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Barriers to Communications Facility Support in China: A Fuzzy DEMATEL Analysis from an Emergency Security Perspective

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Abstract: The importance of reliable communication infrastructure in emergencies, such as disaster relief and real-time decision-making, has become increasingly critical. However, traditional communication support systems often fall short in meeting real-world needs. This study uses the Fuzzy Decision-Making Trial and Evaluation Laboratory (fuzzy-DEMATEL) method to systematically analyze the complex interdependencies among key barriers, providing a comprehensive understanding of the root causes hindering emergency communication capabilities. The research identifies distinct critical factors, such as personnel, which has been underemphasized in existing literature, highlighting the crucial role of frontline staff in maintaining communication systems during crises. The paper also offers policy recommendations to enhance communication facility support, broadening the focus from equipment attributes to include broader systemic and environmental factors. Additionally, it advocates for full lifecycle management of communication facilities, from design and planning to maintenance, in order to improve emergency preparedness. The findings provide valuable insights for policymakers and lay the groundwork for future research aimed at refining emergency communication frameworks, particularly in the context of technological advancements and evolving disaster scenarios.

Keywords: Barriers, Communications Facility Support, Emergency security; Fuzzy DEMATEL

1 INTRODUCTION

Infrastructure is essential to the functioning of any country or region, providing material support for production and daily life and contributing to social well-being [1]. Among the key elements of infrastructure, communication facilities are foundational to the digital economy and the development of modern information societies [2,3,4]. As communication technology becomes more integrated into the economy and society, the telecommunications industry’s role has grown increasingly significant, evolving into a crucial pillar for information transmission [5]. The stability and reliability of communication systems are integral to national security, economic development, and social stability.

Communication security, defined as the protection of infrastructure and data from unauthorized access while ensuring service availability [6,7], is a critical aspect of communication systems. A vital component of communication security is equipment support, which includes maintenance, emergency repairs, and lifecycle management. Adequate equipment support is essential for the regular operation of communication systems and for enabling rapid response in emergencies [8].

In emergency management, communication facility support faces heightened challenges. Emergency security, which ensures the flow of information during crises, plays an essential role in disaster relief, rescue operations, material transportation, and real-time disaster communication [9]. An effective emergency security system, which includes prevention, monitoring, response, and recovery phases [10], is crucial for maintaining social order and ensuring efficient decision-making during emergencies.

Communication facilities are central to this emergency system. Emergency communication mechanisms integrate technological means to create networks that overcome conventional system limitations, directly influencing the efficiency of emergency decision-making and operations [11]. The reliability and coverage of communication facilities are therefore vital for public service delivery and effective governance during emergencies [12]. Major economies, including China, the United States, Japan, and the European Union, have incorporated emergency security into their communication infrastructure. For example, the 2008 Wenchuan earthquake in China highlighted weaknesses in communication systems, prompting the government to enhance seismic analysis and establish more robust emergency communication mechanisms [13]. Similarly, Japan's response to the 2011 earthquake and tsunami, which caused significant delays in restoring communication systems, led to the inclusion of communication support in contingency plans [14].

These events underline the importance of integrating an emergency perspective into the construction of communication support systems. However, the pathway to implementing an effective emergency security framework remains unclear due to multiple, interconnected barriers. Traditional emergency communication systems often fail to meet real-world needs [15], and there is insufficient systemic understanding of how these barriers interact and constrain the effectiveness of communication facilities during emergencies.

As national communication infrastructures grow in complexity, ensuring their resilience during major emergencies becomes more challenging. Communication failures can severely weaken emergency response efforts [16], highlighting the need for countries to improve the resilience of their communication systems. Therefore, a systematic approach to studying the barriers and their interactions is crucial for enhancing the emergency security capabilities of communication facilities.

In China, while communication facility support has achieved significant progress and is globally competitive, challenges remain due to factors such as policy frameworks, technological limitations, population distribution, and geography [17]. These barriers hinder the country's emergency security capabilities, which still require further improvement. This study focuses on China as a case study, a large, developing country committed to strengthening its emergency security infrastructure. The findings offer insights that are applicable not only to China but also to other nations looking to enhance their communication infrastructure.

This research addresses two key questions:

RQ1: What are the primary barriers constraining communication facility support capability in China as it refines its emergency management system?

RQ2: How can the interdependencies among these barriers be identified and addressed to overcome the root causes?

To address the research questions, this study employs the fuzzy Decision-Making Trial and Evaluation Laboratory (fuzzy-DEMATEL) technique to develop an analytical framework that systematically analyzes the complex interdependencies among these barriers. Unlike traditional DEMATEL, fuzzy-DEMATEL is designed to handle fuzzy uncertainty, offering a deeper understanding of causal relationships, and reducing subjective judgment [18,19,20].

2 LITERATURE REVIEW

2.1 *COMMUNICATION FACILITIES AND SUPPORT*

Communication support is defined as the activities organized and implemented to meet the needs of emergency command operations through communication liaison [21]. As a comprehensive system engineering task, it encompasses multiple facets, including infrastructure deployment, technical equipment configuration, and emergency response protocols.

Scholarly work on communication facility support emphasizes systematic construction and operational efficiency. For example, scholars highlight a cyclical management mechanism of "prevention-preparation-response-recovery", outlining stage-specific priorities: risk assessment and optimized facility layout in prevention; backup resources and contingency planning in preparation; rapid deployment and fault repair in response; and post-disaster reconstruction with capacity enhancement in recovery [22]. Concurrently, studies address the optimization of resource allocation. For instance, scholars propose a dynamic resource allocation model utilizing Geographic Information Systems (GIS) and big data analytics [23]. This model aims to optimize the distribution of communication resources by integrating factors such as regional disaster risk, population density, and economic development levels.

The evolution of communication facility support is also closely tied to broader digitalization strategies. Advances in national digital infrastructure initiatives have led to significant achievements, including global leadership in the deployment of technologies such as 5G [24,25]. Despite this progress, disparities in support capabilities persist, notably between urban and rural areas and across different geographical regions. Scholars observe that the focus is shifting from "scale expansion" to "quality improvement", with increasing emphasis on technological upgrades, intelligent management, and enhanced emergency response [26]. For example, smart city developments are fostering the integration of communication facilities with the Internet of Things (IoT) and big data technologies, thereby refining support services.

2.2 *COMMUNICATION FACILITY SUPPORT FROM AN EMERGENCY PERSPECTIVE*

From an emergency management standpoint, communication facility support is intrinsically linked to "emergency communications", defined as communications utilized in urgent situations to save lives or manage crises [27]. The International Telecommunication Union (ITU) characterizes it as the ICT solutions and services that support disaster management authorities across all disaster phases (early warning, preparedness, response, and recovery), emphasizing attributes like reliability, timeliness, and flexibility [28,29]. Emergency command communication support capability thus refers to the integrated capacity through personnel, technology, equipment, and mechanisms to deliver efficient and reliable communication for intelligence gathering, data transmission, and command dispatch at disaster sites. Maintaining uninterrupted communication and ensuring the rapid restoration of damaged systems are critical throughout emergency response and rescue operations [30]. Among available technologies, wireless communication networks are regarded as particularly promising infrastructure for emergency communications [31].

Extant research examining this relationship often focuses on risk prevention and systemic resilience. For example, Kong [32], applying emergency management and resilience theory, developed an evaluation index system for the emergency resilience of construction projects under extreme disasters. By combining the Analytic Hierarchy Process (AHP) with fuzzy comprehensive evaluation, they proposed a method for integrating qualitative and quantitative assessments. Other studies stress the importance of system integration and unified management mechanisms [33], advocating for the incorporation of communication protection into overall emergency security planning with shared information, equipment, and human resources. Empirical examples, such as integrated management practices in Japan, have demonstrated improvements in communication system response efficiency and reductions in economic losses from interruptions.

The integration of communication support within emergency management systems often reflects specific governance frameworks [34]. Some systems are characterized by unified national command, territorial management, and multi-stakeholder collaboration. Strengthening the link between communication protection and emergency security typically requires coordination among government departments, telecommunications enterprises, and social organizations, exhibiting a “mobilization-coordination” dynamic [35]. In such models, telecommunications enterprises often bear responsibility for daily facility maintenance, while government departments coordinate cross-regional and cross-departmental emergency efforts, forming a collaborative pattern. The adoption of technologies like 5G and IoT is further enabling intelligent monitoring and early warning systems [36]. Real-time monitoring of facility status helps identify potential risks proactively, thereby reducing pressure on emergency response. Concurrently, the integration of advanced technologies such as drone inspections and satellite communications into emergency operations is fostering a shift from “passive response” to “active prevention” in communication facility support [37].

2.3 BARRIERS TO EMERGENCY SECURITY OF COMMUNICATION FACILITIES IN CHINA

Despite its importance, the implementation of effective emergency security for communication facilities faces multiple, often context-specific, barriers [38]. Many studies concentrate on technical limitations, including network coverage, equipment reliability, and technological compatibility. Empirical research indicates that inadequate coverage of conventional communication networks in remote and rural areas remains a significant technical barrier for emergency communications [39,40]. Scholars identify poor interoperability between different communication technologies as a major hindrance, as equipment from different manufacturers with varying standards can impede information sharing and collaborative rescue efficiency during emergencies [41]. Furthermore, the reliability and durability of communication equipment in extreme environments are critical concerns, with conventional equipment often suffering performance degradation or failure under such conditions, failing to meet emergency needs [42].

Other lines of inquiry focus on issues such as uneven technological development, gaps in infrastructure coverage, and insufficient backup systems [43]. Regarding emerging technologies, there is a noted need for more comprehensive expertise in emergency security applications, highlighting the potential importance of AI-assisted decision-making [44]. Moreover, despite rapid advancements, gaps remain in core technologies like satellite communication compared to some developed economies, limiting technical support in complex emergency scenarios. Studies of multiple disaster-affected areas reveal pronounced urban-rural disparities in communication technology development, with rural and remote areas possessing relatively backward emergency communication capabilities, complicating effective emergency response. While extensive communication networks exist, significant shortfalls persist in dedicated emergency communication infrastructure. Consequently, recommendations often include strengthening rural infrastructure, improving emergency plans and mechanisms, and increasing stocks of emergency supplies to mitigate regional imbalances [45]. Additionally, backup support systems for communication infrastructure are frequently underdeveloped; many communication-base stations lack independent emergency power supplies, and backup communication links are insufficient, heightening the risk of interruptions. Financial mechanisms for emergency communications also present challenges. Scholars point to two primary issues: a heavy reliance on government appropriations without a diversified funding system, and a lack of long-term investment planning, which undermines sustainability in responding to large-scale, prolonged disasters [46]. Existing research collectively outlines multiple barriers but often lacks a systematic analysis of their underlying causal mechanisms and interacting factors, which hinders the development of comprehensive solutions.

In summary, the barriers to communication facility support are multifaceted, stemming from regional disparities, institutional adaptation challenges, and technological gaps. Infrastructure deficiencies, such as imperfect backup power systems, are prominent. Furthermore, unclear inter-departmental information protocols and potential conflicts between administrative divisions and emergency command structures can impede coordination. Therefore, a systematic analysis of the barriers and their causal interrelationships, tailored to specific national contexts, is of strategic importance for advancing emergency communication capabilities.

2.4 SUMMARY OF EXISTING LITERATURE

Existing research provides in-depth discussions on communication facility support and emergency communications, identifying numerous barriers that require further investigation and refinement, thereby laying a theoretical foundation for this field. However, focused studies on the barriers to communication support within specific emergency management contexts remain limited. This gap will be addressed in the subsequent chapters of this work.

First, research on barriers to communication facility support is often fragmented and lacks a comprehensive, systematic analytical framework. Most studies concentrate on isolated barrier types, such as technological or environmental factors, while other dimensions, including maintenance logistics and personnel incentive structures, remain underexplored. Moreover, there is insufficient analysis of the interactions and intrinsic connections between different barriers. These barriers constitute a complex system where various factors interact and collectively constrain overall support capability.

Second, much of the existing research focuses on general emergency scenarios and lacks specificity to national conditions. Countries with large populations, vast territories, complex geographies, and unique emergency management systems may encounter distinct challenges and manifestations of these barriers. Existing studies often struggle to fully capture these contextual specifics, and quantitative research in this area remains relatively scarce.

Third, the solutions proposed in the literature are frequently superficial, lacking practical and operable strategies tailored to specific contexts. Recommendations often remain at a macro level, such as strengthening infrastructure or improving coordination mechanisms, without providing targeted, actionable measures for barriers. Furthermore, the potential application of new technologies like big data and artificial intelligence to overcome these barriers and enhance support capabilities has not been thoroughly explored.

To address these deficiencies, this study takes communication facility support in emergency security scenarios within a specific national context as its focus. It aims to systematically identify key barriers, employ the fuzzy DEMATEL technique to analyze their interrelationships, and propose targeted solutions considering relevant policies and conditions. This research seeks to enrich the fields of emergency communications and emergency security management, provide practical references for enhancing emergency communication support capabilities, and offer insights for other contexts seeking similar improvements.

3 METHODOLOGY AND DATA

3.1 DEMATEL TECHNOLOGY

The DEMATEL technique not only establishes relationships between variables but also reveals the degree of overall influence among research factors [47]. Centered on graph theory, this technique can handle heterogeneous factors [48], unlike decision tools like SEM or ISM, does not require large amounts of data. Through the influential relation map (IRM), it can clearly distinguish between cause-and-effect groups [49]. The DEMATEL technique is considered most suitable for addressing the research questions, as it effectively reveals causal relationships among system variables [50]. As mentioned previously, we adopt fuzzy-DEMATEL which is an advanced variant of the standard DEMATEL technique to address the fuzziness, bias, and uncertainty inherent in human judgment [19], [51]. By simulating the continuity and uncertainty of human thinking, this method not only identifies key barriers but also reveals the causal hierarchical relationships among them, providing a precise theoretical basis for proposing targeted governance strategies.

As shown in Figure 1, the study follows a three-stage process. Stage 1 established the initial list and identified the barriers to communications facility security support within emergency and crisis context, which was competed in previous section. Stage 2 and 3 are presented in this section.

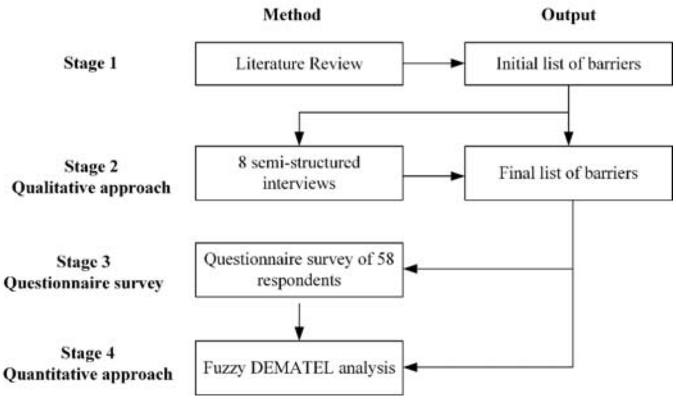

FIGURE 1 RESEARCH FRAMEWORK

3.2 STAGE 2: QUALITATIVE APPROACH AND FINALIZING THE LIST OF BARRIERS

The second stage employed a qualitative method to finalize the list of barriers through eight semi-structured interviews with key stakeholders. This list, along with explanations for each barrier, was translated into Chinese. To ensure clarity and avoid any ambiguity, the translation was cross-verified by two researchers fluent in both English and Chinese.

Subsequently, a qualitative approach was followed, involving the eight interviews to finalize the list of barriers. Leveraging its extensive professional network in the communications sector, the research team conducted the eight semi-structured, face-to-face interviews across three Chinese cities, Chengdu, Beijing, and Tianjin, between January 2025 and April 2025. The eight interviewees were key stakeholders (as shown in Table 1). All participants were managers or senior managers with over three years of industry experience and were considered qualified to provide valuable insights on the initial list of barriers.

TABLE 1. PROFILE OF INTERVIEWEES

Organization type	Number of interviewees
Employees working at a communications facility	4 [2 senior managers, 2 managers]
Management team of the central corporation	2 [1 senior manager, 1 manager]
Scientists and Scholars in relevant fields	2 [1 Professor, 1 Associate Professor]
Total	8

Each interview lasted approximately 40 minutes. The interviewees were asked to review the initial list of barriers, comment on the validity, especially within an emergency and crisis context, and identify any potentially overlooked barriers.

The interview process was concluded after the eighth interview, as subsequent participants no longer provided new insights.

Based on the suggestions received, the financing barrier was merged into the policy barrier. This merger was justified because, within the emergency and crisis context, finance is no longer considered a primary barrier to facility security support. Additionally, a new barrier, location, was added due to its significant role. The interviews also suggested that patrol inspectors should participate in the final survey on data collection, recognizing their important role. The resulting final list of nine barriers is described below:

B1 – Quality: This refers to the weak stability of communications facilities and equipment across various environments. The quality of communications facilities is specifically weakened by their inability to maintain consistent performance and reliability under varying conditions such as extreme temperatures, physical vibrations, electromagnetic interference, and high humidity. These weaknesses often result in unexpected downtime, data packet loss, reduced bandwidth efficiency, and compromised service integrity.

B2 – Location: This barrier pertains to the communications facility being located in a remote or non-urban area, particularly in high-altitude regions with harsh climates and challenging living conditions. Facilities in such locations are exposed to severe climates characterized by biting winds, treacherous terrain, and thin air, which exacerbate already poor living conditions. For instance, facilities in desert areas may overheat and shut down, while coastal installations are vulnerable to salt spray corrosion. These environmental conditions can lead to premature hardware failure, signal attenuation, and increased bit error rates, ultimately undermining system stability.

B3 – Maintenance Convenience: This barrier reflects the difficulty of disassembling, substituting parts, and overall complexity in maintaining facilities and equipment. Maintenance challenges include poor part availability, such as proprietary or obsolete parts, sourcing complexity that requires parts from multiple suppliers with varying reliability, lack of standardization with non-standardized parts making quick replacements impossible, insufficient diagnostics with limited error codes or indicators, and high training demands with complex systems requiring specialized training for basic tasks. These factors increase labor costs and reduce efficiency in maintenance operations.

B4 – Personnel: This refers to the inadequacy of personnel in terms of number, stability, psychological resilience, skills, and dedication. Common issues include chronic understaffing, high turnover rates, reduced capacity to handle crises, insufficient technical expertise, and lack of commitment to responsibilities. These weaknesses ultimately jeopardize the reliability and security of critical communication infrastructure.

B5 – Training: This barrier highlights the inadequacies of the training program, such as infrequent training sessions, insufficient emergency drills, and a lack of new and advanced training methods. Infrequent training hampers skill reinforcement and knowledge retention. Insufficient emergency drills leave personnel unprepared for crisis scenarios due to the lack of realistic, repetitive practice. Moreover, outdated training methods hinder the development of essential skills needed for effectively using modern technology, leading to decreased operational readiness, increased safety risks, and low morale among staff.

B6 – Safeguard: This barrier reflects the weakness or absence of safeguard systems against physical and cyber security threats. Communications facilities often lack adequate protections against these threats, leaving critical infrastructure vulnerable to unauthorized access, data interception, service disruption, and potential compromise of national security. These vulnerabilities arise from systemic weaknesses in the design, implementation, and maintenance phases.

B7 – Advanced Technology: This barrier concerns the weak integration of advanced technologies such as 5G, artificial intelligence (AI), and the Internet of Things (IoT) into security support systems for communications facilities. The challenges include inadequate encryption and authentication mechanisms, gaps in legacy infrastructure, scalability and resource constraints, and lack of standardization and regulatory compliance. These issues prevent robust and seamless implementation of modern technologies.

B8 – Performance Evaluation: This barrier pertains to the weakness in the performance evaluation systems for personnel working at communications facilities. The systems often lack adequate metrics, feedback mechanisms, and alignment with operational goals. A weak performance evaluation system undermines operational excellence, erodes the human foundation of reliable communication, and impairs the facility's ability to respond effectively to both routine and emergency situations.

B9 – Policy and Management: This barrier highlights weaknesses in policy and management, specifically the low priority given to communications facility security support within government policy and corporate strategy. Contributing factors include insufficient strategic prioritization and resource allocation, outdated regulatory frameworks, deficient governance structures, a reactive approach rather than a proactive one, inadequate risk management, and neglect of human factors and supply chain risks. These issues can lead to severe consequences, including increased susceptibility to network outages, data breaches, economic espionage, and threats to national security. Given the interconnected nature of modern infrastructure, a failure in one facility can cause widespread disruption.

3.3 *STAGE 3: SURVEY AND DATA COLLECTION*

Based on the final list of barriers identified above, the researchers designed a questionnaire to collect evaluators' rating on the mutual effects among the barriers, for use in a Fuzzy DEMATEL analysis.

The finalized questionnaire included the identified barriers and their corresponding explanations. Using a convenience sampling approach, supplemented with the snowball method, questionnaires were distributed to potential evaluators across five key stakeholder groups: (1) personnel from communications facilities located in urban areas, (2) personnel from communications facilities located in remote areas, (3) the management teams of central corporations, (4) patrol inspectors assigned by central corporations, and (5) scientists and scholars within relevant field. Participation was voluntary and the respondents were assured of the confidentiality of their responses, which would be used solely for the purposes of academic research. To ensure the data quality and validity of the results, recruitment was restricted to participants holding middle-level (e.g., manager) or senior-level (e.g., senior manager, associate professor, or professor) positions. A total of 110 questionnaires were returned from the five groups of evaluators, among which 58 responses were considered valid and suitable for analysis. Table 2 presents the profile of the valid survey participants.

TABLE 2 EVALUATOR DEMOGRAPHICS

Stakeholder Group	No.	Industry Experiences (years)				Designation	
		1-3	4-7	8-12	≥13	Middle Level	High level
Communications Facilities located in remote areas	12	2	5	5	0	7	5
Communications Facilities located in urban areas	10	5	1	4	0	6	4
Management Teams of central corporation	14	2	7	2	3	8	6
Scientists & Scholars	11	5	2	3	1	4	7
Patrol Inspectors assigned by central corporation	11	3	5	3	0	6	5
Total	58	17	20	17	4	31	27

3.4 *STAGE 4: FUZZY DEMATEL ANALYSIS*

In the third stage, we employed fuzzy DEMATEL technique to analyze the barriers and construct a cause-effect relationship map. Numerous sophisticated techniques are available for analyzing complicated interdependencies among factors, including analytic hierarchy process (AHP), analytic network process (ANP), structural equation modelling (SEM), and interpretive structural modelling (ISM) [52]. Besides these, DEMATEL is a prevalent scientific multi-criteria decision-making (MCDM) technique in recent studies due to its advantage in elucidating the complex structure of direct and indirect cause-effect relationships among barriers [53,54,55,56].

To address the inherent subjectivity, vagueness, and potential bias in human judgment, scholars have developed multiple variants of the standard DEMATEL technique [56]. Fuzzy DEMATEL is one of the most widely methods [54,55,57]. For example, in the research on the evaluation index system of earthquake rescue robots, we adopted the fuzzy DEMATEL method to analyze the causal relationships among 23 evaluation indicators, verifying the effectiveness of this method in the classification of emergency management indicators. We use three-dimensional fuzzy numbers (e.g., 0.75, 1, 0.25) rather two-dimensional grey numbers (e.g., 0.5, 0.25) [56], and it is able to distinguish the complicated factors into cause and effect groups, and manage the inner dependencies [58].

In this study, we applied the fuzzy DEMATEL method to analyze the barriers to communications facility security support within a crisis and emergency context. Its technique is outlined below [49,52,56], building upon the methodologies established in prior research.

Step 1: Finalize the decision variables (final list of barriers)

In this step, the initial list of barriers was finalized through a qualitative process involving 8 interviews (as detailed in Section 3.1). This resulted in the determination of nine key barriers. We set the barriers defined as B={Bi | i=1,2,...,n},n=9.

Step 2: Construct a pairwise comparison matrix for barriers

This step was executed during the survey and data collection phase (Stage 3). In this step, each participant was asked to evaluate the direct influence between pairs of barriers, specifically, the degree to which barrier i affects barriers j. Evaluations were made using the rating scale ranging from 0 to 4 [19], as shown in Table 3, where: 0 = no influence, 1 = very low influence, 2 = low influence, 3 = high influence, and 4 = very high influence. Based on their expertise and industry experience, the participants rated the barrier for each barrier pair. These evaluations were then used to construct the initial direct-relation matrix.

TABLE 3 FUZZY LINGUISTIC SCALE AND TRIANGULAR FUZZY NUMBERS

Effect rating scale	Linguistic Description	Equivalent triangular fuzzy numbers (TFNs)
0	No influence (No)	(0,0,0.25)
1	Very low influence (VL)	(0,0.25,0.5)
2	Low influence (L)	(0.25,0.5,0.75)
3	High influence (H)	(0.5,0.75,1.0)
4	Very high influence (VH)	(0.75,1.0,1.0)

Step 3: Generating the fuzzy initial direct-relation matrix

In this step, triangular fuzzy numbers (TFNs) were employed to establish the fuzzy initial direct-relation matrix. Each TFN is represented by a triplet $[l_{ij}, m_{ij}, r_{ij}]$, where l denotes the smallest possible value, m denotes the most promising value, and r denotes the largest possible value, with the constraint $l \leqslant m \leqslant r$. For the kth participant, the evaluation was denoted as $x_{ij}^k = [l_{ij}^k, m_{ij}^k, r_{ij}^k]$, where k = 1, 2, 3 4...K, and K presents the total number of survey participants. The elements on the main diagonal of the matrix for any participant k ($1 \leqslant k \leqslant K$), denoted $x_{ij}^k = 0$ when i=j, indicating that a barrier does not influence itself.

Using the predefined TFNs scale presented in Table 4 [19,49] , the pairwise comparison matrix obtained in step 2 were transformed into a triangular fuzzy matrix. A sample triangular fuzzy matrix is provided Appendix B.

Step 4: Develop the initial direct-relation matrix (A)

Given that the fuzzy scores are not available for matrix operation, this study employs the technique of converting fuzzy data into crisp scores (CFCS) [59] to defuzzify the complexity of TFNs and convert the aggregated fuzzy data into a shingle crisp value for subsequent analysis. Based on the followed equations, we obtain the initial direct-relation matrix A. A sample of average initial direct-relation crisp matrix is shown in Table 4.

$$a_{ij} = \frac{1}{k\sum x_{\mathrm{kij}}} \qquad (1)$$

$$\mathrm{I_T} = \frac{1}{6}(\mathrm{e} + 4\mathrm{f} + \mathrm{g}) \qquad (2)$$

TABLE 4 AVERAGE INITIAL DIRECT-RELATION MATRIX (Z)

Barrier	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	0.00	0.38	0.82	0.64	0.57	0.68	0.78	0.28	0.40
B2	0.70	0.00	0.85	0.68	0.63	0.61	0.42	0.34	0.41
B3	0.77	0.69	0.00	0.60	0.49	0.50	0.59	0.37	0.33

B4	0.69	0.37	0.57	0.00	0.76	0.72	0.48	0.78	0.80
B5	0.54	0.34	0.59	0.87	0.00	0.64	0.51	0.48	0.44
B6	0.63	0.44	0.45	0.66	0.46	0.00	0.46	0.67	0.69
B7	0.88	0.36	0.73	0.64	0.70	0.58	0.00	0.48	0.47
B8	0.27	0.25	0.40	0.89	0.73	0.68	0.52	0.00	0.70
B9	0.36	0.31	0.45	0.86	0.68	0.77	0.64	0.84	0.00

Step 5: Construct the normalized initial direct relation matrix (D)

$$m = min\left[\frac{1}{max\sum_{j=1}^{n}|a_{ij}|}, \frac{1}{max\sum_{i=1}^{n}|a_{ij}|}\right] \quad (3)$$

$$D = m \times A \quad (4)$$

TABLE 5. NORMALIZED INITIAL DIRECT-RELATION MATRIX (D)

Barrier	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	0.00	0.07	0.16	0.12	0.11	0.13	0.15	0.05	0.08
B2	0.14	0.00	0.16	0.13	0.12	0.12	0.08	0.07	0.08
B3	0.15	0.13	0.00	0.12	0.09	0.10	0.11	0.07	0.06
B4	0.13	0.07	0.11	0.00	0.15	0.14	0.09	0.15	0.15
B5	0.11	0.07	0.11	0.17	0.00	0.12	0.10	0.09	0.09
B6	0.12	0.08	0.09	0.13	0.09	0.00	0.09	0.13	0.13
B7	0.17	0.07	0.14	0.12	0.14	0.11	0.00	0.09	0.09
B8	0.05	0.05	0.08	0.17	0.14	0.13	0.10	0.00	0.13
B9	0.07	0.06	0.09	0.17	0.13	0.15	0.12	0.16	0.00

Step 6: Compute the total relation matrix (T)

$$T = D(I - D)^{-1} \quad (5)$$

Where, I denotes the identity matrix.

Step 7: Calculating the sum of rows (R) and the sum of column (C)

$$R = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \quad (6)$$

$$C = \left(\left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n}\right)^{T} \quad (7)$$

where, R denotes the overall effects of barrier (i) on the barrier (j), and C denotes the overall effects experienced by a barrier (i) from barrier (j).

Step 8: Finalizing the cause-effect map

The data set of (R+C; R-C) values is used to generate a cause-effect relationship map. The value of (R+C), presenting the total effects in term of influenced and influential power, is plotted on the horizontal axe. The value of (R-C), which measure the net cause-effect relationship, is plotted on the vertical axis. Barriers with a positive (R-C) value are categorized as cause barriers; whereas those with a negative (R-C) value are effect barriers

[51] . Furthermore, significant relationships between barriers can be presented by arrows on the cause-effect map to highlight their interdependence.

4 DISCUSSION

4.1 RESULT ANALYSIS

The results obtained from the total relation matrix (T) provide a comprehensive understanding of the interrelationships between the various barriers affecting the support effectiveness of communications facilities in emergency security contexts. Table 6 displays the total relation matrix, where the mean and standard deviation of the values in the matrix are 0.98 and 0.15, respectively. Using the threshold calculation method outlined by Li and Tzeng, and Zhang et al. [60,61], we derived a threshold value of 1.21 by adding 1.5 times the standard deviation to the mean. Values exceeding this threshold in Table 6 represent significant causal relationships and are highlighted in bold text. For instance, B4→B6, B7→B4, and B9→B4 are all notable significant causal paths.

TABLE 6 TOTAL RELATION MATRIX (T)

Barriers	B1	B2	B3	B4	B5	B6	B7	B8	B9
B1	0.91	0.68	1.04	1.18	1.03	1.08	0.97	0.87	0.89
B2	1.05	0.62	1.06	1.20	1.06	1.09	0.92	0.89	0.91
B3	1.00	0.70	0.86	1.13	0.98	1.01	0.90	0.85	0.84
B4	1.13	0.75	1.10	1.20	1.17	1.21	1.02	1.05	1.06
B5	0.98	0.66	0.98	1.19	0.91	1.06	0.91	0.89	0.89
B6	0.99	0.67	0.96	1.16	1.00	0.95	0.90	0.92	0.93
B7	1.10	0.71	1.07	1.23	1.10	1.12	0.88	0.94	0.94
B8	0.94	0.64	0.95	1.20	1.04	1.07	0.91	0.81	0.93
B9	1.04	0.71	1.04	1.30	1.12	1.17	1.00	1.03	0.89

Significant relationships greater than the threshold value (1.21) are B4→B6, B7→B4, B9→B4. Figure 2 illustrates the cause-effect diagram, where all significant cause-effect relationships are mapped with arrows pointing from cause barriers to effect barriers. The diagram clearly shows the directional flow of influence among the barriers, helping to identify which barriers play central roles in supporting communications facility effectiveness. In Table 7, the ranking of barriers is presented from the perspectives of R+C (total relation) and R-C (cause-effect) values. These rankings provide further insight into the significance of each barrier and its interrelationships.

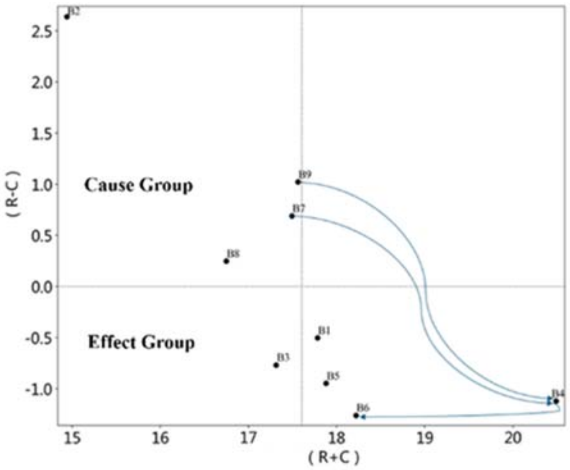

FIGURE 2 CAUSE-EFFECT DIAGRAM

Table 7 presents the ranking of barriers based on their centrality and causality values, helping to assess their relative importance in the system. As seen in the Table 7, the barrier with the highest R+C value is B4 (Personnel), indicating its critical role in the overall effectiveness of communications facility support. This barrier is particularly influential due to its strong interconnections with other barriers, including B9 (Policy and management) and B7 (Advanced technology), which exert significant chain impacts on the system through the mediating role of B4. B4 also influences B6 (Safeguard), further affecting the support effectiveness of communications facilities.

TABLE 7 RANKING OF BARRIERS

Barriers	R+C	Ranking	R-C	Ranking
B1	17.78	4	-0.50	5
B2	14.94	9	2.64	1
B3	17.32	7	-0.77	6
B4	20.49	1	-1.12	8
B5	17.88	3	-0.95	7
B6	18.22	2	-1.26	9
B7	17.49	6	0.69	3
B8	16.75	8	0.25	4
B9	17.56	5	1.02	2

In contrast, B2 (Location) and B9 (Policy and management) are identified as the most influential cause barriers, with high R-C values. These barriers serve as primary drivers in enhancing communications facility support by influencing various effect barriers. Among these, B9 (Policy and management) exerts a more prominent effect on the overall system.

When examining the effect barriers, B6 (Safeguard) stands out as having the lowest R-C value, making it a critical prerequisite for the smooth functioning of communications facility support. The completeness and effectiveness of security safeguards—both physical and cyber—are essential for ensuring the safety and stability of communications infrastructure.

From this analysis, the most influential barrier is B4 (Personnel), which plays a pivotal role in improving the support effectiveness of communications facilities. This insight aligns with the findings of previous studies but offers a more nuanced understanding of the unique challenges faced in China's communications facility support system, especially given the uneven distribution of resources and varied emergency communication requirements. It suggests that managers should prioritize personnel-related interventions, focusing on personnel development, training, and resource allocation to address the challenges in emergency response.

4.2 *SENSITIVITY ANALYSIS*

To validate the robustness of the results, five sensitivity analyses were conducted with different expert groups, as shown in Table 8. These analyses confirm that B4 (Personnel) remains the most influential barrier across different expert groups, reinforcing its role as the key factor affecting the support effectiveness of communications facilities. Additionally, B2 (Location) and B9 (Policy and management) emerge as the most significant cause barriers, with their driving effects on other barriers being far greater than the reverse impact.

TABLE 8 COMPARISON OF SENSITIVITY ANALYSIS RESULTS

Barriers		B1	B2	B3	B4	B5	B6	B7	B8	B9
Communications Facilities located in remote areas	R+C	19.34	17.38	18.54	22.46	19.41	20.33	18.96	18.10	19.30
	Ranking	4	9	7	1	3	2	6	8	5
	R-C	-0.06	2.23	-1.22	-1.36	-0.62	-1.10	0.95	0.24	0.94
	Ranking	5	1	8	9	6	7	2	4	3
Communications Facilities located in urban areas	R+C	14.43	12.31	13.51	16.02	12.87	14.36	13.82	12.88	12.95
	Ranking	2	9	5	1	8	3	4	7	6
	R-C	-0.77	1.63	-0.19	-0.62	-0.47	-0.54	0.49	0.10	0.37

	Ranking	9	1	5	8	6	7	2	4	3
Management Teams of central corporation	R+C	16.30	14.72	16.03	19.19	16.99	16.49	15.88	15.29	15.96
	Ranking	4	9	5	1	2	3	7	8	6
	R-C	-0.69	2.98	-0.08	-1.18	-0.97	-0.89	0.27	-0.50	1.06
	Ranking	6	1	4	9	8	7	3	5	2
Scientists & Scholars	R+C	8.77	7.40	9.71	10.65	10.39	10.09	11.12	9.60	10.20
	Ranking	8	9	6	2	3	5	1	7	4
	R-C	-0.16	2.23	-1.08	-0.58	-1.10	-1.79	0.32	0.77	1.40
	Ranking	5	1	7	6	8	9	4	3	2
Patrol Inspectors assigned by central corporation	R+C	13.56	9.59	12.39	15.21	12.70	12.96	10.75	11.92	12.67
	Ranking	2	9	6	1	4	3	8	7	5
	R-C	-0.25	1.32	-0.37	-0.85	-0.39	-0.40	0.83	0.11	0.00
	Ranking	5	1	6	9	7	8	2	3	4

The sensitivity analysis results further demonstrate consistency with the Fuzzy DEMATEL data processing findings above, suggesting that the rankings of barrier importance remain stable across different expert inputs. The small variations observed in the cause-effect diagrams are negligible, which supports the robustness of the results and their applicability for decision-making purposes.

In conclusion, the combination of Fuzzy DEMATEL and sensitivity analysis underscores the critical importance of personnel (B4) in ensuring the effectiveness of communications facility support in emergency security contexts. The findings also emphasize the need to address location (B2) and policy and management (B9) as fundamental drivers of system improvement. These insights provide valuable guidance for managers and policymakers in optimizing communications infrastructure and enhancing resilience during emergencies.

5 CONCLUSIONS

This study investigates the effectiveness of communications facility support within the context of emergency security, particularly when addressing complex and uncertain scenarios. The findings provide valuable practical insights for enhancing support strategies and improving operational resilience in such critical situations.

5.1 *KEY FINDINGS*

First, the role of personnel as the frontline support force in communications facilities is central to the effectiveness of emergency security operations. A well-trained and experienced team is crucial in identifying and addressing potential security risks, thereby improving the overall support effectiveness of communications facilities. While performance evaluation is often seen as a key factor influencing personnel, our research suggests that advanced technology and policy and management have a more significant impact on personnel [62]. Advanced technology demands specific skills from the personnel, contributing to a more scientific and efficient approach to maintaining stable operations. For example, recent research emphasizes the use of AI-driven real-time monitoring and unmanned aerial vehicle (UAV) communication platforms to optimize fault diagnosis and scheduling during emergencies [63]. Moreover, the policy and management barrier can shape the size, structure, and development direction of the personnel team, ensuring that personnel are better equipped to handle crises and improve overall facility support. Therefore, it is essential for managers to not only promote team-building driven by emerging technologies but also to foster talent development from a policy and management perspective, enhancing personnel's abilities in rapid adaptation, flexible problem-solving, and cross-scenario collaboration [64].

Second, the location of communications facilities plays a significant role in determining their overall support effectiveness. As an objective constraint, location must be carefully considered during the site selection phase of facility construction. Failing to account for environmental factors during site selection can lead to multiple barriers affecting communications facility support. Senior managers from various enterprises have endorsed this view during our field surveys, emphasizing that the geographical location is a crucial factor and should be prioritized in the early stages of configuration. Additionally, regulatory authorities should strengthen their policy guidance role to promote the development of essential support factors. For instance, government measures such as financial subsidies and tax reductions can encourage enterprises to invest in the research, development, and upgrading of communications facilities, improving the overall support system.

Finally, although safeguard measures have been well-researched [65], the context of emergency management introduces new requirements. In major emergency events, the reliability and load-bearing capacity of communications facilities are severely tested. The application of advanced technology and policy management influence the safeguard barrier by optimizing technology selection and enhancing performance. Therefore, to strengthen communications facility support, clear guiding plans need to be established, resources should be concentrated on key areas and critical links, and real-time security status tracking should be implemented, enabling process innovation.

5.2 *THEORETICAL CONTRIBUTIONS*

This paper makes several important contributions to the existing literature. First, it is one of the first studies to systematically analyze the barriers affecting the support effectiveness of communications facilities, particularly under the framework of emergency security. By using the Fuzzy DEMATEL method combined with sensitivity analysis, this study ensures the validity and reliability of the findings.

Second, this study identifies B4 (Personnel) as a crucial barrier, which has been largely overlooked in previous literature. Personnel are not only essential in maintaining long-term stability but also serve as the primary force for addressing complex issues, including the application of new technologies, policies, and management within the context of emergency management.

Lastly, the policy recommendations proposed in this study offer significant practical value. Unlike previous studies, the policy implications of this research have expanded the barrier scope from a focus on the inherent attributes of equipment to include systematic factors such as environmental conditions and social development. Furthermore, the research content has shifted from focusing solely on the operation and maintenance of communications equipment to enhancing overall emergency communication support capabilities. In terms of implementation, the study advocates for a transition from post-event handling of communication equipment support to a full lifecycle approach, which includes design, planning, implementation, and maintenance.

5.3 *PRACTICAL IMPLICATIONS*

The practical implications of this study are aimed at improving the effectiveness of communication facility support in emergency security contexts. First, the research emphasizes the importance of training, team building, and performance evaluation, highlighting the need for the ongoing development of personnel to handle new technologies and crisis situations. This suggests that managers must invest in both the technological capabilities of their teams and the organizational structures that support effective communication facility operations.

Second, the importance of location in the design and construction of communications facilities cannot be overstated. Geographical considerations must be prioritized during the planning stages to prevent environmental factors from hindering operations in critical moments. Policymakers should take an active role in supporting these efforts by incentivizing improvements in infrastructure, particularly in underdeveloped or remote areas.

Finally, the study stresses the need for advanced safeguard measures that can withstand the pressures of emergency management. Real-time monitoring, AI, and other emerging technologies are essential in ensuring the resilience of communications facilities during large-scale emergencies.

5.4 FUTURE DIRECTIONS

While this study offers valuable insights, several directions for future research remain. First, integrating quantitative approaches based on emergency disaster types and risk sources would allow researchers to assess the intensity of risks and their effects on communication equipment. This would enable better equipment maintenance measures and resource allocation strategies [66].

Second, future research could focus on case studies of communication equipment support in typical emergency management scenarios. This approach would help identify bottlenecks, blockages, and breakpoints, thus providing more targeted decision-making support.

Finally, long-term research could be conducted to track the dynamic evolution of barriers in communication equipment support. By analyzing how technological advancements and policy adjustments affect the overall support system, future studies could offer more comprehensive insights into the long-term improvements needed in the communication support system.

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