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Research article

Game analysis on regenerative synergy mechanism of the supply chain of integrate infrastructure engineering

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Abstract: How to ensure the smooth implementation of convergent infrastructure engineering as the risk of sudden public events persists, allowing the engineering supply chain companies to break through the blockages to regenerate collaboratively and form a regenerated collaborative union. By establishing a mathematical game model, this paper explores the synergistic mechanism of supply chain regeneration for convergent infrastructure engineering, which takes into account cooperation and competition, investigates the impact of supply chain nodes' regeneration capacity and economic performance, as well as the dynamic changes in the importance weights of supply chain nodes, when adopting the collaborative decision of supply chain regeneration, the benefits of the supply chain system, are more than those when suppliers and manufacturers "act of one's own free will" by making decentralized decisions to undertake supply chain regeneration separately. All the investment costs of supply chain regeneration are higher than those in non-cooperative games. Based on the comparison of equilibrium solutions, it was found that exploring the collaborative mechanism of its convergence infrastructure engineering supply chain regeneration provides useful arguments for the emergency re-engineering of the engineering supply chain with a tube mathematical basis. Through constructing a dynamic game model for the exploration of the supply chain regeneration synergy mechanism, this paper provides methods and support for the emergency synergy among subjects of infrastructure construction projects, especially in improving the mobilization effectiveness of the entire infrastructure construction supply chain in critical emergencies and enhancing the emergency re-engineering capability of the supply chain.

Keywords: integrate infrastructure engineering; supply chain; regenerative mechanism; synergy mechanism; game analysis

1. Introduction

The demand side of the integration infrastructure project has an eager and positive response to supply chain regeneration in the context of sudden public events and scarcity of resources that will be transmitted through contractual transactions between any enterprise in the supply chain and spread, which in turn will lead to a chain reaction of node enterprises and the whole supply chain, an active and effective synergy is conducive to breaking the economic blockade, rapidly restoring production and enhancing the resilience to risks. The new era shows the accumulation of overlapping states, constant emergence of high-risk factors, emergency events, and threats to several industries and even to the whole world. Infrastructure construction project emergency management is a comprehensive, multi-level, and integrated system, which contains many stakeholders, among which regeneration is an important direction in infrastructure engineering management research [5].With the complexity of emergency event risk, all supply chain node subjects and departments are required to achieve multi-level, multi-link, and multi-faceted effective collaboration, Raweewan et al. [6] identified that information sharing was a key building block for supply chain synergies, in the case of Chen et al. [7], the supply chain system coordination mechanism is constructed based on the decision structure and the nature of demand, While Padiyar et al. [8] developed a multi-level inventory model for a supply chain with imperfect production deterioration of multiple items based on uncertainty and ambiguity in the perspective of multiple supply chain management. As for Muller's [9] research on engineering construction projects, it is believed that its essential disposable nature determines the characteristics of irreversibility. While the synergy of each subject of the supply chain covered also shows a dynamic evolutionary trend. thus, how to ensure the effective operation of convergence infrastructure projects it is crucial to explore its supply chain synergy regeneration mechanism.

The concept of integrating emergency management and supply chain management was introduced by Clausen et al. [10] in 2001 as disruption management. According to Barroso et al. [11], the supply chain nodes may be affected by various factors, especially infrastructure risks, and they suggested measures to improve the resilience of the supply chain, such as improving supply chain information sharing, while Simatupang et al. [12] also proposed various models of supply chain synergy to evaluate the resilience and stability of the supply chain in the face of crisis. As for Kevin et al. [13], the negative effects of supply chain disruptions on companies are analyzed. Many scholars have conducted extensive research on supply chain emergency management with various perspectives and approaches. According to the mathematical game perspective, however, supply chain enterprises are irrational in performing supply chain regeneration, as performing supply chain regeneration implies more cost investment and benefit loss, thus they want to minimize the loss under the contingency and get the possibility of "rebirth" [14,15]; at the same time, they want not to perform or less perform the extra cost of supply chain regeneration [16], and let the upstream and downstream enterprises bear it [17]. Upstream and downstream enterprises should bear the additional costs. Under the risk of public emergencies, the whole supply chain faces the possibility of breakage and alliance disintegration.

Although scholars have partially studied supply chain risks, most of them are based on the position of core enterprises. There is an insufficient degree of identification of the location of supply chain plant node enterprises [18,19]. Persistence of the risk of unexpected accidents poses new challenges and requirements for the response speed of the nodal subjects of the supply chain system and the ability to collaborate [20], which severely affects the achievement of the original objectives of each nodal enterprise of the supply chain if it is unable to respond promptly [21]. This also adds difficulty to the implementation of emergency management in infrastructure construction enterprises. Researchers are also increasingly experimenting with the use of advanced optimization algorithms to solve responses that generate major decision problems. Zhao et al. [22] used online learning to obtain the optimal solution and behavior for solving the optimization goal decision strategy. Considering the relationship between the supply chain and various stakeholders, Dulebenets et al. [23] proposed a new adaptive polyploid memetic algorithm (APMA) to optimize truck scheduling problems, to improve the quality of decision schemes, then Masoud et al. [24] proposed a metaheuristic algorithm for berth scheduling in Marine container terminals to improve the computational power and quality in the face of large-scale decision problems, to explore higher solutions. This also adds difficulty to the implementation of emergency management in infrastructure construction enterprises. Therefore, with the background of emergencies under uncertainty, this paper uses each node of the supply chain as the starting point for the study and establishes a dynamic game model. Based on the above analysis, we investigate the synergistic mechanism of supply chain regeneration of convergence infrastructure engineering by establishing a mathematical game model to investigate the regeneration ability and economic performance impact of supply chain nodes, as well as the dynamic change of the importance weight of supply chain nodes.

2. Materials and methods

2.1. Models and hypothesis

The awareness of emergency regeneration of infrastructure engineering supply chain enterprises in various countries has continued to increase due to the frequent occurrence of unexpected public events in recent years. While some enterprises simply do not undertake or do not have the ability to supply chain regeneration, there are nevertheless some enterprises that change in time, seek regeneration opportunities, become the key force of engineering supply chain regeneration, and play a leading role. Systematic research on supply chain regeneration in the case of emergency response to risks of public emergencies is lacking. Nevertheless, based on the government's emergency management and supervision and control, ensuring the smooth implementation of infrastructure projects is an important part of the socioeconomic development and construction, especially the emergency regeneration of the supply chain of integrated infrastructure projects responsible for the interface between traditional and new infrastructures is a top priority, which urgently needs to explore the relevant management mechanisms for regeneration synergy. This paper considers a secondary supply chain consisting of upstream suppliers and downstream manufacturers based on the supply chain of converged infrastructure engineering, with the assumption that the emergency regeneration demand for converged infrastructure engineering under the risk of unexpected public events is stochastic, that the suppliers provide the manufacturers with raw materials and components required for engineering products, among others, both suppliers and manufacturers in the supply chain are completely rational, with all regeneration behaviors aimed at benefit Maximization is the goal, fusion infrastructure engineering demand depends on the regeneration capacity of the S supply chain and the price of fusion infrastructure engineering. Suppliers supply according to manufacturers' orders for raw materials. Therefore, this paper considers:

The level of supply chain regeneration for the supply chain system is

$$S_{SC} = i_m s_m + i_S s_s \left(0 < i_s, \mathrm{i}_m < 1, \mathrm{i}_s + i_m = 1\right). \tag{1}$$

Among them, s_s and s_m are the supply chain regeneration capacity of suppliers and manufacturers, while i_s , i_m is the important weight of suppliers and manufacturers in the supply chain, respectively. The influence on the demand side of the project can be expressed to reflect the efficiency of the supply chain regeneration capacity of this node enterprise for the demand impact.

The ultimate convergence infrastructure engineering price demand function is given by

$$y(x) = \psi s - x + \gamma = \gamma + \psi\left(i_s s_s + i_m s_m\right) - x\left(\gamma > 0, \psi > 0\right), \tag{2}$$

where γ represents the market potential of the products related to convergence infrastructure engineering, with ψ being the influence factor of the supply chain regeneration capacity on the demand for convergence infrastructure engineering, which could also be described as the demand-side sensitivity factor to supply chain regeneration.

When the supply chain node enterprises implement supply chain regeneration, additional costs will be paid, in addition to the concave function nature between this cost and the supply chain regeneration capacity, the cost function of supply chain regeneration for suppliers and manufacturers can be expressed respectively as follows.

$$c_s\left(s_s\right) = \frac{1}{2}\xi_s s_s^2\left(\xi_s > 0\right),\ c_m\left(s_m\right) = \frac{1}{2}\xi_m s_m^2\left(\xi_m > 0\right). \tag{3}$$

Where, the ξ_s, ξ_m represents the supply chain regeneration behavioral efficiency of suppliers and manufacturers respectively, (The lower ξ corresponds to the higher behavioral efficiency), and the behavioral efficiency is mainly reflected in the regeneration cost of supply chain enterprises. It means that to achieve the same regeneration goal, the regeneration behaviorally inefficient enterprises need to spend more time, labor, material, and financial resources than the regeneration behaviorally efficient enterprises. Therefore, the simplification assumes that the unit cost of the fusion infrastructure engineering supplier, and the manufacturer is 0. The cost of sales is 0, the order quantity is *x,* and the price is ω. Then the benefits function of the supply chain regeneration system is respectively expressed in terms that

$$\Phi_s = -c_s\left(s_s\right) + \omega x = -\frac{1}{2}\xi_s s_s^2 + \omega x, \tag{4}$$

$$\Phi_m = -c_m\left(s_m\right) + \left(y - \omega\right)x = -\frac{1}{2}\xi_m s_m^2 + \left[\gamma + \psi\left(i_s s_s + i_m s_m\right) - x - \omega\right]x, \tag{5}$$

$$\Phi_{sc} = \Phi_s + \Phi_m = -\frac{1}{2}\left(\xi_s s_s^2 + \xi_m s_m^2\right) + \left[\gamma + \psi\left(i_s s_s + i_m s_m\right) - x\right]x. \tag{6}$$

2.2. Non-cooperative supply chain regeneration

The following will establish the ABC three-stage dynamic model and solve the model separately. The effects of differentiated supply chain regeneration behaviors on the regeneration capacity and economic efficiency of the supply chain of converged infrastructure engineering are examined.

2.2.1. No supplier participation in regeneration synergy

With the original suppliers not participating in regeneration synergy, the manufacturers related to convergence infrastructure engineering are unable to request upstream suppliers, with no initiative to implement regeneration from the original suppliers. Thus, manufacturers in the engineering supply chain can only find other ways to seek other suppliers by various means, which are, $s_{m1} \equiv s_m > 0$, $s_{s1} = s_s = 0$. The decision process of the supply chain is as follows.

The A-stage, the engineering-related manufacturer determines the regeneration behavior, whether to participate in regeneration or not, and matches an optimal regeneration capacity value s_{m1}; the B-stage, the optimal price ω_1 of other alternative suppliers; and the C-stage, from the manufacturer determines the optimal order quantity x_1 according to the market situation under the risk of unexpected events.

Then at *C-stage*, the manufacturer orders quantity x_1 to maximize its benefit,

$$\Phi_{m1} = -\frac{1}{2}\xi_m s_m^2 + \left(\gamma + \psi i_m s_{m1} - x_1 - \omega_1\right) x_1 . \tag{7}$$

The first-order conditions are

$$\frac{\partial \Phi_{m1}}{\partial x_1} = -2x_1 + \gamma + \psi i_m s_{m1} - \omega_1 = 0 \Rightarrow x_1 = \left(\gamma + \psi i_m s_{m1} - \omega_1\right) / 2 . \tag{8}$$

In the *B-stage*, with other suppliers speculating on the manufacturer's order quantity in C-stage, the optimal raw material price ω_1 is chosen to achieve benefit max.

$$\Phi_{s1} = \omega_1 x_1\left(\omega_1, \mathrm{s}_{m1}\right) = \frac{1}{2}\omega_1\left(\gamma + \psi i_m s_{m1} - \omega_1\right). \tag{9}$$

The first-order conditions are

$$\frac{\partial \Phi_{s1}}{\partial \omega_1} = \frac{1}{2}\left(\gamma + \psi i_m s_{m1}\right) - \omega_1 = 0 \Rightarrow \omega_1 = \frac{1}{2}\left(\gamma + \psi i_m s_{m1}\right). \tag{10}$$

At the *A-stage,* based on the other available supplies, the manufacturer determines the regenerative behavior strategy, which matches the optimal value of regenerative capacity to maximize its benefits.

$$\max_{s_{m1}} \Phi_{m1} = \frac{1}{8}\left(\gamma + \psi i_m s_{m1}\right) - \xi_m s_{m1} = 0 \Rightarrow s_{m1} = \frac{\gamma \psi i_m}{8\xi_m - \psi^2 i_m^2} . \tag{11}$$

The first-order conditions are

$$\frac{\partial \Phi_{m1}}{\partial s_{m1}} = \frac{1}{8}\psi i_m\left(\gamma + \psi i_m s_{m1}\right) - \xi_m s_{m1} = 0 \Rightarrow s_{m1} = \frac{\gamma \psi i_m}{8\xi_m - \psi^2 i_m^2} . \tag{12}$$

The second-order conditions are

$$\frac{\partial \Phi_{m1}^2}{\partial s_{m1}} = -\xi_m + \frac{1}{8}\psi^2 i_m^2 . \tag{13}$$

To ensure that the benefit of the engineering manufacturing party is a concave function about the value of its supply chain regenerative capacity s_{m1}, assumption, $\xi_m > \frac{1}{8}\psi^2 i_m^2$. The equation is for the marginal impact of the regenerative behavior of the manufacturing related to the integration infrastructure engineering on the demand (ψi_m).

By substituting Eq (12) into Eqs (8) and (10), it is obtained that the price and order quantity is in case of risk of unexpected public events.

$$\omega_1^* = \frac{4\gamma\xi_m}{-\psi^2 i_m^2 + 8\xi_m}, x_1^* = \frac{2\gamma\xi_m}{-\psi^2 i_m^2 + 8\xi_m}. \tag{14}$$

The equilibrium revenue by substituting (12) and (14) is obtained as

$$\Phi_{s1}^* = \frac{8\gamma^2\xi_m^2}{\left(-\psi^2 i_m^2 + 8\xi_m\right)^2}, \tag{15}$$

$$\Phi_{m1}^* = \frac{\gamma^2\xi_m}{2\left(-\psi^2 i_m^2 + 8\xi_m\right)}, \tag{16}$$

$$\Phi_{s1}^* = \frac{\gamma^2\xi_m\left(-\psi^2 i_m^2 + 24\xi_m\right)}{2\left(-\psi^2 i_m^2 + 8\xi_m\right)^2}. \tag{17}$$

2.2.2. Non-participation of the manufacturing side in regenerative synergy

Under the circumstances, the manufacturing side of the supply chain is not involved in regenerative synergy, which is mostly due to the forced production interruptions caused by special risks, so it is not able to participate in regenerative synergy. When there is production interruption on the manufacturing side of the project and the supply exceeds the demand in the market, in consideration of the future long-term benefits, providers will generally choose to maintain the supply chain core enterprises or seek other demand sides to maximize the benefits. Therefore, the only suppliers in the converged infrastructure engineering supply chain actively implement regeneration strategies when $s_{s2} \equiv s_s > 0$, $s_{m2} \equiv s_m = 0$.

In the *A-stage*, the supplier determines the regeneration behavior, that is whether to participate in regeneration, matched with an optimal regeneration capacity value s_{s2}; in the *B-stage*, the supplier's optimal price ω_2; and in the *C-stage*, the optimal order quantity x_2 of other manufacturing partners.

Therefore, in the *C-stage*, the manufacturer orders quantity x_2 to maximize its benefit,

$$\Phi_{m2} = \left(\gamma_s - x_2 - \omega_2 + \psi i_s s\right) x_2. \tag{18}$$

The first-order conditions are

$$\frac{\partial\Phi_{m2}}{\partial x_2} = \gamma - \omega_2 + \psi i_s s_{s2} - 2x_2 = 0,$$

$$\Rightarrow x_2 = \frac{1}{2}\left(\gamma + \psi i_s s_{s2} - \omega_2\right). \tag{19}$$

At *B-stage*, the other suppliers guess the manufacturer's order quantity at C-stage and choose the optimal raw material price ω_2. To achieve benefit max,

$$\Phi_{s2} = -\frac{1}{2}\xi_s s_{x2}^2 + \omega_2 x_2\left(\omega_2, \mathrm{s}_{s2}\right) = -\frac{1}{2}\xi_s s_{s2}^2 + \omega_2\left(\psi i_s s_{s2} - \omega_2\right). \tag{20}$$

The first-order conditions are

$$\frac{\partial \Phi_{s2}}{\partial \omega_2} = \frac{1}{2}\left(\gamma + \psi i_s s_{s2}\right) - \omega_2 = 0,$$

$$\Rightarrow \omega_2 = \frac{1}{2}\left(\gamma + \psi i_s s_{s2}\right). \tag{21}$$

At the *A-stage*, suppliers match a regenerative capacity value *A* to maximize their benefits, and the max function is

$$\max_{s_{s2}} \Phi_{s2} = -\frac{1}{2}\xi_s s_{s2} + \frac{1}{8}\left(\gamma + \psi i_s s_{s2}\right)^2. \tag{22}$$

The first-order condition is

$$\frac{\partial \Phi_{s2}}{\partial s_{s2}} = \left(\frac{1}{4}\psi^2 i_s^2 - \xi_s\right) s_{s2} + \frac{1}{4}\gamma\psi i_s,$$

$$\Rightarrow s_{s2}^* = -\frac{\gamma\psi i_s}{\psi^2 i_s^2 - 4\xi_s}. \tag{23}$$

The second-order condition are

$$\frac{\partial^2 \Phi_{s2}}{\partial s_{s2}^2} = -\xi_s + \frac{1}{4}\psi^2 i_s^2. \tag{24}$$

To ensure that the engineering supply side benefit is a concave function about the value of its supply chain regenerative capacity s_{s2}, assume that $\xi_s > \frac{1}{4}\beta^2 i_s^2$. In that case, substituting Eq (23) into Eqs (19) and (21) yields equilibrium prices and order quantities of

$$\omega_2^* = \frac{2\gamma\xi_s}{-\psi^2 i_s^2 + 4\xi_s}, x_2^* = \frac{\gamma\xi_s}{-\psi^2 i_s^2 + 4\xi_s}. \tag{25}$$

Substituting Eq (23) and Eq (25) yields,

$$\Phi_{m2}^* = \frac{\gamma^2\xi_s^2}{\left(-\psi^2 i_s^2 + 4\xi_s\right)^2}, \tag{26}$$

$$\Phi_{s2}^* = \frac{\gamma^2\xi_s}{2\left(-\psi^2 i_s^2 + 4\xi_s\right)}, \tag{27}$$

$$\Phi_{sc2}^{*} = \frac{\gamma^2 \xi_s \left(-\psi^2 i_s^2 + 6\xi_s\right)}{2\left(-\psi^2 i_s^2 + 4\xi_s\right)^2}. \tag{28}$$

2.2.3. Regeneration by parties alone without cooperative regeneration

Convergence infrastructure engineering-related manufacturing parties alone take regeneration synergy without requiring upstream suppliers to regenerate synergy, which not only fails to share the regeneration cost but also fails to eradicate the supply chain disruption when the risk of public emergencies occurs. According to the economic man theory, some engineering suppliers can benefit from speculative behavior currently. Consequently, the parties alone take non-cooperative regeneration to do their own thing, that is $s_{s3} \equiv s_s > 0$, and $s_{m3} \equiv s_m > 0$, still take ABC three-stage dynamic game.

In the *A-stage*, the nodal firm parties alone take non-cooperative regeneration behavior, whether they participate in regeneration or not, with each party matching an optimal regeneration capacity value s_{s3} and separately; the *B-stage* suppliers' optimal price ω_3, and the *C-stage* is the manufacturer's optimal order quantity x_3. Following is the model building and solving.

Therefore, at *C-stage*, the manufacturer orders quantity x_3 to maximize its own benefit.

$$\Phi_{m3} = -\frac{1}{2}\xi_m s_{m3}^2 + \left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right) - x_3 - \omega_3\right] x_3. \tag{29}$$

The first-order condition are

$$\frac{\partial \Phi_{m3}}{\partial x_3} = \gamma - \omega_3 - 2x_3 + \psi\left(i_s s_{s3} + i_m s_{m3}\right) = 0,$$

$$\Rightarrow x_3 = \frac{1}{2}\left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right) - \omega_3\right]. \tag{30}$$

At the *B-stage*, the supplier guesses the manufacturer's order quantity at the C-stage and chooses the optimal raw material price ω_3. The supplier realizes the benefits max,

$$\Phi_{s3} = -\frac{1}{2}\xi_s s_{s3}^2 + \frac{1}{2}\omega_3\left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right) - \omega_2\right]. \tag{31}$$

The first-order condition is

$$\frac{\partial \Phi_{s3}}{\partial \omega_3} = \frac{1}{2}\left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right)\right] - \omega_3 = 0,$$

$$\Rightarrow \omega_3 = \frac{1}{2}\left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right)\right]. \tag{32}$$

At the *A-stage*, the supplier matches a regenerative capacity value s_{s3}, s_{m3} to maximize its own benefit, and the max function is

$$\max_{s_{s3}} \Phi_{s3} = -\frac{1}{2}\xi_s s_{s3}^2 + \frac{1}{8}\left[\gamma + \left(\psi i_s s_{s3} + \psi i_m s_{m3}\right)\right]^2. \tag{33}$$

The manufacturing party max function becomes

$$\max_{s_{m3}} \Phi_{m3} = -\frac{1}{2}\xi_m s_{m3}^2 + \frac{1}{16}\left[\gamma + \left(\psi i_s s_{s3} + \psi i_m s_{m3}\right)\right]^2. \tag{34}$$

First-order decision conditions for each party.

$$\frac{\partial \Phi_{s3}}{\partial s_{s3}} = -\xi_s s_{s3} + \frac{1}{4}\psi i_s \left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right)\right] = 0, \tag{35}$$

$$\frac{\partial \Phi_{m3}}{\partial s_{m3}} = -\xi_m s_{m3} + \frac{1}{8}\psi i_m \left[\gamma + \psi\left(i_s s_{s3} + i_m s_{m3}\right)\right] = 0. \tag{36}$$

The regeneration capacity of each party is divided into

$$s_{s3}^* = \frac{2\gamma\psi i_s \xi_m}{-\psi^2 i_m^2 \xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2 \xi_m}, \tag{37}$$

$$s_{m3}^* = \frac{\gamma\psi i_m \xi_s}{-2\psi^2 i_s^2 \xi_m + 8\xi_s\xi_m - \psi^2 i_m^2 \xi_s}. \tag{38}$$

Letting $8\xi_s\xi_m - 2\beta^2 i_s^2 \xi_m - \beta^2 i_m^2 \xi_2 > 0$, it is obtained that

$$\frac{\psi^2 i_s i_m}{-\psi^2 i_s^2 + 4\xi_s} = \frac{ds_{s3}}{ds_{m3}} > 0,$$

$$\frac{\psi^2 i_s i_m}{-\psi^2 i_s^2 + 4\xi_s} = \frac{ds_{s3}}{ds_{m3}} > 0.$$

It indicates that the implementation of regeneration behaviors by all parties in the supply chain has an intrinsic incentive utility when the node enterprises of the converged infrastructure engineering supply chain have regeneration awareness. That is to say, the regeneration strategy determined by any party of the engineering supply chain will trigger other parties in the chain to adopt regeneration behaviors, which will link the improvement of emergency regeneration capacity of the whole supply chain of converged infrastructure engineering. In turn,

$$\omega_3^* = \frac{4\gamma\xi_s\xi_m}{-\psi^2 i_m^2 \xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2 \xi_m}, \quad x_3^* = \frac{2\gamma\xi_s\xi_m}{-\psi^2 i_m^2 \xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2 \xi_m}. \tag{39}$$

Substituting the variables, the supplier profit is

$$\Phi_{m3}^* = \frac{2\gamma^2 \xi_s \xi_m^2 \left(-\psi^2 i_s^2 + 4\xi_s\right)}{\left(-\psi^2 i_m^2 \xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2 \xi_m\right)^2}. \tag{40}$$

Manufacturing side profit is

$$\Phi_{m3}^{*} = \frac{\gamma^2 \xi_s^2 \xi_m \left(-\psi^2 i_m^2 + 8\xi_m\right)}{2\left(-\psi^2 i_m^2 \xi_s + 8\xi_s \xi_m - 2\psi^2 i_s^2 \xi_m\right)^2}. \tag{41}$$

Supply chain system profit is

$$\Phi_{sc3}^{*} = \frac{\gamma^2 \xi_s \xi_m \left(-\psi^2 i_m^2 \xi_s + 24\xi_s \xi_m - 4\psi^2 i_s^2 \xi_m\right)}{2\left(-\psi^2 i_m^2 \xi_s + 8\xi_s \xi_m - 2\psi^2 i_s^2 \xi_m\right)^2}. \tag{42}$$

2.3. Cooperative supply chain regeneration

The regenerative synergy perspective based on convergent infrastructure engineering supply chain discusses the regenerative synergistic behavior adopted by the parties on the chain and the engineering SC regenerative synergistic capability. The SC system gains if the chain parties aim at the SC system gain to the max and the overall linkage synergy.

$$\Phi_{sc4} = \Phi_{s4} + \Phi_{m4} = -\frac{1}{2}\left(\xi_s s_{s4}^2 + \xi_m s_{m4}^2\right) + \left[\gamma + \psi\left(i_s s_{s4} + i_m s_{m4}\right) - x_4\right] x_4. \tag{43}$$

The regenerative synergy strategy from the overall benefit of the supply chain system depends on the order quantity *q*, and the regenerative synergy capacity for s_{s4}, s_{m4}. Accordingly, let the variable be 0 and derive

$$\frac{\partial \Phi_{sc4}}{\partial x_4} = \psi\left(i_s s_{s4} + i_m s_{m4}\right) + \gamma - 2x_4 = 0, \tag{44}$$

$$\frac{\partial \Phi_{sc4}}{\partial s_{s4}} = -\xi_s s_{s4} + \psi i_s x_4 = 0, \tag{45}$$

$$\frac{\partial \Phi_{sc4}}{\partial s_{m4}} = -\xi_m s_{m4} + \psi i_m x_4 = 0, \tag{46}$$

$$s_{s4} = \frac{s_{m4} i_s \xi_m}{i_m \xi_s}, \tag{47}$$

$$x_4 = \frac{1}{2}\left[\gamma + \psi\left(i_s s_{s4} + i_m s_{m4}\right)\right]. \tag{48}$$

In this case, the supplier order quantity is

$$s_{s4}^{*} = \frac{\gamma \psi i_s \xi_m}{-\psi^2\left(i_s^2 \xi_m + i_m^2 \xi_s\right) + 2\xi_s \xi_m}. \tag{49}$$

Regeneration synergy capacity on the manufacturing side,

$$x_4^{*} = \frac{\gamma \xi_s \xi_m}{-\psi^2\left(i_s^2 \xi_m + i_m^2 \xi_s\right) + 2\xi_s \xi_m}. \tag{50}$$

The optimum order quantity is

$$x_4^* = \frac{\gamma\xi_s\xi_m}{-\psi^2\left(i_s^2\xi_m + i_m^2\xi_s\right) + 2\xi_s\xi_m}. \tag{51}$$

SC system gain is

$$\Phi_{sc4}^* = \frac{\gamma^2\xi_s\xi_m}{2\left[-\psi^2\left(i_s^2\xi_m + i_m^2\xi_s\right) + 2\xi_s\xi_m\right]}. \tag{52}$$

3. Comparative analysis of regenerative synergy capacity and economic performance of enterprises

Above is the mathematical model and its solution for several regenerative synergy approaches of SC in fusion infrastructure engineering, we will attempt to compare and analyze the SC nodes enterprises and regenerative synergy capacity in these circumstances in turn and try to give related proofs.

Demonstrate that the following holds under the participation constraints of $\xi_m > \frac{1}{8}\psi^2 i_m^2$, $\xi_s > \frac{1}{4}\psi^2 i_s^2$, $8\xi_s\xi_m - 3\psi^2 i_s^2\xi_m - 3\psi^2 i_m^2\xi_s > 0$. So (1) $s_{s4}^* > s_{s3}^* > s_{s2}^*$, $s_{m4}^* > s_{m3}^* > s_{m2}^*$, (2) $x_4^* > x_3^* > x_2^*$, $x_4^* > x_3^* > x_1^*$, (3) $\Phi_{s3}^* > \Phi_{s2}^*, \Phi_{s3}^* > \Phi_{s1}^*, \Phi_{m3}^* > \Phi_{m2}^*, \Phi_{m3}^* > \Phi_{m1}^*, \Phi_{sc4}^* > \Phi_{sc3}^* > \Phi_{sc2}^*, \Phi_{sc4}^* > \Phi_{sc3}^* > \Phi_{sc1}^*$.

To prove that.

(1) From the equilibrium solution of the regenerative synergistic capacity in the above, it follows that,

$$\frac{s_{s3}^*}{s_{s2}^*} = \frac{-\psi^2 i_s^2 + 4\xi_s}{\gamma\psi i_s} \times \frac{2\gamma\psi i_s\xi_m}{-\psi^2 i_m^2\xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2\xi_m} = \frac{-2\psi^2 i_s^2\xi_m + 8\xi_s\xi_m}{-\psi^2 i_m^2\xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2\xi_m} > 1, \tag{53}$$

$$\frac{s_{s4}^*}{s_{s3}^*} = \frac{-\psi^2 i_m^2\xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2\xi_m}{2\gamma\psi i_s\xi_m} \times \frac{\gamma\psi i_s\xi_m}{-\psi^2 i_m^2\xi_s + 2\xi_s\xi_m - \psi^2 i_s^2\xi_m} = \frac{4\xi_s\xi_m - \psi^2 i_s^2\xi_m - \frac{1}{2}\psi^2 i_m^2\xi_s}{2\xi_s\xi_m - \psi^2 i_s^2\xi_m - \psi^2 i_m^2\xi_s} > 1. \tag{54}$$

That is, $s_{s4}^* > s_{s3}^* > s_{s2}^*$, Similarly, $s_{m4}^* > s_{m3}^* > s_{m1}^*$.

(2) The optimal order quantity of the above content

$$x_1^* = \frac{2\gamma\xi_m}{-\psi^2 i_m^2 + 8\xi_m} = \frac{2\gamma\xi_s\xi_m}{-\psi^2 i_m^2\xi_s + 8\xi_s\xi_m}, \tag{55}$$

$$x_2^* = \frac{\gamma\xi_s}{-\psi^2 i_s^2 + 4\xi_s} = \frac{2\gamma\xi_s\xi_m}{-2\psi^2 i_s^2\xi_m + 8\xi_s\xi_m}, \tag{56}$$

$$x_3^* = \frac{2\gamma\xi_s\xi_m}{-\psi^2 i_m^2\xi_s + 8\xi_s\xi_m - 2\psi^2 i_s^2\xi_m}. \tag{57}$$

Obviously, $x_3^* > x_2^*, x_3^* > x_1^*$

$$\frac{x_4^*}{x_3^*}=\frac{-\psi^2 i_m^2\xi_s+8\xi_s\xi_m-2\psi^2 i_s^2\xi_m}{2\gamma\xi_s\xi_m}\times\frac{\gamma\xi_s\xi_m}{-\psi^2\left(i_s^2\xi_m+i_m^2\xi_s\right)+2\xi_s\xi_m},$$

$$=\frac{-2\psi^2 i_m^2\xi_s+16\xi_s\xi_m-4\psi^2 i_s^2\xi_m}{-4\psi^2 i_m^2\xi_s+8\xi_s\xi_m-4\psi^2 i_s^2\xi_m}>1. \tag{58}$$

then $x_4^*>x_3^*$.

(3) Revenue equilibrium solution,

$$\frac{\Phi_{m3}^*}{\Phi_{m1}^*}=\frac{2\left(-\psi^2 i_m^2+8\xi_m\right)}{\gamma^2\xi_m}\times\frac{\gamma^2\xi_s^2\xi_m\left(-\psi^2 i_m^2+8\xi_m\right)}{2\left(-\psi^2 i_m^2\xi_s+8\xi_s\xi_m-2\psi^2 i_s^2\xi_m\right)^2}=\frac{\left(8\xi_s\xi_m-\psi^2 i_m^2\xi_s\right)^2}{\left(-\psi^2 i_m^2\xi_s+8\xi_s\xi_m-2\psi^2 i_s^2\xi_m\right)^2}>1, \tag{59}$$

$$\Phi_{m3}^*-\Phi_{m2}^*=-\frac{\gamma^2\xi_s^2}{\left(-\psi^2 i_s^2+4\xi_s\right)^2}+\frac{\gamma^2\xi_s^2\xi_m\left(8\xi_m-\psi^2 i_m^2\right)}{2\left(-\psi^2 i_m^2\xi_s+8\xi_s\xi_m-2\psi^2 i_s^2\xi_m\right)^2},$$

$$=-\frac{1}{16}\gamma^2\xi_s^2\left[\frac{1}{\left(\xi_s-\frac{1}{4}\psi^2 i_s^2\right)^2}-\frac{\xi_m^2-\frac{1}{8}\psi^2 i_m^2\xi_m}{\left(\xi_s\xi_m-\frac{1}{4}\psi^2 i_s^2\xi_m-\frac{1}{8}\psi^2 i_m^2\xi_s\right)^2}\right],$$

$$=\left(\frac{1}{4}\gamma\psi\right)^2\frac{\frac{1}{8}i_m^2\xi_s^4\xi_m-\frac{1}{64}\psi^2 i_m^4\xi_s^4-\frac{1}{128}\psi^4 i_s^4 i_m^2\xi_s^2\xi_m}{\left(\xi_s-\frac{1}{4}\psi^2 i_s^2\right)^2\left(\xi_s\xi_m-\frac{1}{4}\psi^2 i_s^2\xi_m-\frac{1}{8}\psi^2 i_m^2\xi_s\right)^2},$$

$$=\left(\frac{1}{4}\gamma\psi\right)^2\frac{\frac{1}{4}\psi^2 i_s^2 i_m^2\xi_s^2\xi_m\left(\xi_s-\frac{1}{4}\psi^2 i_s^2\right)+\frac{1}{8}\left[i_m^2\xi_s^3\left(\xi_s\xi_m-\frac{1}{4}\psi^2 i_s^2\xi_m-\frac{1}{8}\psi^2 i_m^2\xi_s\right)\right]}{\left(\xi_s-\frac{1}{4}\psi^2 i_s^2\right)^2\left(\xi_s\xi_m-\frac{1}{4}\psi^2 i_s^2\xi_m-\frac{1}{8}\psi^2 i_m^2\xi_s\right)^2}>0 \tag{60}$$

Thus, the proof knows that $\Phi_{m3}^*>\Phi_{m2}^*$, $\Phi_{m3}^*>\Phi_{m1}^*$. Similarly, $\Phi_{s3}^*>\Phi_{s2}^*$, $\Phi_{s3}^*>\Phi_{s1}^*$, then $\Phi_{sc3}^*>\Phi_{sc2}^*$, $\Phi_{sc3}^*>\Phi_{sc1}^*$.

Proof $\Phi_{sc4}^*>\Phi_{sc3}^*$.

$$\frac{\Phi_{sc4}^*}{\Phi_{sc3}^*}=\frac{2\left(8\xi_s\xi_m-\psi^2 i_m^2\xi_s-2\psi^2 i_s^2\xi_m\right)^2}{\gamma^2\xi_s\xi_m\left(24\xi_s\xi_m-\psi^2 i_m^2\xi_s-4\psi^2 i_s^2\xi_m\right)}\times\frac{\gamma^2\xi_s\xi_m}{2\left(2\xi_s\xi_m-\psi^2 i_m^2\xi_s-\psi^2 i_s^2\xi_m\right)} \tag{61}$$

$$\frac{A}{B}=\frac{\left(8\xi_s\xi_m-\psi^2 i_m^2\xi_s-2\psi^2 i_s^2\xi_m\right)^2}{\left(24\xi_s\xi_m-\psi^2 i_m^2\xi_s-4\psi^2 i_s^2\xi_m\right)\left(2\xi_s\xi_m-\psi^2 i_m^2\xi_s-\psi^2 i_s^2\xi_m\right)} \tag{62}$$

The calculation leads to

$$A=\psi^4 i_m^4\xi_s^2+4\psi^4 i_s^4\xi_m^2+4\psi^4 i_s^2 i_m^2\xi_s\xi_m-16\psi^2 i_m^2\xi_s^2\xi_m-32\psi^2 i_s^2\xi_s\xi_m^2+64\xi_s^2\xi_m^2, \tag{63}$$

$$B=\psi^4 i_m^4 \xi_s^2+4\psi^4 i_s^4 \xi_m^2+5\psi^4 i_s^2 i_m^2 \xi_s \xi_m-26\psi^2 i_m^2 \xi_s^2 \xi_m-32\psi^2 i_s^2 \xi_s \xi_m^2+48\xi_s^2 \xi_m^2, \tag{64}$$

$$A-B=-\psi^4 i_s^2 i_m^2 \xi_s \xi_m+10\psi^2 i_m^2 \xi_s^2 \xi_m+16\xi_s^2 \xi_m^2. \tag{65}$$

Since $\xi_s > \frac{1}{4}\psi^2 i_s^2$, then, $10\psi^2 i_m^2 \xi_s > 2.5\psi^4 i_s^2 i_m^2$ knows $A-B>0$. Therefore, $\frac{\Phi_{sc4}^*}{\Phi_{sc3}^*}=\frac{A}{B}>1$ obtains $\Phi_{sc4}^* > \Phi_{sc3}^*$.

With the above proof, it is inferred that the cooperative regeneration of all parties on the fusion infrastructure SC is due to non-cooperative regeneration, moreover, the cooperative approach taken among SC parties is conducive to driving the SC system revenue to a better level, which effectively responds to the risk of public emergencies, promotes the regeneration of engineering supply chain effectively, and enhances the emergency response capability of SC parties. As a result, the integration of infrastructure engineering supply chain parties' overall regeneration synergy will be a powerful multi-win strategy choice.

4. Conclusions

The paper examined the situation of weight coefficients of each party in the secondary SC, establish and solve the mathematical model of dynamic SC game model with three different decision-making methods, which found that the regeneration synergistic behavior of each node enterprise on the SC has a linkage promotion effect. The problem of "how to regenerate, which way to regenerate" and "what way to regenerate is better" is also discussed and analyzed. The benefits of the SC system are greater than the benefits of regeneration when the engineering supply chain is cooperatively regenerated, while the regeneration capacity of each party is improved. In addition, it is found that the cooperative regeneration strategy improves the demand when the supply chain is blocked and interrupted, which is conducive to revitalizing the market and promoting the possibility of "rebirth" of each chain node of the integrated infrastructure engineering supply chain under the risk of sudden public time. Thus, the integration of infrastructure engineering supply chain regeneration synergy mechanism not only provides useful arguments for the emergency re-engineering of the engineering supply chain based on mathematics but also provides important information and significance for engineering management practice. In the complicated context of significant emergencies, there is a critical need for theoretical support and methodological guidance to improve emergency synergy among supply chain subjects. As the game analysis model constructed in this paper has certain extensibility, the emergency regeneration synergy of different strategies with different supply chain nodes can be explored and compared. In addition, the study of this paper is to establish a game analysis model to predict the behavior of each supply chain node, and to find the promoting effect of the cooperative symbiosis behavior of enterprises at each supply node. However, subsequent studies need further the development of machine learning algorithms, uncertainty modeling, a new image processing, combined with a wider range of supply chain logistics subjects. Refer to Tirkolaee et al. [25] to develop a novel mixed-integer linear programming (MILP) model in municipal solid waste (MSW) management and designed based on a multi-objective simulated annealing algorithm (MOSA), As Özmen et al. [26,27] indicated, key variables would be affected by the fluctuation of unknown factors and other parameters, so it was necessary to expand the analysis of related complex networks and environments. Time-discrete TE regulatory systems were important to determine the parameters of unknown systems. Therefore, combining the above-related factors and further combining them with practical applications is the goal of our follow-up work. The in-depth optimization algorithm of this study is to analyze and optimize the evolution of infrastructure engineering enterprises on the supply chain node. To improve the quality of the behavioral decision when emergencies, explore the decision-making behavior of higher, more high quality, to better cope with the effects of the abrupt change.

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Conflict of interest

The authors declare there is no conflict of interest.

Data availability

The data used to support the findings of this study are included within the article.

References

1. M. A. Momeni, S. Yaghoubi, M. R. M. Aliha, A cost sharing-based coordination mechanism for multiple deteriorating items in a one manufacture-one retailer supply chain, *J. Ind. Eng. Manage. Stud.*, **6** (2019), 79–110. https://doi.org/10.22116/jiems.2019.87661
2. D. Berlin, A. Feldmann, C. Nuur. The relatedness of open-and closed-loop supply chains in the context of the circular economy, framing a continuum, *Cleaner Logistics Supply Chain*, **2022** (2022), 100048. https://doi.org/10.1016/j.clscn.2022.100048
3. D. Das, A. Datta, P. Kumar, Y. Kazancoglu, M. Ram, Building supply chain resilience in the era of COVID-19: An AHP-DEMATEL approach, *Oper. Manage. Res.*, **15** (2022), 249–267. https://doi.org/10.1007/s12063-021-00200-4
4. M. S. Golan, L. H. Jernegan, I. Linkov, Trends and applications of resilience analytics in supply chain modeling: Systematic literature review in the context of the COVID-19 pandemic, *Environ. Syst. Decisions*, **40** (2020), 222–243. https://doi.org/10.1111/jscm.12162
5. M. Bosch-Rekveldt, Y. Jongkind, H. Mooi, H. Bakker, A. Verbraeck, Grasping project complexity in large engineering projects: The TOE (technical, organizational and environmental) framework, *Int. J. Proj. Manage.*, **29** (2011), 728–739. https://doi.org/10.1016/j.ijproman.2010.07.008
6. M. Raweewan, W. G. Ferrell Jr, Information sharing in supply chain collaboration, *Comput. Ind. Eng.*, **126** (2018), 269–281. https://doi.org/10.1016/j.cie.2018.09.042
7. L. Chen, X. Zhao, O. Tang, L. Price, S. Zhang, W. Zhu, Supply chain collaboration for sustainability: A literature review and future research agenda, *Int. J. Prod. Econ.*, **194** (2017), 73–87. https://doi.org/10.1016/j.ijpe.2017.04.005
8. S. V. S. Padiyar, V. Vandana, N. Bhagat, S. R. Singh, B. Sarkar, Joint replenishment strategy for deteriorating multi-item through multi-echelon supply chain model with imperfect production under imprecise and inflationary environment, *RAIRO Oper. Res.*, **56** (2022), 3071–3096. https://doi.org/10.1051/ro/2022071

9. R. Müller, R. Turner, E. S. Andersen, J. Shao, Ø. Kvalnes, Ethics, trust, and governance in temporary organizations, *Proj. Manage. J.*, **45** (2014), 39–54. https://doi.org/10.1002/pmj.21432
10. J. Clausen, J. Larsen, A. Larsen, J. Hansen, Disruption management-operations research between planning and execution, *Or-ms Today*, **28** (2001), 40–43.
11. A. P. Barroso, V. H. Machado, A. R. Barros, V. C. Machado, Toward a resilient supply chain with supply disturbances in *2010 IEEE International Conference on Industrial Engineering and Engineering Management*, **46** (2010), 245–249. https://doi.org/10.1109/IEEM.2010.5674462
12. T. M. Simatupang, A. C. Wright, R. Sridharan, The knowledge of coordination for supply chain integration, *Bus. Process Manage. J.*, **8** (2002), 289–308. https://doi.org/10.1108/14637150210428989
13. K. B. Hendricks, V. R. Singhal, Association between supply chain glitches and operating performance, *Manage. Sci.*, **51** (2005), 695–711. https://doi.org/10.1287/mnsc.1040.0353
14. N. O. Hohenstein, Supply chain risk management in the COVID-19 pandemic: Strategies and empirical lessons for improving global logistics service providers' performance, *Int. J. Logistics Manage.*, **33** (2022), 1336–1365. https://doi.org/10.1108/IJLM-02-2021-0109
15. M. Hussain, M. Malik, Organizational enablers for circular economy in the context of sustainable supply chain management, *J. Cleaner Prod.*, **256** (2020), 120375. https://doi.org/10.1016/j.jclepro.2020.120375
16. D. Ivanov, Exiting the COVID-19 pandemic: After-shock risks and avoidance of disruption tails in supply chains, *Ann. Ope. Res.*, **2021** (2021), 1–18. https://doi.org/10.1007/s10479-021-04047-7
17. V. Jain, S. Kumar, A. Kumar, C. Chandra. An integrated buyer initiated decision-making process for green supplier selection, *J. Manuf. Syst.*, **41** (2016), 256–265. https://doi.org/10.1016/j.jmsy.2016.09.004
18. M. A. Momeni, V. Jain, K. Govindan, A. Mostofi, S. J. Fazel, A novel buy-back contract coordination mechanism for a manufacturer-retailer circular supply chain regenerating expired products, *J. Cleaner Prod.,* **375** (2022), 133319. https://doi.org/10.1016/j.jclepro.2022.133319
19. F. Naz, A. Kumar, A. Majumdar, R. Agrawal, Is artificial intelligence an enabler of supply chain resiliency post COVID-19? An exploratory state-of-the-art review for future research, *Oper. Manage. Res.*, **15** (2022), 378–398.
20. P. K. Tarei, G. Kumar, M. Ramkumar, A mean-variance robust model to minimize operational risk and supply chain cost under aleatory uncertainty: A real-life case application in petroleum supply chain, *Comput. Ind. Eng.*, **166** (2022), 107949. https://doi.org/10.1016/j.cie.2022.107949
21. A. Rehman, M. S. S. Jajja, S. Farooq, Manufacturing planning and control driven supply chain risk management: A dynamic capability perspective, *Trans. Res. Part E*, **167** (2022), 102933. https://doi.org/10.1016/j.tre.2022.102933
22. H. Zhao, C. Zhang, An online-learning-based evolutionary many-objective algorithm, *Inf. Sci.*, **509** (2020), 1–21. https://doi.org/10.1016/j.ins.2019.08.069
23. M. A. Dulebenets, An adaptive polyploid memetic algorithm for scheduling trucks at a cross-docking terminal, *Inf. Sci.*, **565** (2021), 390–421. https://doi.org/10.1016/j.ins.2021.02.039
24. M. Kavoosi, M. A. Dulebenets, O. Abioye, J. Pasha, O. Theophilus, H. Wang, et al., Berth scheduling at marine container terminals: A universal island-based metaheuristic approach, *Maritime Bus. Rev.*, **5** (2019), 30–66. https://doi.org/10.1108/MABR-08-2019-0032

25. E. B. Tirkolaee, A. Goli, S. Gütmen, G. W. Weber, K. Szwedzka, A novel model for sustainable waste collection arc routing problem: Pareto-based algorithms, *Ann. Oper. Res.*, **2022** (2022), 1–26. https://doi.org/10.1007/s10479-021-04486-2
26. A. Özmen, E. Kropat, G. W. Weber, Spline regression models for complex multi-modal regulatory networks, *Optim. Methods Software*, **29** (2014), 515–534. https://doi.org/10.1080/10556788.2013.821611
27. A. Özmen, E. Kropat, G. W. Weber, Robust optimization in spline regression models for multi-model regulatory networks under polyhedral uncertainty, *Optimization*, **66** (2017), 2135–2155. https://doi.org/10.1080/02331934.2016.1209672