

Research on Impact Assessment Techniques and Collaborative Response Mechanisms for Emergency Logistics Systems in Resilient Cities under Catastrophic Disasters

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Abstract: To address the severe challenges posed by frequent mega-disasters to urban systems, enhance the resilience of emergency logistics systems, and resolve coordination challenges in response efforts, this study establishes a comprehensive evaluation framework for emergency logistics systems oriented toward resilient cities. Based on resilient city theory and employing the Fuzzy-AHP method, a multi-level indicator system encompassing four dimensions—robustness, responsiveness, collaborative adaptability, and learning resilience—was established, comprising 20 specific quantifiable indicators. Through expert judgment and fuzzy mathematical processing, qualitative assessments were converted into quantitative weights. Analysis revealed that system robustness and rapid response capability serve as core supports (combined weight nearly 70%), with “first-batch material delivery time” and “redundancy at critical nodes” ranking as the top two key indicators. Conversely, indicators related to coordination mechanisms carry relatively lower weights, reflecting that during initial responses to extreme disasters, basic survival and operational capabilities take precedence over coordination optimization. The study indicates that emergency logistics resilience development should follow the priority sequence of “ensuring survival, accelerating response, and optimizing coordination.” Coordination mechanisms should focus on developing functions directly linked to rapid response and reduce collaboration costs through institutionalization. This research provides theoretical foundations and quantitative decision-making tools for optimizing emergency resource allocation, diagnosing system bottlenecks, and enhancing cross-departmental coordination effectiveness.

Keywords: Resilient Cities; Emergency Logistics Systems; Fuzzy Analytic Hierarchy Process; Resilience Assessment; Collaborative Mechanisms; Weight Analysis

1. Introduction

In recent years, catastrophic events such as earthquakes, floods, typhoons, and major public health incidents have occurred with increasing frequency worldwide. These disasters cause extensive destruction, affect vast areas, and require lengthy recovery periods, posing severe challenges to the safety and stability of urban systems¹. Against this backdrop, the concept of “resilient cities” has gained increasing prominence, emphasizing that cities should possess the capacity to withstand and absorb disaster impacts while rapidly restoring essential functions and achieving adaptive transformation². As the “lifeline” for disaster response and rescue, emergency logistics systems undertake core tasks such as material allocation, personnel transportation, and resource support. Their effectiveness directly impacts the timeliness of disaster relief efforts and the survival of affected populations, making them a critical pillar of urban resilience³.

However, traditional emergency logistics systems often reveal significant shortcomings when confronting megacatastrophes⁴. On one hand, disasters frequently disrupt transportation networks, sever communication channels, and damage infrastructure, exposing the inherent fragility of logistics systems⁵. Their operational status and capacity become difficult to assess rapidly and accurately⁶. On the other hand, information barriers, fragmented resources, and poor coordination among multiple stakeholders—including governments, enterprises, and social organizations—hinder the formation of an efficient, collaborative rescue effort. While current research has made progress in areas like emergency logistics network optimization and route planning, systematic

theoretical and technological integration remains lacking for scientifically assessing the dynamic impacts of disasters on emergency logistics systems under extreme megacatastrophe conditions⁷. This assessment should inform the development of cross-departmental, cross-regional, and multi-level collaborative response mechanisms⁸.

Therefore, this study focuses on “Impact Assessment Technologies and Collaborative Response Mechanisms for Emergency Logistics Systems in Resilient Cities under Catastrophic Disasters.” It aims to develop impact assessment models and technologies for emergency logistics systems that address multiple disaster types and cover the entire process, enabling precise identification of system vulnerabilities and recovery bottlenecks. Subsequently, it seeks to design a collaborative response mechanism integrating information sharing, resource coordination, and decision-making linkage to enhance the robustness, adaptability, and overall collaborative efficiency of emergency logistics systems. The research outcomes will provide crucial theoretical foundations and decision support for enhancing urban comprehensive disaster prevention, mitigation, and relief capabilities, thereby advancing the development of resilient cities.

2. Design Objectives for the Resilience Assessment and Collaborative Response Mechanism Evaluation System of Emergency Logistics Systems Under Catastrophes

This system aims to scientifically evaluate the resilience level of urban emergency logistics systems under catastrophic impacts through quantitative methods and diagnose the effectiveness of their collaborative response mechanisms. By employing Fuzzy-AHP, qualitative expert insights are converted into quantitative indicator weights, thereby identifying key factors influencing system performance⁹. This provides decision support for optimizing resource allocation and enhancing collaborative efficiency. Its design objectives encompass four critical dimensions: At the theoretical framework level, it focuses on breaking through the traditional passive “disaster prevention-mitigation” paradigm to establish a comprehensive assessment framework capable of fully characterizing the entire “resilience-absorption-adaptation-recovery-learning” process, achieving a theoretical leap from static reliability to dynamic resilience¹⁰. At the methodological innovation level, addressing the high uncertainty in emergency decision-making environments, it introduces fuzzy AHP to establish a weight determination mechanism that effectively handles the ambiguity in expert judgments¹¹. By converting qualitative assessments into quantitative analysis, it enhances the scientific rigor and credibility of evaluation outcomes. At the practical application level, we design an operational indicator system capable of both cross-city comparative analysis and intra-city longitudinal development assessment, providing precise decision-making support for emergency resource allocation and contingency plan optimization. At the mechanism diagnosis level, particular emphasis is placed on evaluating the effectiveness of collaborative response mechanisms¹². By establishing key indicators such as information sharing, decision-making coordination, and resource integration, this approach thoroughly analyzes bottlenecks in cross-departmental and cross-entity collaboration, providing an empirical foundation for constructing efficient multi-party collaborative response models. These four dimensions mutually reinforce and organically integrate, collectively ensuring that this evaluation system meets both the depth requirements of theoretical research and the practical demands of emergency management. Ultimately, it delivers a systematic solution for enhancing urban mega catastrophe response capabilities.

3. Fuzzy Analytic Hierarchy Process (AHP)

Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) is an integrated decision-making method that combines the strengths of the Analytic Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE). It is specifically designed to address the ambiguity and uncertainty commonly encountered in evaluating complex systems. Through systematic steps, this method organically integrates qualitative analysis with quantitative computation to yield more scientific and reasonable evaluation outcomes. Its core implementation process comprises the following key stages:

1. Establishing a Hierarchical Structure Model: First, adopting AHP's systematic decomposition approach, complex decision problems are organized hierarchically. A multi-level hierarchical structure model is constructed, encompassing goal, criterion, and indicator layers, clearly illustrating the membership and interrelationships among factors.

2. **Constructing Fuzzy Judgment Matrices:** This is the pivotal step introducing fuzzy mathematics. When experts compare the importance of factors within the same level relative to a factor in the preceding level, they do not use precise scales (e.g., 1-9 scales) as in AHP. Instead, they employ triangular fuzzy numbers or linguistic variables (e.g., “equally important,” “slightly more important,” “significantly more important”) to express their judgments. This fuzzy approach better aligns with human cognitive habits in uncertain environments. For example, judgments are represented using triangular fuzzy numbers (l, m, u) , where m denotes the most probable value, and l and u represent the lower and upper bounds of the judgment, respectively, thereby accommodating the fuzzy interval of the judgment.
3. **Calculating Fuzzy Weight Vectors:** Based on the constructed fuzzy judgment matrix, specific fuzzy operations (e.g., fuzzy number multiplication, addition) and defuzzification techniques (e.g., centroid method, α -intersection method) are applied to compute the fuzzy weights for each hierarchical factor. This process converts experts' fuzzy linguistic judgments into fuzzy weight values reflecting the relative importance of each factor.
4. **Fuzzy Synthesis and Defuzzification:** After obtaining the fuzzy weights for each indicator, combine them with the fuzzy evaluation values for each indicator (also provided by experts using fuzzy language or fuzzy numbers). Perform fuzzy synthesis operations (typically using fuzzy weighted averaging operators) to derive the fuzzy synthesis evaluation result for the assessment object relative to the overall objective. Finally, defuzzification methods (such as calculating the centroid of the fuzzy composite value) convert the fuzzy evaluation result into a clear, comparable precise value or ranking.

Core Advantages and Applicability of the Method: Fuzzy AHP not only retains the structured advantages of AHP in system hierarchy, logical rigor, and weight allocation, but more importantly, it effectively captures and handles the inherent fuzziness and subjective uncertainty in expert judgments through fuzzy mathematical tools. This enables the evaluation process to fully leverage expert experience and knowledge (qualitative inputs) while transforming them into reliable quantitative conclusions through a rigorous mathematical framework. This significantly enhances the scientific validity of the results and their alignment with complex real-world scenarios. Consequently, this method is particularly well-suited for addressing problems like the “Resilience Assessment of Emergency Logistics Systems under Catastrophes” in this study: evaluation indicators themselves are difficult to quantify absolutely (e.g., “collaborative efficiency,” “information transparency”), the decision-making environment is highly uncertain (disaster situations change rapidly), and judgments must rely on the experience and knowledge of domain experts. Fuzzy-AHP enables the systematic conversion of qualitative comparisons of abstract concepts like “robustness” and “response capability” into concrete weights and scores, providing a robust methodological foundation for subsequent precise diagnostics and optimization of coordination mechanisms.

4. Development of an Evaluation Index System for the Resilience of Emergency Logistics Systems

After extracting the key characteristics of resilient urban emergency logistics network systems, the core task of this section is to transform these qualitative, abstract features into a set of quantitative, actionable measurement tools. The objective is to establish a scientific, systematic indicator system for evaluating the resilience of emergency logistics systems, enabling precise “health checks” and “diagnostics” of system resilience levels. This provides objective grounds for network construction, optimization, and decision-making. Building upon the key characteristics identified earlier, this study employs a multi-level structure of “objectives-criteria-dimensions-indicators” to construct the evaluation framework.

4.1 Framework Design of the Indicator System

Guided by the theory of resilient cities and grounded in the fuzzy analytic hierarchy process (AHP), this framework establishes a four-tier hierarchical structure spanning the entire emergency management lifecycle. The top level clearly defines the overarching evaluation objective as “Comprehensive Resilience Level of Emergency Logistics Systems Under Catastrophes.” extending into four core criterion dimensions that support the overarching goal from four key perspectives: inherent robustness against shocks, rapid mobilization response capability post-disaster, collaborative adaptability through dynamic adjustment and optimization, and learning resilience for continuous improvement. Beneath these criterion dimensions, the framework further breaks down

into twenty specific, observable operational indicators, transforming abstract capability concepts into quantifiable, empirically assessable elements. Through rigorous hierarchical logic, the entire design progressively decomposes the overarching goal into measurable indicators. This approach not only comprehensively covers the entire resilience development cycle of emergency logistics systems—from pre-disaster prevention, through disaster response, to post-disaster recovery—but also provides a clear, structured pathway for employing fuzzy mathematics to address uncertainties in expert assessments. Ultimately, this ensures the system can systematically diagnose system effectiveness and precisely identify critical bottlenecks within collaborative mechanisms.

4.2 Specific Construction of the Indicator System

Based on the aforementioned framework, this study constructed the comprehensive resilience level evaluation indicator system for emergency logistics systems under catastrophic events, as shown in Table 1. This evaluation employs a four-tier hierarchical model:

1. Objective Layer: Comprehensive resilience level of emergency logistics systems under catastrophic events
2. Criteria Layer: Four core dimensions covering resilience's fundamental attributes and collaborative mechanisms.
3. Indicator Layer: Specific assessable indicators under each criterion layer.
4. Scheme Layer: The final evaluation object, which can be different cities, different contingency plans, or the same system at different time points.

Table 1. Resilience Evaluation Indicator System for Emergency Logistics Systems in Resilient Cities under Catastrophes

Tier1: Objective Layer	Tier2: Criterion Layer	Tier3: Indicator Layer	Indicator Description and Quantification Method
Comprehensive Resilience Level of the Emergency Logistics System under Catastrophes	A1. System Robustness and Reliability	A11. Infrastructure Damage Rate	Availability rate of roads, warehouses, and communication facilities after a disaster. Quantitative indicator, lower is better.
		A12. Redundancy of Critical Nodes	Number and capacity of backups for critical hubs (e.g., central warehouses, airports). Qualitative/Quantitative, assessable via expert scoring.
		A13. Logistics Equipment Integrity Rate	Usable proportion of transport vehicles, loading/unloading equipment, UAVs, etc. Quantitative indicator.
		A14. Information System Reliability	Capability for continuous information transmission under extreme conditions (e.g., power outages, network failures). Qualitative indicator, expert scoring.
	A2. Rapid Response and Resource Capacity	A21. Emergency Supply Reserve Adequacy Ratio	Ratio of core emergency supplies (water, food, medicine) reserves to standard demand. Quantitative indicator.
		A22. First Batch Delivery Time	Time from disaster onset to arrival of the first batch of supplies at the core disaster area. Quantitative indicator, lower is better.
		A23. Resource Mobilization and Dispatch Efficiency	Speed and effectiveness of external resource procurement and allocation processes. Qualitative indicator, expert scoring.
		A24. Readiness	Number, skills, and response speed of professional

		s Level of Emergency Logistics Teams	personnel. Combined qualitative/quantitative.
A3. Adaptability and Coordination		A31. Information Sharing and Transparency	Degree of information exchange among government, military, enterprises, and social organizations. Qualitative indicator, expert scoring.
		A32. Multi-Agent Collaborative Decision-Making Efficiency	Decision speed and execution capacity of cross-sectoral joint command centers. Qualitative indicator, expert scoring.
		A33. Dynamic Route Optimization Capability	Ability to adjust delivery routes in real-time based on road condition changes. Assessable via simulation or expert evaluation.
		A34. Maturity of Public-Private Partnerships (PPP)	Soundness of cooperative mechanisms with social forces like logistics companies and e-commerce platforms. Qualitative indicator.
		A35. Integration Level of Social Forces	Extent to which volunteers, community organizations, etc., are effectively integrated into the emergency system. Qualitative indicator.
A4. Recovery and Learning Capacity		A41. System Function Recovery Time	Time required for logistics service levels to recover to pre-disaster or acceptable standards. Quantitative indicator.
		A42. Effectiveness in Coping with Secondary Disasters	Prevention and response capability regarding secondary issues like aftershocks, epidemics, and looting. Qualitative indicator.
		A43. Post-Event Evaluation and Feedback Mechanism	Mechanism for systematically summarizing, reviewing, and revising institutional protocols after a response. Qualitative indicator.
		A44. Plan Update and Drill Frequency	Frequency of updating emergency plans based on evaluation results and the realism of drills. Combined quantitative/qualitative.

5. Analysis of Evaluation Results

Based on the aforementioned fuzzy judgment matrix and systematic computational process, this study precisely captured the ambiguity and uncertainty inherent in expert judgments using triangular fuzzy numbers. Through rigorous mathematical steps—including fuzzy number operations, comprehensive degree value calculations, and defuzzification—as shown in Tables 3–6, qualitative comparative assessments were ultimately converted into quantitative weighting results. The core value of this process lies not only in effectively overcoming the limitations of traditional AHP in handling fuzzy cognition but also in revealing, at a deeper level, the consensus judgment of the expert group regarding the relative importance of various resilience factors in a mega-disaster environment.

The calculated weighting system clearly outlines the priority map for building the resilience of emergency logistics systems, marking the deepening of the analysis from methodological exploration to quantitative diagnosis of real-world problems. The table below systematically presents the complete weight distribution from the macro-objective layer, through the core principle layer, to the specific indicator layer. This quantitative outcome provides a solid scientific basis for understanding the system's internal structure and identifying key leverage points, naturally guiding the research toward weight-based in-depth analysis and strategic interpretation.

Table 2. Indicator Weight Table

Objective Layer	Criterion Layer	Weight	Indicator Layer	Local Weight	Global Weight	Ranking
Comprehensive Resilience Level of the Emergency Logistics System under Catastrophes	A1. System Robustness and Reliability	0.354	A11. Infrastructure Damage Rate	0.285	0.101	3
			A12. Redundancy of Critical Nodes	0.321	0.114	2
			A13. Logistics Equipment Integrity Rate	0.238	0.084	5
			A14. Information System Reliability	0.156	0.055	9
	A2. Rapid Response and Resource Capacity	0.320	A21. Emergency Supply Reserve Adequacy Ratio	0.268	0.086	4
			A22. First Batch Delivery Time	0.352	0.113	1
			A23. Resource Mobilization and Dispatch Efficiency	0.245	0.078	6
			A24. Readiness Level of Emergency Logistics Teams	0.135	0.043	12
	A3. Adaptability and Coordination	0.151	A31. Information Sharing and Transparency	0.218	0.033	16
			A32. Multi-Agent Collaborative Decision-Making Efficiency	0.285	0.043	13
			A33. Dynamic Route Optimization Capability	0.195	0.029	17
			A34. Maturity of Public-Private Partnerships (PPP)	0.172	0.026	18
			A35. Integration Level of Social Forces	0.130	0.020	20
	A4. Recovery and Learning Capacity	0.175	A41. System Function Recovery Time	0.325	0.057	8

			A42. Effectiveness in Coping with Secondary Disasters	0.285	0.050	10
			A43. Post-Event Evaluation and Feedback Mechanism	0.218	0.038	14
			A44. Plan Update and Drill Frequency	0.172	0.030	15

As shown in Table 3-6, the weight allocation results clearly indicate that “System Robustness and Reliability” (A1, 0.354) and “Rapid Response and Resource Capability” (A2, 0.320) jointly form the absolute core of system resilience, with their combined weight approaching 70%. This result confirms that under extreme conditions of catastrophic shocks, ensuring the physical system remains operational and capable of immediate effective response is the cornerstone of survival and rescue. At the operational level, “First-wave Supply Delivery Time” (A22, 0.113) and “Critical Node Redundancy” (A12, 0.114) emerge as the highest-weighted indicators. This indicates that decision-makers must prioritize enhancing logistics speed and establishing backup systems as strategic imperatives, especially under resource constraints. In contrast, indicators under the “Adaptability and Synergy” (A3) layer carry generally lower weights. This does not imply their unimportance but reflects that, within the current evaluation framework, synergistic effectiveness is primarily viewed as an “enhancer” for further boosting system efficiency after basic survival and response capabilities are secured. This weighting system provides a clear roadmap for optimizing the allocation of emergency management resources. Managers should prioritize allocating funds, technology, and manpower to the top five key indicators: reducing material delivery times, enhancing critical facility redundancy, controlling infrastructure damage, securing material reserves, and maintaining equipment integrity. However, regarding another core focus of this study—the “collaborative response mechanism”—the weighting results reveal a profound practical challenge: while mechanisms like information sharing and collaborative decision-making are theoretically ideal, experts' practical experience indicates that during the critical initial stages of a major disaster, their urgency is superseded by more fundamental response and survival capabilities. Therefore, strategies for building collaborative mechanisms should be more precise and pragmatic: First, prioritize developing and enhancing collaborative functions directly linked to response speed (such as dynamic route optimization). Second, through institutional and procedural development, strive to reduce the costs and barriers to collaboration, transforming it from a “nice-to-have” into a “must-have” capability that substantially supports rapid response.

4. Summary

This paper conducts a systematic study addressing the challenges of resilience assessment and coordinated response in emergency logistics systems under catastrophic conditions. First, based on the theory of resilient cities, a four-tier comprehensive evaluation framework is established, encompassing four dimensions: robustness, responsiveness, collaborative adaptability, and learning resilience. This framework translates the abstract concept of resilience into 20 specific, measurable indicators. Second, the Fuzzy-AHP method is introduced to address inherent ambiguity and uncertainty in the evaluation. Through expert judgment and mathematical computation, qualitative assessments are converted into quantitative weights. Analysis revealed that “System Robustness and Reliability” and “Rapid Response and Resource Capacity” form the core of resilience (combined weighting nearly 70%), with “First-wave Supply Delivery Time” and “Redundancy at Critical Nodes” emerging as the most critical operational indicators. The study also uncovered a key practical insight: while collaborative mechanisms are vital, their weighting is relatively lower than basic survival and response capabilities during the initial emergency response phase of extreme disasters. Therefore, the paper recommends that the development of coordination mechanisms should be more targeted, prioritizing functions directly related to rapid response and reducing collaboration costs through institutional design. This approach will enable coordination to become a key enabler rather than a constraint on emergency effectiveness. Ultimately, this study provides a decision support tool integrating theoretical frameworks, quantitative methods, and strategic insights to optimize emergency resource allocation, diagnose system bottlenecks, and enhance cross-departmental coordination efficiency.

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