

Emergency production dispatching under sudden disruptions: A tripartite evolutionary game approach

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ABSTRACT

Sudden disruptions, including equipment failures, supply interruptions, and extreme events, can quickly make shop-floor schedules infeasible. Yet emergency production dispatching is often treated as a stand-alone rescheduling problem that overlooks coordination and enforcement. This study frames disruption response in industrial parks as a coupled production-control and governance problem and develops a tripartite evolutionary game model involving a local coordination authority, manufacturing firms, and an upper-level government. The model examines how proactive dispatching, cooperative rescheduling, and supervision co-evolve under bounded rationality. Using replicator dynamics, Jacobian stability analysis, and numerical simulations, we identify the conditions under which cooperative emergency dispatching becomes stable. The findings are based on a simulation-based evolutionary game model rather than on calibrated industrial case data. Results show that resource support, cooperation gains, and credible penalties promote proactive dispatching, whereas high adjustment costs weaken firms' willingness to cooperate. Rising monitoring costs reduce the attractiveness of strict supervision, while effective horizontal cooperation partly substitutes for vertical enforcement. From a practical perspective, emergency dispatching is more effective when firms' adjustment burdens are reduced, repeated cooperation is rewarded, passive behavior is credibly disciplined, and supervision remains effective but sustainable.

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1. Introduction

In recent years, manufacturing systems have been increasingly exposed to sudden disruptions such as natural hazards, major accidents, pandemics, cyber incidents, and critical utility outages [1]. These shocks can trigger abrupt capacity loss, material shortages, and cascading schedule infeasibility across workshops, plants, and industrial parks [2]. In shop-floor execution, delayed dispatching and rescheduling may amplify work-in-process accumulation, delivery failures, and ripple effects along supply networks [3]. Consequently, emergency production dispatching, such as rapid rescheduling and real-time production control after a disruption, has become a central issue in production planning, scheduling, and control under risk and uncertainty.

However, emergency dispatching in real manufacturing settings is rarely a purely technical optimization problem. Particularly in manufacturing clusters and industrial parks, it is a multi-actor coordination process. A local coordination authority must activate emergency plans and mobilize shared resources; manufacturing firms must decide whether to cooperate with rescheduling measures such as capacity sharing and overtime; and upper-level government agencies often intervene through supervision and resource support. Because these actors face different costs,

constraints, and accountability pressures, technically feasible dispatching policies may fail to materialize when incentives are misaligned.

To address this challenge, this study frames disruption response as a coupled production-control and governance problem. We develop a tripartite evolutionary game model involving a local coordination authority, manufacturing firms, and an upper-level government. The study examines how proactive dispatching, cooperative rescheduling, and supervision co-evolve under bounded rationality. The contributions are threefold. First, the study reframes emergency production dispatching as a coupled governance and scheduling implementation problem rather than a purely technical optimization task. Second, it provides a tractable tripartite evolutionary mechanism to explain when cooperative dispatching becomes evolutionarily stable. Third, it offers policy and managerial insights on how to design incentive-compatible emergency dispatching schemes that converge reliably under bounded rationality.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the problem description and the tripartite evolutionary game model. Section 4 analyzes the stability of equilibrium points. Section 5 reports numerical simulations and sensitivity analyses. The final section summarizes conclusions and implications.

2. Literature review

A substantial literature has examined manufacturing disruption management through operations research and industrial engineering approaches, including predictive-reactive rescheduling, dynamic scheduling, robust and stochastic formulations, dispatching and repair heuristics, and simulation-based optimization [4-6]. Meanwhile, Industry 4.0 and smart manufacturing infrastructures have advanced data-driven decision support for real-time monitoring and schedule adaptation, with recent reviews highlighting digitally enabled smart manufacturing scheduling [7]. However, much of this scheduling-centric research evaluates performance conditional on implementable schedules, often treating stakeholder compliance, information sharing, and cross-organizational coordination as exogenous or costless. This assumption is restrictive when emergency dispatching depends on multi-actor joint action under accountability and incentive conflicts.

Existing studies have increasingly viewed disruption response as shaped by behavioral, organizational, and governance factors. Research on environmental emergencies highlights the role of rescuers' emotions and occupational safety [8], while other studies examine incentives, safety compliance, and public-private collaboration in disruption contexts [9, 10]. Game-theoretic models have been used to explain how subsidies, penalties, and contract terms affect stakeholder participation in emergency collaboration, post-disruption recovery, and resource sharing [11, 12]. Related studies further show that financial constraints, capacity limits, and procurement decisions jointly influence disaster and emergency response effectiveness [13]. However, many existing models remain dyadic, such as supplier-manufacturer interactions, and often rely on full-rationality, static, or leader-follower assumptions. These settings limit their ability to capture boundedly rational adaptation and enforcement dynamics in time-pressured emergencies. Although tripartite evolutionary games have been applied in some emergency management contexts, their use in emergency production dispatching and industrial-park rescheduling remains limited, particularly for explaining the co-evolution of vertical supervision and horizontal capacity reallocation.

Studies on industrial and social accident decision-making have shown that negative emotions, decision concerns, task modes, and risk preferences affect decision time, confidence, and behavioral choices [14, 15]. Evolutionary game theory offers a natural analytical lens for this problem because emergency response strategies are shaped by bounded rationality, learning, and repeated interactions across drills and real incidents. Rather than assuming perfect rationality, evolutionary games describe how strategy shares evolve based on relative payoffs and how a system may converge to an evolutionary stable strategy under specific incentive and cost structures [16]. Recent studies have applied tripartite evolutionary game frameworks to technology adoption and multi-stakeholder coordination in production and logistics [17, 18]. Recent studies have further used this approach to examine manufacturing capacity sharing and AI delivery technology adoption, showing its applicability to multi-stakeholder strategy evolution in production and

logistics systems [19, 20]. These studies typically combine equilibrium stability analysis with numerical simulation to identify the parameters that drive convergence to desirable states. Nonetheless, the application of such frameworks to emergency production dispatching, especially under vertical administrative governance, remains underdeveloped.

3. Evolutionary game theory model

3.1 Basic assumptions and game description

To study implementable emergency production dispatching, we consider a tripartite evolutionary interaction within an industrial park or manufacturing cluster. In this setting, disruptions may render pre-planned schedules infeasible and require rapid rescheduling and capacity reallocation. The three stakeholders are a local coordination authority, manufacturing firms, and an upper-level government. In this study, emergency production dispatching is interpreted as the implementation process that makes disrupted production plans executable, rather than as a substitute for a shop-floor scheduling or rescheduling algorithm. Operationally, it may involve order resequencing, machine reassignment, changeover acceleration, overtime arrangement, expedited procurement, temporary outsourcing, cross-firm capacity sharing, and delivery-priority adjustment. A scheduling model may generate candidate rescheduling plans and indicators such as recovery time, tardiness reduction, throughput loss, capacity utilization, and adjustment cost, while the governance layer developed here explains whether these plans can be implemented through proactive coordination, firm cooperation, and appropriate supervision. The local coordination authority represents the industrial-park operator or regional manufacturing coordination office responsible for activating emergency production plans, integrating information, and organizing cross-firm dispatching. Manufacturing firms execute shop-floor actions such as sequence changes, changeovers, overtime, expedited procurement, and temporary capacity sharing. The upper-level government acts as a supervisory and support body that enforces compliance and allocates emergency resources when needed. The model focuses on how vertical supervision and horizontal capacity reallocation jointly shape the evolution of implementable dispatching.

Hypothesis 1 (Bounded rationality and evolutionary adaptation). The local coordination authority, manufacturing firms, and the upper-level government are denoted as Player 1, Player 2, and Player 3. Decision-makers operate under bounded rationality and cannot fully anticipate others' actions in time-pressured disruption response. Strategy adjustments follow payoff-driven learning, imitation, or reinforcement based on observed performance in drills and real incidents. As disruption experiences accumulate, the proportions of agents adopting alternative strategies evolve over time and may converge to an evolutionarily stable state.

Hypothesis 2 (Strategic choice and probability). Each player has two alternative strategies. The local coordination authority chooses proactive dispatching or passive response. Let the probability of proactive dispatching be $x \in [0,1]$, and passive response be $1 - x$. Manufacturing firms choose active cooperation or non-cooperation in emergency rescheduling and capacity reallocation. Let the probability of active cooperation be $y \in [0,1]$, and non-cooperation be $1 - y$. The upper-level government chooses between strict supervision and loose supervision. Let the probability of strict supervision be $z \in [0,1]$ and that of loose supervision be $1 - z$.

Hypothesis 3 (Payoffs of the local coordination authority). If the local coordination authority adopts proactive dispatching, it incurs a coordination cost D reflecting plan activation, cross-firm dispatching, information integration, and resource mobilization, and obtains an operational continuity benefit B , representing improved delivery reliability and reduced disruption losses at the system level. Under strict supervision, it can receive resource support A , such as emergency funding, logistics capacity, or prioritized utilities. When firms actively cooperate, the authority gains an additional effectiveness benefit C , reflecting higher implementability of rescheduling, faster recovery of throughput, and reduced spillovers enabled by capacity pooling. If the authority adopts a passive response, it suffers a delay-related loss E , may be penalized by the upper-level government F , and experiences a credibility loss G that weakens its future coordination capability.

Hypothesis 4 (Payoffs of the manufacturing firms). If a manufacturing firm chooses active cooperation, it gains a reputation benefit and may receive a local incentive H , but bears adjustment costs J , including overtime, setup and changeover, sequence deviations, expedited procurement, and additional coordination effort. Non-cooperation avoids part of J in the short run but results in a reputation loss K and a penalty L associated with noncompliance in emergency production arrangements. When proactive dispatching and cooperation occur jointly, manufacturing firms obtain a long-term collaboration payoff X , capturing persistent advantages such as preferential access to shared resources, repeated coordination efficiency, and improved recovery performance in subsequent disruptions.

Hypothesis 5 (Payoffs of the upper-level government). Strict supervision yields a system stability benefit M and a regulatory performance payoff P , reflecting reduced regional production interruptions and improved resilience of manufacturing supply capacity, but incurs supervision and coordination costs Q . When the local coordination authority is proactive, an additional resilience gain O is realized through reduced cascading risks and faster restoration of production and logistics functions. Loose supervision leads to a credibility loss R and an escalation risk cost S , as local inaction or firm noncompliance can amplify disruption impacts and require higher-cost interventions later.

3.2 Evolutionary game model design

Following the established hypotheses above, the strategic interaction is encapsulated within a mixed-strategy game framework, which is detailed in Table 1.

Table 1 Tripartite payoff matrix

Manufacturing firms		Upper-level government		
		Strict supervision (z)	Loose supervision ($1 - z$)	
Local coordination authority	Proactive dispatching (x)	Active cooperation (y)	$A + B + C - D - I$ $H + I - J - N + X$ $M + O + P - Q - A$	$A + B + C - D - I$ $H + I - J + X$ $-R - S$
		Non-cooperation ($1 - y$)	$A + B - D + L$ $-K - L - N$ $M + O + P - Q - A$	$A + B - D + L$ $-K - L$ $-R - S$
	Passive dispatching ($1 - x$)	Active cooperation (y)	$-D - E - F - G - I$ $H + I - J - N$ $M + P - Q$	$-D - E - F - G - I$ $H + I - J$ $-R - S$
		Non-cooperation ($1 - y$)	$-D - E - F - G + L$ $-K - L - N$ $M + P - Q$	$-D - E - F - G + L$ $-K - L$ $-R - S$

4. Model analysis

4.1 Evolution and stable strategy of local coordination authority

Upon examining Table 1, it is evident that the anticipated payoff E_{11} of the local coordination authority when adopting proactive dispatching is given by Eq. 1.

$$E_{11} = yz(A + B + C - D - I) + y(1 - z)(A + B + C - D - I) + (1 - y)z(A + B - D + L) + (1 - y)(1 - z)(A + B - D + L) \tag{1}$$

The expected return E_{12} for the local coordination authority when adopting a passive response is calculated as shown in Eq. 2.

$$E_{12} = yz(-D - E - F - G - I) + y(1 - z)(-D - E - F - G - I) + (1 - y)z(-D - E - F - G + L) + (1 - y)(1 - z)(-D - E - F - G + L) \tag{2}$$

The overall payoff E_1 for the local coordination authority is given by Eq. 3.

$$E_1 = xE_{11} + (1 - x)E_{12} \tag{3}$$

Therefore, the replicator dynamic equation describing the evolution of the local coordination authority's strategy can be expressed by Eq. 4.

$$\begin{aligned}
 F(x) &= \frac{dx}{dt} = x(E_{11} - E_1) = x(1-x)(E_{11} - E_{12}) \\
 &= -x(x-1)(A+B+E+F+G+Cy)
 \end{aligned}
 \tag{4}$$

The derivative of $F(x)$ with respect to x can be obtained in Eqs. 5 and 6.

$$\frac{d(F(x))}{dx} = (1-2x)(A+B+E+F+G+Cy)
 \tag{5}$$

$$G(y, z) = A+B+E+F+G+Cy
 \tag{6}$$

When $y = \frac{A+B+E+F+G}{-C}$, $\frac{d(F(x))}{dx} \equiv 0$; when $y \neq \frac{A+B+E+F+G}{-C}$, $F(x) = 0$, then $x = 0$ and $x = 1$ are two equilibrium points and need to be classified and discussed.

Proposition 1. If the probability y of manufacturing firms choosing active cooperation is higher than $\frac{A+B+E+F+G}{-C}$, x will be stable at 1. Conversely, if y is lower than $\frac{A+B+E+F+G}{-C}$, the probability x will be stable at 0 as presented in Eq. 7.

$$x = \begin{cases} 0 & y < \frac{A+B+E+F+G}{-C} \\ [0,1] & y = \frac{A+B+E+F+G}{-C} \\ 1 & y > \frac{A+B+E+F+G}{-C} \end{cases}
 \tag{7}$$

The replication dynamics and the evolutionary stable strategies associated with the local coordination authority’s preference for proactive measures are illustrated in Fig. 1. Here, V_{12} represents the probability x that the local coordination authority adopts proactive dispatching, whereas V_{11} denotes the probability $1-x$ that it adopts passive dispatching. Proposition 1 indicates that when manufacturing firms exhibit a higher tendency y to actively cooperate in emergency rescheduling and resource reallocation, the local coordination authority is more likely to converge to proactive dispatching. Conversely, if firms tend to withhold cooperation and free-ride on others’ adjustment efforts, the local coordination authority’s incentives to mobilize resources and coordinate emergency dispatching weaken, and the evolutionary dynamics drive it toward a passive response. As a result, the evolutionary process ultimately leads the local coordination authority to favor proactive emergency dispatching as the stable strategy in manufacturing disruption recovery.

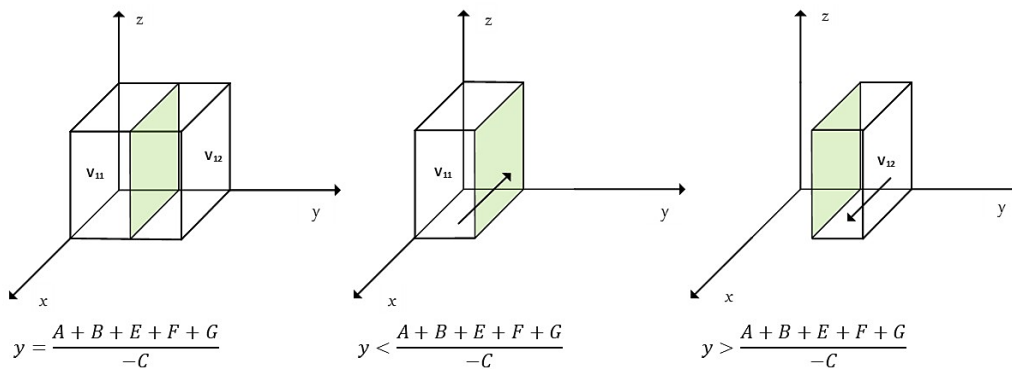


Fig. 1 Strategic evolution landscape of local coordination authority

4.2 Evolution and stable strategy of manufacturing firms

The expected return E_{21} of the manufacturing firms choosing active cooperation is shown in Eq. 8.

$$\begin{aligned}
 E_{21} &= xz(H+I-J-N+X) + x(1-z)(H+I-J+X) \\
 &+ (1-x)z(H+I-J-N) + (1-x)(1-z)(H+I-J)
 \end{aligned}
 \tag{8}$$

The expected return E_{22} of the manufacturing firms choosing non-cooperation is obtained according to Eq. 9.

$$E_{22} = xz(-K - L - N) + x(1 - z)(-K - L) + (1 - x)z(-K - L - N) + (1 - x)(1 - z)(-K - L) \tag{9}$$

The average return E_2 of the manufacturing firms choosing the mixed strategy is derived as presented in Eq. 10.

$$E_2 = yE_{21} + (1 - y)E_{22} \tag{10}$$

The replication dynamic equation for the active cooperation strategy is given by Eq. 11, and the derivative of $F(y)$ with respect to y can be obtained in Eq. 12.

$$F(y) = \frac{dy}{dt} = y(E_{21} - E_2) = -y(y - 1)(H + I - J + K + L + X * x) \tag{11}$$

$$\frac{d(F(y))}{dy} = (1 - 2y)(H + I - J + K + L + Xx) \tag{12}$$

When $x = \frac{H+I-J+K+L}{-X}$, $\frac{d(F(y))}{dy} \equiv 0$; when $x \neq \frac{H+I-J+K+L}{-X}$, $F(y) = 0$, then $y = 0$ and $y = 1$ are two equilibrium points and need to be classified and discussed.

Proposition 2. If the likelihood x that the local coordination authority adopts proactive emergency production dispatching is higher than $\frac{H+I-J+K+L}{-X}$, the proportion of manufacturing firms choosing active cooperation in emergency rescheduling will converge to 1. Conversely, if the probability x is lower than $\frac{H+I-J+K+L}{-X}$, the proportion of firms choosing active cooperation will converge to 0. To sum up, the probability y of manufacturing firms choosing active cooperation is shown in Eq. 13.

$$y = \begin{cases} 0 & \text{if } x < \frac{H + I - J + K + L}{-X} \\ [0,1] & \text{if } x = \frac{H + I - J + K + L}{-X} \\ 1 & \text{if } x > \frac{H + I - J + K + L}{-X} \end{cases} \tag{13}$$

The replication dynamics and the evolutionary stable strategies associated with manufacturing firms' preference for active cooperation are illustrated in Fig. 2. Here, V_{21} represents the probability that manufacturing firms adopt active cooperation, whereas V_{22} denotes the probability of non-cooperation. Proposition 2 implies that when the local coordination authority actively initiates emergency dispatching, firms are more likely to participate in implementable rescheduling actions, thereby converging to active cooperation. In contrast, when the local coordination authority remains passive and provides limited coordination, firms face weaker incentives and fewer long-term benefits from participating, and the evolutionary dynamics drive them toward non-cooperation.

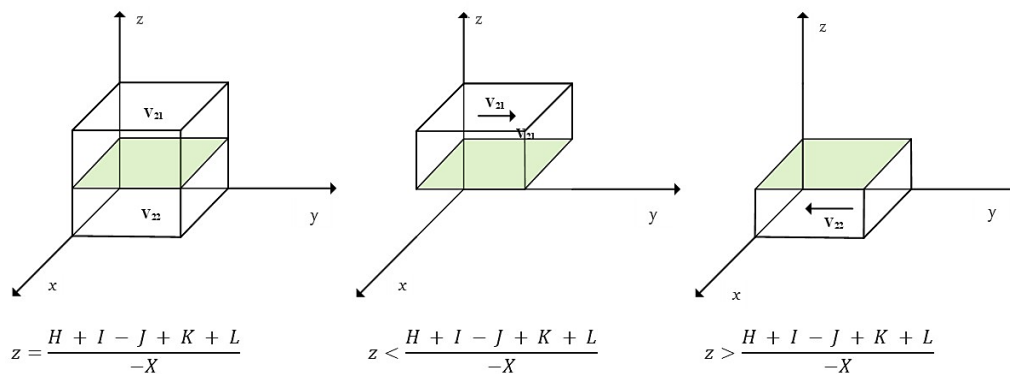


Fig. 2 Strategic evolution landscape of manufacturing firms

4.3 Evolution and stable strategy of upper-level government

The expected return E_{31} of the upper-level government choosing strict supervision is listed in Eq. 14.

$$E_{31} = xy(M + O + P - Q - A) + x(1 - y)(M + O + P - Q - A) + (1 - x)y(M + P - Q) + (1 - x)(1 - y)(M + P - Q) \tag{14}$$

The expected return E_{32} for the upper-level government opting for loose supervision is calculated in Eq. 15.

$$E_{32} = xy(-R - S) + x(1 - y)(-R - S) + (1 - x)y(-R - S) + (1 - x)(1 - y)(-R - S) \tag{15}$$

The average expected income E_3 of the upper-level government follows directly from Eq. 16.

$$E_3 = zE_{31} + (1 - z)E_{32} \tag{16}$$

Therefore, the upper-level government replication dynamic equation can be expressed by Eq. 17, and the derivative of $F(z)$ with respect to z can be obtained in Eq. 18.

$$F(z) = \frac{dz}{dt} = z(E_{31} - E_3) = -z(z - 1)(M + P - Q + R + S - Ax + Ox) \tag{17}$$

$$\frac{d(F(z))}{dz} = (1 - 2z)(M + P - Q + R + S - Ax + Ox) \tag{18}$$

When $x = \frac{M+P-Q+R+S}{A-O}$, $\frac{d(F(z))}{dz} \equiv 0$; when $x \neq \frac{M+P-Q+R+S}{A-O}$, $F(z) = 0$ then $z = 0$ and $z = 1$ are two equilibrium points and need to be classified and discussed.

Proposition 3. If the value of x falls below $\frac{M+P-Q+R+S}{A-O}$, the likelihood of the upper-level government enforcing stringent oversight remains consistently at its maximum; if the probability x is higher than $\frac{M+P-Q+R+S}{A-O}$, the chance of the upper-level government opting for stringent supervision will consistently be at its minimum. The probability z of the superior government choosing strict supervision is shown in Eq. 19.

$$z = \begin{cases} 1 & x < \frac{M + P - Q + R + S}{A - O} \\ [0,1] & x = \frac{M + P - Q + R + S}{A - O} \\ 0 & x > \frac{M + P - Q + R + S}{A - O} \end{cases} \tag{19}$$

Fig. 3 illustrates the dynamics of replication and the evolutionary stable strategies pertaining to the upper-level government's selection of strict supervision measures.

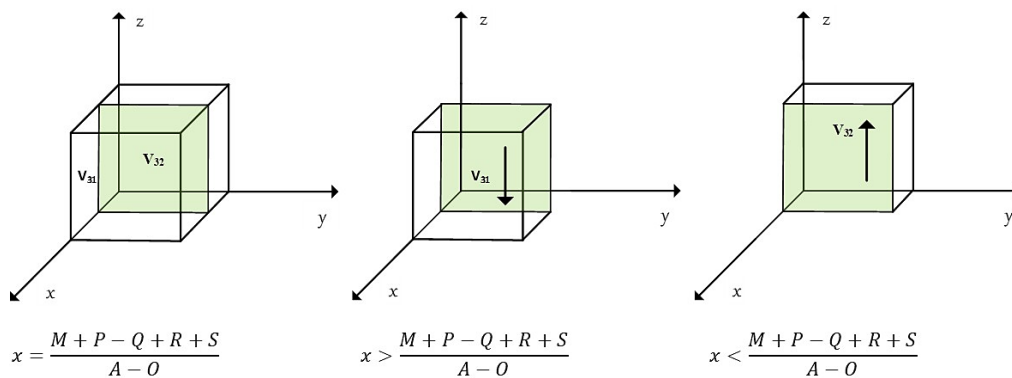


Fig. 3 Strategic evolution landscape of upper-level government

V_{31} signifies the likelihood of the upper-level government opting for strict supervision, whereas V_{32} denotes the chance of selecting a loose supervision approach. Proposition 3 delineates that in the scenario where the local coordination authority is inclined towards passive dispatching, the upper-level government will be more likely to implement strict regulatory strategies. On the other hand, if the local coordination authority demonstrates proactive dispatching, the higher authority will be inclined to adopt a more relaxed regulatory approach.

4.4 System evolution stability analysis

By solving the system of equations where $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$ simultaneously, we obtain eight candidate equilibrium points corresponding to the pure-strategy combinations of the three players, namely $E_1(0,0,0)$, $E_2(0,1,0)$, $E_3(0,0,1)$, $E_4(0,1,1)$, $E_5(1,0,0)$, $E_6(1,1,0)$, $E_7(1,0,1)$ and $E_8(1,1,1)$. These equilibria represent the corner solutions of the state space, where each strategy share takes a boundary value of 0 or 1 and the population adopts a single strategy with certainty. We then evaluate local stability at each equilibrium by substituting these points into the Jacobian matrix and examining the signs of the associated eigenvalues. This study focuses on pure-strategy boundary equilibria because they correspond to institutionally interpretable long-run regimes in emergency production dispatching, such as proactive dispatching versus passive response, active cooperation versus non-cooperation, and strict supervision versus loose supervision. Interior mixed equilibria may exist when payoff differences are exactly balanced, but in this application they are better understood as threshold or indifference states rather than robust governance regimes. Therefore, the subsequent stability analysis concentrates on pure-strategy equilibria, while mixed equilibria are acknowledged as a possible direction for future extensions.

According to Lyapunov stability theory, local stability in a replicator dynamic system can be assessed by examining the eigenvalues of the Jacobian matrix of the system at an equilibrium point [21]. The Jacobian is obtained by taking the first-order partial derivatives of the replicator dynamic equations with respect to the state variables, and it therefore summarizes how small perturbations in strategy proportions propagate through the evolutionary process. An equilibrium is asymptotically stable if the real parts of all eigenvalues are strictly negative, implying that any small deviation from the equilibrium decays over time and the trajectories converge back to that point. By contrast, if at least one eigenvalue has a non-negative real part, the equilibrium is locally unstable, because perturbations will not be damped and may instead grow or drive the system toward alternative equilibria. In this study, the derivative matrix, denoted here as J , is defined in the subsequent manner in Eq. 20.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{20}$$

$$= \begin{bmatrix} (1-2x)(A+B+E+F+G+C*y) & -x(x-1)C & 0 \\ -y(y-1)X & (1-2y)(H+I-J+K+L+Xx) & 0 \\ -z(z-1)(O-A) & 0 & (1-2z)(M+P-Q+R+S-Ax+Ox) \end{bmatrix}$$

By substituting E_1 through E_8 into the Jacobian matrix, the eigenvalues of the equilibrium points in Table 2 can be obtained. As shown in Table 2, the equilibrium points E_1 at the origin, E_2 , E_3 and E_4 each have positive eigenvalues. Consequently, points E_1 through E_4 do not represent evolutionarily stable strategies (ESS).

Table 2 Eigenvalue analysis of the Jacobian matrix at equilibrium points

Equilibrium point	λ_1	λ_2	λ_3	Stability conclusion	Condition
$E_1(0,0,0)$	$A+B+E+F+G$	$H+I+K+L-J$	$M+P+R+S-Q$	Unstable point	
$E_2(0,1,0)$	$A+B+C+E+F+G$	$J-I-H-K-L$	$M+P+R+S-Q$	Unstable point	
$E_3(0,0,1)$	$A+B+E+F+G$	$H+I+K+L-J$	$Q-P-M-R-S$	Unstable point	
$E_4(0,1,1)$	$A+B+C+E+F+G$	$J-I-H-K-L$	$Q-P-M-R-S$	Unstable point	
$E_5(1,0,0)$	$-A-B-E-F-G$	$H+I-J+K+L+X$	$M+O+P-Q+R+S-A$	ESS	Eigenvalues are all less than 0
$E_6(1,1,0)$	$-A-B-C-E-F-G$	$J-I-H-K-L-X$	$M+O+P-Q+R+S-A$	ESS	Eigenvalues are all less than 0
$E_7(1,0,1)$	$-A-B-E-F-G$	$H+I-J+K+L+X$	$A+Q-M-O-P-R-S$	ESS	Eigenvalues are all less than 0
$E_8(1,1,1)$	$-A-B-C-E-F-G$	$J-I-H-K-L-X$	$A+Q-M-O-P-R-S$	ESS	Eigenvalues are all less than 0

The system shows four stable states under certain conditions. Notably, the equilibrium state $E_8(1,1,1)$ is particularly noteworthy as it represents an ideal balance. In this state, the local coordination authority initiates proactive dispatching, and manufacturing firms engage in active cooperation, all under the strict supervision of higher-level governments. This equilibrium symbolizes the effective collaboration among various entities. However, it is important to note that this stable state does not represent the Pareto optimal state of the system. The Pareto optimal state is identified as $E_6(1,1,0)$, characterized by more relaxed supervision from higher-level governments. Concurrently, local coordination authority and manufacturing firms demonstrate enhanced cooperative behaviors, leading to the minimal total system cost. Nevertheless, achieving this equilibrium typically necessitates substantial autonomy on the part of both local coordination authority and manufacturing firms. The stability conditions of equilibrium point $E_8(1,1,1)$ are listed in Eqs. 21 and 22.

$$J - I - H - K - L - X < 0 \quad (21)$$

$$A - M - O - P + Q - R - S < 0 \quad (22)$$

The following section of this research employs numerical simulations to visualize the interactions among the three emergency entities at the equilibrium state $E_8(1,1,1)$.

5. Numerical simulation analysis

In the initial stages of the numerical simulations conducted in Python, assigning values to parameters that influence the system is crucial. The literature primarily presents two methods for parameter assignment. One is based on theoretical stability analysis, and the other is based on empirical data from real cases [22]. Due to the scarcity of real-life data, this study opts for a parameter assignment method grounded in the results of stability analysis.

The parameters are normalized payoff values for simulation-based mechanism analysis rather than direct monetary estimates from a specific industrial park. Nevertheless, they have observable industrial counterparts. Coordination costs, firm adjustment costs, and supervision costs can be linked to labor hours, communication costs, overtime, changeover, setup, expedited procurement, outsourcing, inspection frequency, and monitoring expenditure, while operational benefits can be proxied by reductions in recovery time, order tardiness, work-in-process accumulation, and throughput loss. Thus, the numerical setting is used as a theoretically consistent baseline scenario, and future studies may calibrate the parameters using scheduling logs, MES/ERP records, disruption reports, and cost accounting data.

Therefore, the managerial implications derived from the simulations should be understood as mechanism-oriented implications based on comparative parameter changes, rather than as precise predictions for a particular industrial park. The sensitivity analysis is used to test how changes in key payoff components affect evolutionary trajectories under the same baseline structure.

Specifically, this study assigns values to the parameters of the tripartite evolutionary game system. These assignments are designed to ensure that the parameters comply with the stability determination theorem for the equilibrium point $E_8(1,1,1)$ in the system. The details of the parameter assignments are as follows.

$$\begin{array}{llllll} A = 4 & B = 2 & C = 1.5 & E = 2.2 & F = 2.5 & G = 3 \\ H = 1.8 & I = 0.9 & J = 6 & K = 3.5 & L = 1.3 & M = 2.6 \\ O = 1 & P = 1.7 & Q = 5 & R = 5 & S = 1.9 & X = 0.8 \end{array}$$

5.1 Initial evolution path analysis

Using the parameter values specified above, numerical experiments were conducted, and the initial evolutionary trajectory of the system is shown in Fig. 4. The numerical simulation results are consistent with the theoretical analysis. Specifically, the stability of the equilibrium point $E_8(1,1,1)$ dictated the parameter assignments, and the simulation results evolved toward this state, thereby validating the accuracy of the theoretical predictions. Furthermore, it is observed that the convergence state of the system remains consistent across different initial conditions. This indicates that while the initial values influence the rate of system evolution, they do not affect the system's eventual stable state. The stability of the system remains intact regardless of variations in initial conditions, as these do not alter the fundamental stability judgment criteria.

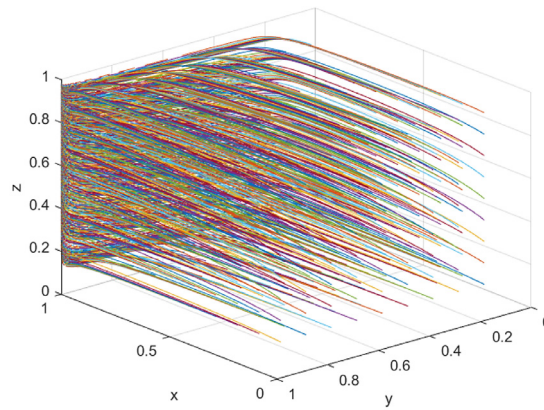


Fig. 4 Initial trajectory of the system's equilibrium at the point (1,1,1)

5.2 Sensitivity analysis

The initial evolutionary path indicates that the system's stable state depends on the characteristic values of each equilibrium point. To reduce the influence of initial-value fluctuations in the sensitivity analysis, the initial strategy probabilities of all three game players are uniformly set to 0.5.

Local coordination authority's proactive dispatching and resource support from the upper-level government

In the simulations, upper-level government resource support was set to $A = 4, 8,$ and $16,$ with the evolutionary trajectories shown in Fig. 5. The results indicate that higher support accelerates the local coordination authority's convergence toward proactive dispatching by reducing the coordination burden of rescheduling, information integration, and cross-plant capacity pooling. Meanwhile, increased support makes the upper-level government more inclined toward looser supervision, reflecting the budgetary and administrative burden of combining strict oversight with substantial support. By contrast, support has limited direct impact on manufacturing firms' strategies, since it mainly operates through the vertical government-to-authority channel. Unless converted into firm-level compensation for changeover, overtime, or expedited procurement costs, firms do not treat it as an immediate payoff improvement.

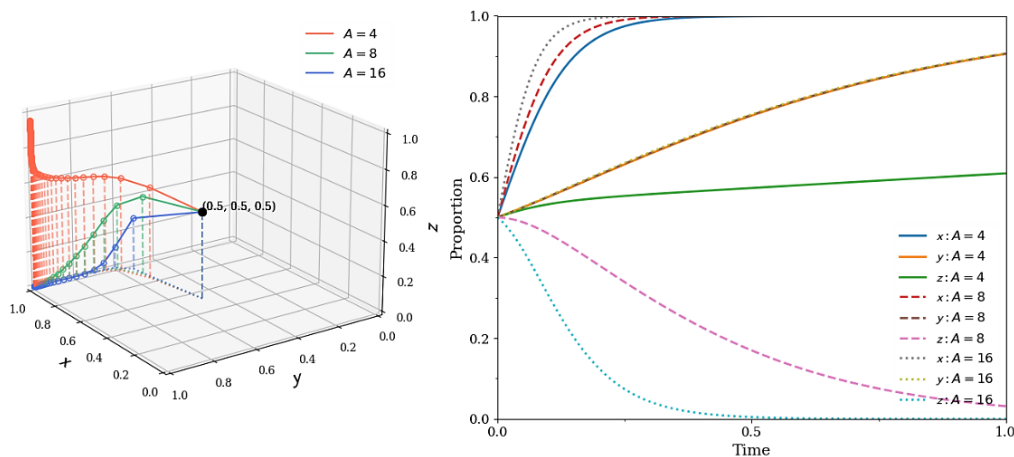


Fig. 5 The impact of changes in upper-level resource support

Dispatching effectiveness gains generated by manufacturing firms' active cooperation

To assess cooperation-driven effectiveness gains, we set the additional gain from firms' active cooperation to $C = 1, 15,$ and $45,$ with evolutionary trajectories shown in Fig. 6. The results indicate that higher C accelerates the local coordination authority's convergence toward proactive emergency dispatching by improving schedule feasibility, shortening recovery time, and reducing shop-floor congestion such as work-in-process accumulation and cross-plant spillovers. Meanwhile, as C increases, the upper-level government becomes less inclined to maintain strict

supervision, suggesting that stronger horizontal coordination reduces the marginal returns of costly vertical enforcement. Overall, cooperation-induced effectiveness gains mainly affect the authority’s dispatching stance and secondarily influence supervisory intensity.

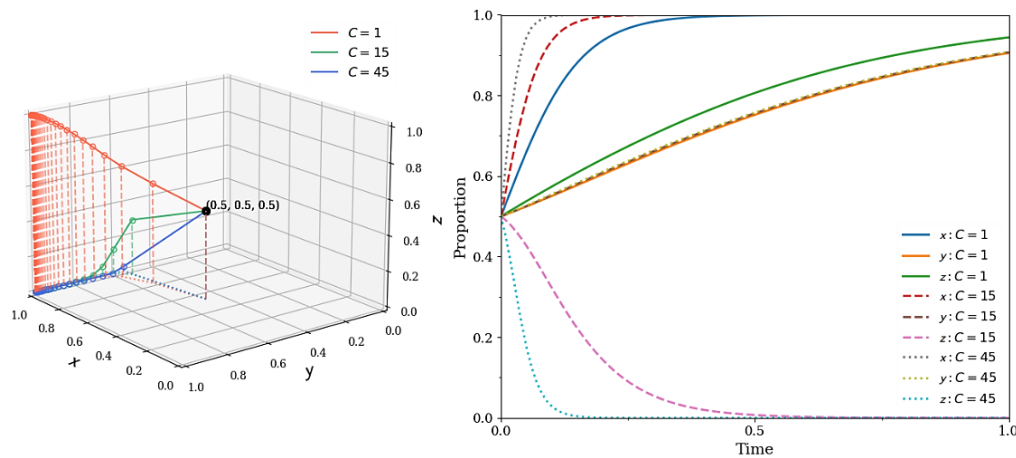


Fig. 6 The impact of changes in cooperation gains from firms’ active collaboration

Passive dispatching by the local coordination authority and penalties imposed by the upper-level government

In the simulations, the penalty intensity imposed by the upper-level government on the local coordination authority’s passive dispatching was set to $F = 2, 5, \text{ and } 10$, and the corresponding evolutionary trajectories are presented in Fig. 7. The results show that stronger penalties reduce the local coordination authority’s tendency to remain passive and accelerate its shift toward proactive emergency dispatching. Meanwhile, the upper-level government’s propensity to maintain strict supervision declines as F increases, suggesting an adaptive response under bounded rationality. Once deterrence effectively disciplines passive behavior, the marginal return to sustained high-intensity supervision diminishes relative to its costs. The role of penalties is therefore analogous to that of cooperation-induced effectiveness gains (parameter C) in promoting proactive dispatching, implying that an implementable emergency dispatching scheme should combine credible sanctions with mechanisms that enhance the operational benefits of cooperation.

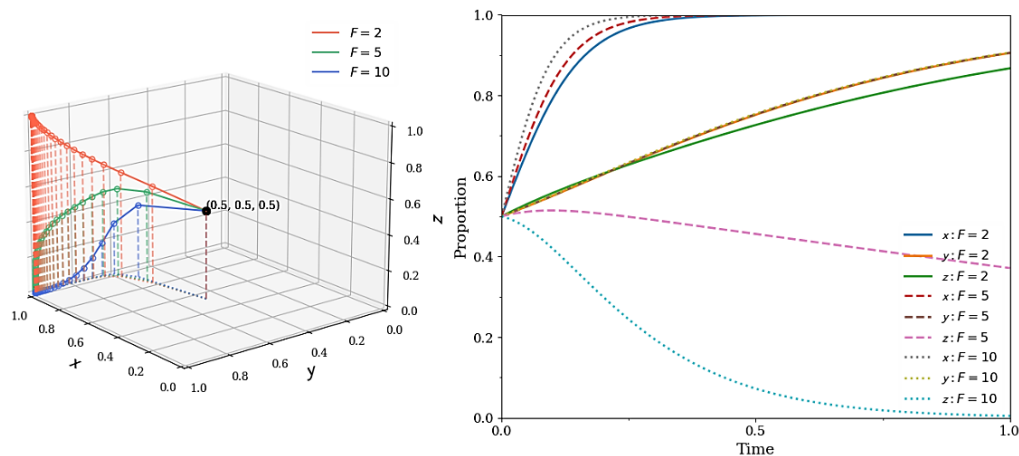


Fig. 7 The impact of changes in penalty F imposed by the upper-level government

Manufacturing firms’ dispatching adjustment costs

The adjustment costs borne by manufacturing firms when engaging in cooperative emergency re-scheduling and capacity reallocation were set to $J = 6, 12, \text{ and } 24$, with the simulation results reported in Fig. 8. Higher adjustment costs slow convergence toward active cooperation. When J increases from 6 to 12, non-cooperation becomes more attractive. The impact is concentrated on firms’ own strategy dynamics, while the local coordination authority and the upper-level

government are only weakly affected, indicating that dispatching adjustment costs mainly operate through firms' private cost-benefit calculus. From a policy and mechanism design perspective, lowering the effective adjustment costs through targeted compensation, expedited procurement support, or temporary capacity subsidies can increase firms' willingness to cooperate and improve the implementability and stability of emergency dispatching at the industrial-park level.

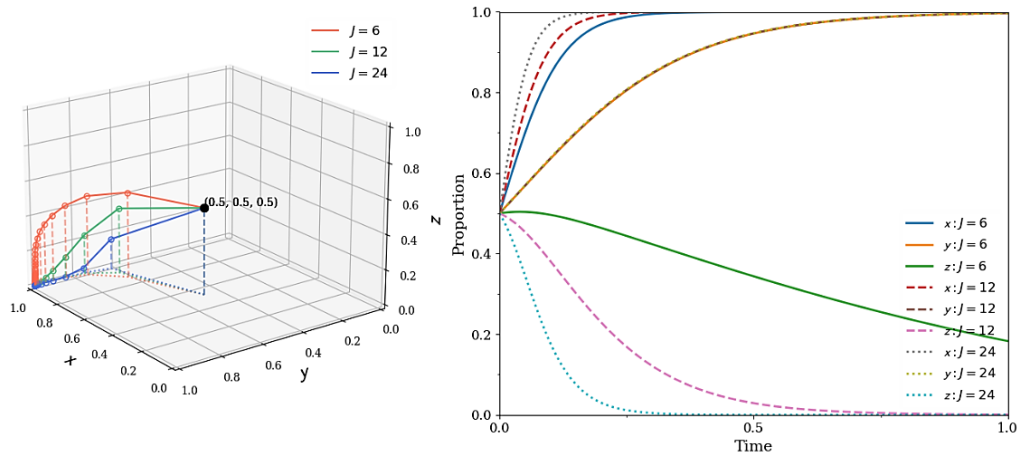


Fig. 8 The impact of firms' resource adjustment costs

Supervision costs of the upper-level government

In the simulations, the supervision cost borne by the upper-level government under strict supervision was set to $Q = 5, 10, \text{ and } 20$, and the corresponding evolutionary trajectories are presented in Fig. 9. The results show that higher supervision costs reduce the attractiveness of strict supervision and shift the upper-level government toward looser supervision, with a noticeable change as Q increases from 10 to 20. This pattern is consistent with boundedly rational adjustment. As enforcement becomes more expensive, its net payoff declines relative to a low-intensity supervisory stance. The direct impact of supervision cost on the local coordination authority and manufacturing firms is limited, implying that supervision cost mainly operates through the upper-level government's own cost-benefit calculus. Therefore, effective oversight design should prioritize cost-efficient enforcement and monitoring arrangements so that supervisory intensity remains sustainable without undermining the overall stability of emergency dispatching.

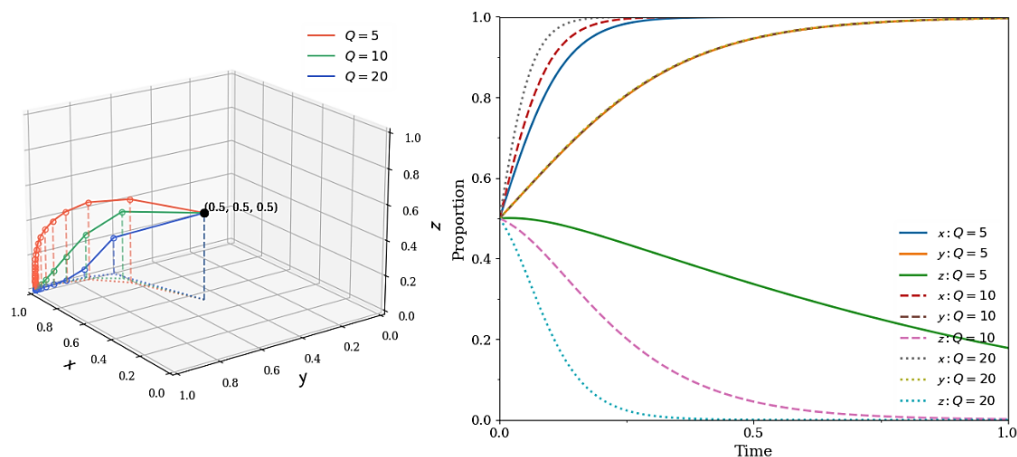


Fig. 9 The impact of changes in the supervision cost

Long-term collaboration payoffs for manufacturing firms

The long-term collaboration payoff for manufacturing firms was set to $X = 0.8, 28, \text{ and } 56$, with results shown in Fig. 10. Larger X accelerates firms' convergence toward active cooperation, especially in the early evolutionary stage, while its marginal effect weakens as the system stabilizes. This suggests that long-term benefits, such as preferential access to shared capacity, priority

support in future disruptions, and relational gains from coordination, can motivate cooperation but show diminishing returns. X has limited direct influence on the local coordination authority and upper-level government, indicating that public actors' strategies depend on broader cost-benefit considerations. Therefore, policy design should strengthen credible long-term cooperation rewards while coordinating them with enforcement and support instruments.

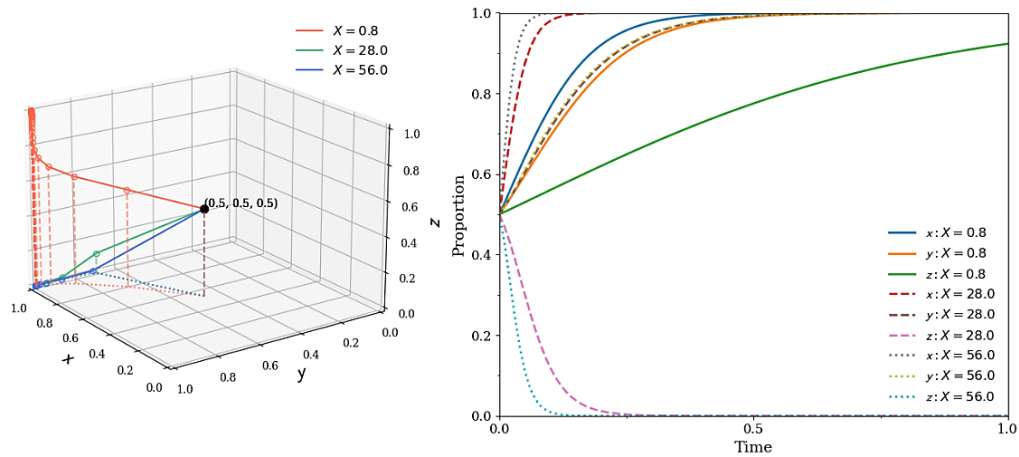


Fig. 10 The impact of changes in the long-term collaboration payoff X

5.3 Comparison of simulation analysis results

Local coordination authority

Across the sensitivity experiments, the local coordination authority's shift toward proactive dispatching is mainly shaped by resource support (A), cooperation-induced effectiveness gains (C), and penalties for passive response (F). Greater upper-level resource support accelerates proactive dispatching by easing implementation constraints in emergency plan activation, schedule revision, information integration, and cross-plant capacity pooling. Higher cooperation-induced effectiveness gains further reinforce this shift by improving schedule feasibility, reducing shop-floor congestion, and supporting throughput recovery. Stronger penalties for passive dispatching also discourage delayed coordination by increasing the expected cost of inaction. Overall, proactive dispatching becomes evolutionarily stable when the authority has sufficient enabling capacity (A), can convert cooperation into execution gains (C), and faces credible discipline (F) against passivity.

Manufacturing firms

Manufacturing firms' strategy dynamics are mainly driven by adjustment costs (J) and long-term collaboration payoffs (X), reflecting a private implementation calculus distinct from public actors. Higher adjustment costs slow the shift toward active cooperation and may push firms toward non-cooperation once costs become moderate, suggesting that the key bottleneck is often shop-floor feasibility rather than willingness. These costs include overtime, changeovers, sequence deviations, expedited procurement, temporary capacity rental, and coordination effort. In contrast, larger long-term collaboration payoffs promote early cooperation, although their marginal effect weakens as the system stabilizes. Overall, firms cooperate when short-run execution costs (J) are manageable and participation offers credible future advantages (X), such as priority access to shared capacity and stable cross-firm routines.

Upper-level government

The upper-level government's supervisory strategy is mainly driven by strict supervision cost (Q), which includes monitoring, inspection, and coordination expenses during disruptions. As Q increases, the system shifts toward looser supervision, reflecting boundedly rational adjustment to the declining net returns of costly oversight. Higher resource support (A) also weakens strict supervision by increasing fiscal and administrative burdens. Moreover, stronger cooperation-induced effectiveness gains (C) and penalties on passive dispatching (F) reduce the need for

continuous high-intensity enforcement. This indicates a substitution mechanism: when horizontal cooperation improves rescheduling implementability or deterrence disciplines passivity, strict supervision yields smaller marginal benefits. Therefore, sustainable oversight should rely on cost-efficient monitoring, selective enforcement, and dynamic adjustment according to rescheduling implementability and firm-level cooperation effectiveness.

In this study, emergency production dispatching is interpreted as the implementation process that makes disrupted production plans executable, rather than as a substitute for a shop-floor scheduling or rescheduling algorithm. Operationally, it may involve order resequencing, machine reassignment, changeover acceleration, overtime arrangement, expedited procurement, temporary outsourcing, cross-firm capacity sharing, and delivery-priority adjustment. A scheduling model may generate candidate rescheduling plans and indicators such as recovery time, tardiness reduction, throughput loss, capacity utilization, and adjustment cost, while the governance layer developed here explains whether these plans can be implemented through proactive coordination, firm cooperation, and appropriate supervision.

6. Conclusion

This study develops a tripartite evolutionary game model to explain how emergency production dispatching becomes implementable when disruptions invalidate shop-floor schedules and require rapid rescheduling. The findings show that emergency dispatching is not only a technical rescheduling problem, but also a governance implementation problem shaped by coordination, firm cooperation, and supervision.

The main implication is that robust disruption response requires a balanced mechanism that reduces firms' adjustment burdens, strengthens repeated cooperation benefits, maintains credible discipline, and calibrates supervision intensity to actual rescheduling implementability. The model is most applicable to settings with a similar coordination-cooperation-supervision structure, such as manufacturing clusters, shared-capacity platforms, multi-plant production networks, and regional emergency supply coordination systems. Future research can calibrate the payoff parameters with industrial data and connect the governance layer to optimization-based rescheduling models.

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