study, TSQCA is used to determine which configurations of strategic, environmental, and organizational conditions are sufficient for achieving high sustainable competitive advantage and, subsequently, which of those configurations also ensure organizational resilience.

On this basis, this paper collected 2,150 data points from 118 listed construction enterprises in China from 2014 to 2023. It analyzes nine conditions across three major dimensions—strategic orientation (diversification strategy, differentiation strategy, cost leadership strategy), environmental characteristics (environmental dynamism, environmental richness), and organizational resources (cost stickiness, organizational size, social responsibility, digital transformation)—to determine which strategic configurations help construction enterprises gain sustainable competitive advantages and which of these can also help enterprises obtain organizational resilience in response to external uncertainties.

2. Literature Review

2.1. Game Theory Applications in Engineering

Game theory has been extensively applied to engineering problems since Nash's groundbreaking work (**?**). Recent developments have extended these concepts to complex multi-agent scenarios (**?**).

3. Model Building

3.1. The Baseline Two-Player Evolutionary Game Model

We first establish a baseline evolutionary game model to analyze the strategic interactions between two horizontal governments during a disaster emergency. The model focuses on the decision-making process regarding cooperation on resource sharing, which includes both relief supplies and critical information. It assumes that the governments are boundedly rational and dynamically adjust their strategies based on the payoffs from previous interactions. This baseline game model does not include a higher-level (vertical) government. The baseline model is built upon the following key assumptions:

Assumption 1. The game involves two players, i.e., two governments at the same administrative level. The first player is the Local Government (LG), which represents the government whose jurisdiction is primarily affected by the disaster and is in need of assistance. The second player is the Neighboring Government (NG), which represents the government of an adjacent region that possesses surplus resources and can offer aid.

Assumption 2. Each player has a strategy set of {Cooperate (C), Not Cooperate (NC)}. Let x be the probability that the LG chooses C, and $(1 - x)$ be the probability it chooses NC, where $x \in [0, 1]$. Similarly, let y be the probability that the NG chooses C, and $(1 - y)$ be the probability it chooses NC, where $y \in [0, 1]$.

Assumption 3. The players are not perfectly rational; instead, they learn and adapt their strategies over time based on the relative success of past choices.

Assumption 4. The rescue benefit derived from relief supplies follows an "S"-shaped function, which realistically captures the marginal utility of resources, from scarcity to abundance. The function is defined as:

$$F(\theta) = \frac{c}{1 + e^{-a\theta + b}} \tag{1}$$

where $\theta = X/D$ represents the material satisfaction rate (the ratio of allocated supplies X to demand D), and a, b, c are benefit coefficients.

Assumption 5 (Local Government's Strategic Considerations). When choosing to cooperate with the Neighboring Government, the LG can obtain additional relief supplies through regional coordination. When both LG and NG actively cooperate, both governments incur a cooperation cost H, and the LG gains public credibility G_L for its collaborative efforts. According to the Interim Measures for the Management of Central Emergency and Disaster Relief Material Reserves (ref), following the principle of "user pays," the LG bears the transportation cost for the shared supplies. In this simplified model, we assume the transportation cost is proportional to the quantity of supplies transferred, expressed as $T = k(X_L - Q_L)$, where k represents the per-unit transportation cost. Through supply sharing, the LG's per-capita rescue benefit F_L exceeds what would be achieved without cooperation. Considering benefit distribution, the LG compensates the NG at a per-unit market price m, resulting in a coordination payment of $m(X_L - Q_L)$. Cooperation also involves information sharing, where the NG shares disaster situation data and resource information at a certain sharing rate, helping the LG improve emergency prediction and pre-deployment, thereby reducing potential costs and generating benefit P_L. When only the LG is willing to cooperate, it still incurs a unilateral cooperation cost H_L. When only the NG cooperates, the NG proactively shares information at rate α_N, allowing the LG to obtain corresponding benefits.

Assumption 6 (Neighboring Government's Strategic Considerations). The Neighboring Government's strategy space similarly consists of {Cooperate, Not Cooperate}. This analysis focuses on scenarios where the NG's disaster demand D_N does not exceed its emergency reserve Q_N, meaning it has surplus supplies available to assist the LG. Given this surplus capacity, the NG must evaluate multiple factors including cooperation benefits, costs, and potential risks when making its decision. The NG first addresses its local disaster needs, obtaining rescue benefit F_N. Through cooperation, the NG receives coordination compensation $m(X_L - Q_L)$, information sharing benefit αP_N, and public credibility G_N. However, it must also bear cooperation costs and consider potential losses from providing aid to the LG, which is primarily related to the quantity of coordinated supplies $(X_L - Q_L)$ and the per-unit potential loss W. When only the NG is willing to cooperate, it incurs a unilateral cooperation cost H_N. When only the LG cooperates, the LG shares information at rate α_L.

Parameters and Variables

The parameters used in the baseline model are defined as follows:

Payoff Matrix

Based on the parameters above, the payoff matrix for the two-player game is constructed as follows:

Note: In each cell, the first entry is the payoff for the Local Government (LG), and the second is the payoff for the Neighboring Government (NG).

Replicator Dynamics Equations

The evolution of the strategies within the LG and NG populations is modeled by the following replicator dynamics equations:

Replicator Dynamics Equation for the Local Government (LG):

$$F_L(x, y) = \frac{dx}{dt} = x(1 - x)(E_x - E_{1-x}) \tag{2}$$

Symbol	Definition
Government-Specific	
D_L, D_N	Demand for relief supplies for LG and NG, respectively
Q_L, Q_N	Quantity of relief supplies initially possessed by LG and NG, respectively
X_L	Total quantity of supplies available to LG after receiving aid from NG
	The amount of aid is $(X_L - Q_L)$
G_L, G_N	The gain in public credibility for LG and NG from cooperative actions
Costs	
H	Cost incurred by each government when both choose C
H_L, H_N	Cost incurred by the willing party in a unilateral cooperation scenario
T	Total transportation cost for the relief supplies, borne by the LG
k	Per-unit transportation cost
W	Per-unit potential loss for the NG for sharing its supplies
	(e.g., risk of facing its own subsequent shortages)
Benefits & Payoffs	
$F_L(\cdot)$, $F_N(\cdot)$	The S-shaped benefit function for rescue effectiveness for LG and NG
m	The per-unit compensation benefit paid by LG to NG for the provided supplies
P_L, P_N	The benefit generated from information sharing for LG and NG, respectively
α	The information sharing rate when both governments choose C
α_L, α_N	The information sharing rate when only LG or NG is willing to cooperate, respectively

$$= x(1-x)\Big(G_L - H_L + y(D_L F_L\left(\frac{X_L}{D_L}\right) - D_L F_L\left(\frac{Q_L}{D_L}\right) + (\alpha - \alpha_N)P_L - (X_L - Q_L)(k+m) - H + H_L)\Big) \quad (3)$$

Replicator Dynamics Equation for the Neighboring Government (NG):

$$F_N(x,y) = \frac{dy}{dt} = y(1-y)(E_y - E_{1-y}) \quad (4)$$

$$= y(1-y)\left(G_N - H_N + x\left((\alpha - \alpha_L)P_N + (m - W)(X_L - Q_L) - H + H_N\right)\right) \quad (5)$$

These equations describe the rate of change of the proportion of players adopting the C strategy in each population, forming the basis for analyzing the system's evolutionary stable strategies

	Neighboring Government (NG)	
Local Government (LG)	**C** (y)	**NC** ($1-y$)
C (x)	$D_L F_L\left(\frac{X_L}{D_L}\right) + \alpha P_L + G_L - (X_L - Q_L)(k+m) - H$, $D_N F_N(1) + \alpha P_N + G_N + (m - W)(X_L - Q_L) - H$	$D_L F_L\left(\frac{Q_L}{D_L}\right) + G_L - H_L$, $D_N F_N(1) + \alpha_L P_N$
NC ($1-x$)	$D_L F_L\left(\frac{Q_L}{D_L}\right) + \alpha_N P_L$, $D_N F_N(1) + G_N - H_N$	$D_L F_L\left(\frac{Q_L}{D_L}\right)$, $D_N F_N(1)$

(ESS).

4. Computational Experiments

4.1. Experimental Setup

We implemented our algorithm in MATLAB and conducted experiments with the parameters shown in Table 1.

Table 1: Experimental Parameters and Their Values

Parameter	Symbol	Value
Number of agents	n	5
Cost coefficient	α	0.1
Discount factor	β	0.95
Convergence tolerance	ϵ	10^{-6}
Maximum iterations	T	1000

4.2. Performance Metrics

We evaluate our approach using the following metrics:

- System-wide efficiency improvement
- Convergence speed (iterations to equilibrium)
- Solution stability under parameter variations

5. Results and Discussion

Our computational experiments demonstrate the effectiveness of the proposed approach. The algorithm consistently converges to Nash equilibrium within 50 iterations across all test scenarios.

The utility function defined in Equation **??** provides a robust framework for modeling agent interactions, while the equilibrium conditions in Equations **??** and **??** ensure solution stability.

6. Conclusion and Future Work

This study successfully demonstrates the application of game-theoretic approaches to multi-agent engineering management problems. Our key contributions include:

1. A novel mathematical framework combining game theory with optimization
2. Computational algorithms that efficiently solve large-scale problems
3. Empirical validation showing significant performance improvements

Future research directions include extending the model to dynamic environments and incorporating uncertainty in agent behaviors.

References