Developing Urban Emergency Shelter Systems for Multi-Hazard Coupled Risks: A Case Study of Beijing

Authors
LI Xiang, XIA Chenhong, WANG Wei

Abstract
With extreme disasters occurring more frequently and urban spatial systems becoming increasingly complex, emergency shelter systems face multiple challenges under multi-hazard coupled risks, including inadequate structural adaptability, weak functional coordination, and delayed response mechanisms. Existing studies tend to focus on single-hazard scenarios and facility siting, while offering insufficient understanding of disaster-chain pressure mechanisms, spatial response logics, and systematic construction pathways. Following the analytical sequence of "risk identification - structural diagnosis - system reconstruction," this study develops an integrated cognitive framework for emergency shelter systems under multi-hazard disturbance scenarios and uses Beijing as an empirical case. It identifies the linkage mechanisms of multi-hazard chains and the heterogeneous pressure patterns they generate in urban space; diagnoses functional mismatches and response imbalances in the current shelter system in terms of type classification, hierarchical configuration, and operational mechanisms from the perspectives of population exposure and spatial adaptation; and proposes a reconstruction pathway that includes reshaping shelter types, coordinating spatial layouts, and building resilient operational mechanisms. These strategies are further tested and integrated with Beijing's planning standards and local practices. The study aims to provide theoretical support and spatial-governance strategies for megacities facing the complex evolution of disaster chains, and to promote the transformation of emergency shelter systems from static facility configurations to dynamic and resilient structures.

Keywords
multi-hazard coupled risk; emergency shelter system; structural response mechanism; system reconstruction pathway

Introduction

Against the combined background of intensifying climate change and increasingly dense urban space, extreme disasters are becoming more frequent, more compound in type, and more prone to chain transmission. They are reshaping traditional patterns of urban safety. The triggering effects among multiple hazards have become stronger, making disaster impacts more uncertain and spatially heterogeneous. In highly mixed and densely populated first-tier cities, disaster "pressure" tends to concentrate in structurally vulnerable areas, challenging the tolerance and regulation capacity of urban systems. Emergency shelter systems, as key nodes connecting disaster response, population evacuation, and order restoration, have therefore become an important support for urban resilience.

In recent years, national and local authorities in China have issued a series of policy and technical documents, including the Guidelines on Strengthening the Construction of Emergency Shelters issued by 12 ministries and commissions, the national standard Classification and Grading of Emergency Shelters (GB/T 44013-2024), and Beijing's local standard Classification and Grading of Emergency Shelters (DB11/T 2141-2023). These documents define the logic for emergency, short-term, and long-term shelters from the perspectives of shelter duration and spatial coordination, promoting a transition from static facility provision to multi-objective shelter systems. Yet under the real-world conditions of disaster-chain linkage, high spatial complexity, and differentiated governance mechanisms, current shelter systems still face insufficient response coordination, weak spatial fit, and limited structural coupling capacity. Systematic, forward-looking, and practice-oriented research is urgently needed.

The shelter-space system has gradually become a key topic in resilient-city research. Wei et al. [1] and Hung et al. [2] argue that resilience is reflected not only in a system's capacity to absorb and recover, but also in structural transformation and functional adaptation; emergency spaces should therefore be treated as key units with dynamic-response attributes. Liu et al. [3] propose that shelters should be configured through dynamic coupling among population distribution, access routes, and evacuation capacity, and that evacuation simulation and network accessibility models should be introduced for spatial optimization. Ahmed and Guyton [4], from the perspective of systemic risk, emphasize that the pressure state and functional mismatch of shelter structures should be central governance concerns. Ran et al. [5] construct a disaster-prevention zoning system based on service levels and siting radius; Wang et al. [6] propose that facilities should realize nested conversion between ordinary and emergency functions; and Zhu et al. [7] attempt to dynamically evaluate shelter capacity through disaster-scenario simulation and big-data analysis. These studies provide a solid foundation for theory, methodology, and empirical research, but three gaps remain.

First, existing research generally focuses on single-hazard response or static configuration, lacking an integrated analysis of the "pressure - response - regulation" relationship in urban systems under disaster-chain linkage [8]. Second, attention remains concentrated on facility siting and shelter-capacity assessment, with insufficient modeling of internal structural imbalance, functional mismatch, and fragmented mechanisms. Third, shelter systems have not yet been effectively embedded in resilience-governance frameworks, and therefore lack organizational adaptation logics for complex disturbances and spatial-structure evolution.

Building on this research context, this study focuses on Beijing. Since Beijing built China's first emergency shelter in 2003, the earthquake emergency shelter in Yuandadu City Wall Ruins Park, it has developed more than 1,810 emergency shelters of various levels and types. The sample size is large, but current problems remain significant. As a megacity located on the northern wing of the North China seismic belt, Beijing faces long-term natural risks including earthquakes and meteorological disasters. Because of the complexity and vulnerability of urban operations, overlapping disasters may cause greater losses and damage. Beijing therefore urgently needs comprehensive planning and optimization of its emergency shelter system from systemic and resilience perspectives.

This article develops an integrated framework combining disaster-linkage identification, spatial-structure diagnosis, and system reconstruction. It seeks to promote the transformation of emergency shelter systems from static facility provision to dynamic resilience systems capable of addressing complex disturbances. Following the main line of "multi-hazard coupled risk orientation," it conducts analysis through three logics: risk identification, structural diagnosis, and system reconstruction. It first identifies linkage mechanisms among hazards such as earthquakes and rainstorms and the heterogeneous pressure patterns they generate in urban space. It then diagnoses response bottlenecks in shelter types, hierarchical connections, and operational mechanisms by considering population sensitivity and spatial adaptability. Finally, it proposes a reconstruction pathway covering type-system reshaping, spatial-layout coordination, and operational-mechanism optimization, thereby forming a shelter-system reconstruction scheme for multi-hazard coupled scenarios.

1. Risk Identification Logic of Shelter Systems Under Multi-Hazard Coupled Scenarios

Under the combined effects of multi-hazard superposition and compound disturbance, urban emergency shelter systems face a multi-layered pressure structure generated by external risk drivers, internal structural responses, and systemic failures. Beijing, as a typical megacity, has complex spatial morphology, highly coupled functional areas, and diverse hazard types. Its shelter system is therefore highly representative and demonstrative at the national level. Starting from disaster mechanisms, this section first analyzes how multiple hazards affect the spatial system and generate pressure. It then focuses on the coupling between spatial structure and population characteristics to reveal the formation logic of system exposure. Finally, it identifies the forms of exposure imbalance and functional mismatch in the shelter system, providing the problem basis and structural foundation for subsequent strategies.

1.1 Identifying Multi-Hazard Disaster Chains and Action Mechanisms

With the increasing frequency of extreme climate events and the growing coupling of urban functions, the linked evolution of multiple hazards has become an important variable affecting the stability of urban safety systems. Unlike traditional single-hazard models, multi-hazard coupled risks show strong chain-transmission characteristics. These include the superposition of physical hazards, interlinked disruption of functional systems, and amplification effects in social systems [9]. Beijing has complex geological structures and has historically experienced earthquakes, rainstorms, mountain floods, and secondary disasters. Its built-up areas are concentrated, and underground spaces are intensively used, making disaster chains highly correlated in both vertical and horizontal spatial dimensions.

Based on a risk-matrix model that evaluates hazards according to disaster intensity and occurrence frequency, this study sorts nine major hazard types: earthquakes, floods, geological hazards, fires, extreme weather, hazardous chemicals, mining accidents, social security incidents, and epidemics. It then constructs a multi-hazard propagation network [10] and, through literature review and the event-chain principle, identifies their action pathways in spatial dimensions (Figure 1). From the perspective of hazard interaction, earthquakes may trigger building collapse, traffic disruption, and fire-related secondary disasters; floods may paralyze underground facilities and increase crowd-concentration risks; and epidemics strengthen the vulnerability of public places. In Beijing's high-density urban pattern, interactions among multiple hazards are more likely to overlap and amplify in the central city and the sub-center, forming a typical city-level chain-propagation process.

Multiple hazards can therefore occur concurrently or accumulate in phases, producing nonlinear disturbances in urban spatial structures. These compound mechanisms spread spatially through risk-transmission pathways and form "high-pressure risk zones" centered on dense urban functions, infrastructure nodes, and crowd-concentration areas [11]. In this process, different hazards, because of variations in their causal factors, rhythms of action, and propagation structures, are projected into a common spatial reference system through differences in factor weights, co-occurrence strength, and chain-linkage patterns. This creates comparable spatial responses and gives hazard characteristics an endogenous integrated expression within the compound-risk framework.

Identifying multi-hazard linkage can thus be translated into a process of spatial-layer overlay and chain analysis, abstracting common action mechanisms and extracting Beijing's overall hazard-linkage response pattern and heterogeneous compound-risk map. To construct this map, the study uses ArcGIS for spatial-layer overlay and chain analysis. It first selects historical event data for major hazards such as earthquakes, floods, fires, extreme weather, and hazardous-chemical accidents, along with hazard-impact factors such as terrain slope, building density, underground-space distribution, population density, and infrastructure-node density, as well as socioeconomic exposure data. These data are used to generate hazard-intensity layers. It then applies multi-source-data-driven disaster co-occurrence network analysis and chain-transmission modeling. Through text mining and co-word statistics, it identifies co-occurrence frequencies and semantic associations among hazards, constructs a quantitative interaction matrix, and uses weighted degree centrality and betweenness centrality to determine key triggering hazards and propagation paths [12]. Based on co-occurrence probability thresholds, hazard associations are classified as low-frequency (<10%), medium-frequency (10%-30%), and high-frequency (>30%). Weighted overlay analysis is then used to generate a spatial distribution map of multi-hazard compound risk.

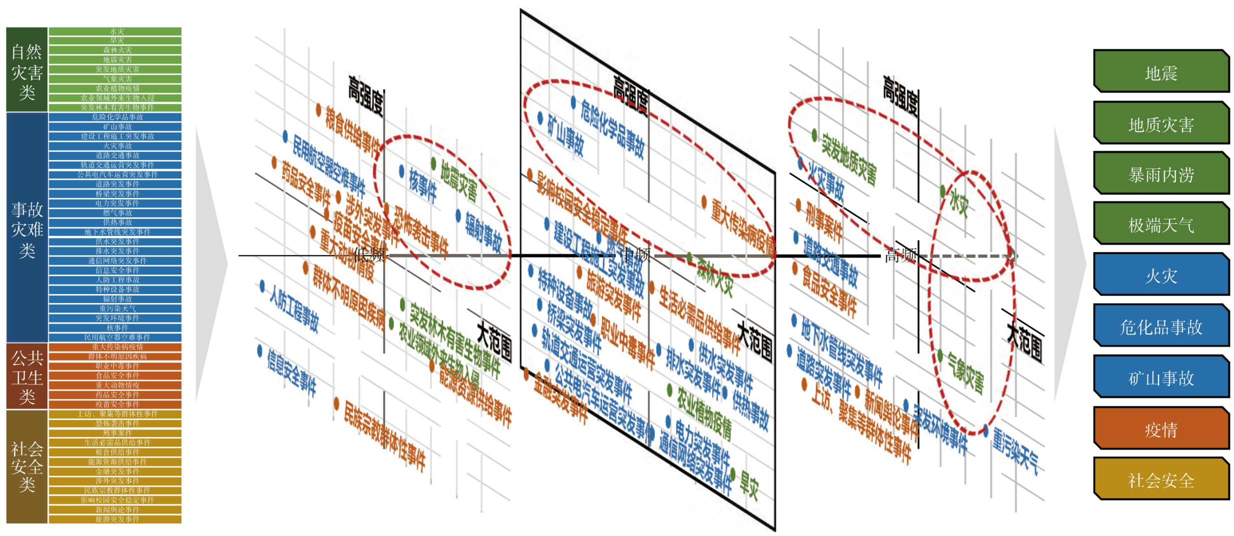

Figure 1. Chain Reaction Stages and System-Impact Structure of Different Disaster Types

The figure classifies natural disasters, accidents, public-health events, and social-security events, and links them to representative hazards such as floods, drought, forest fires, earthquakes, geological hazards, extreme weather, hazardous chemicals, mining accidents, traffic and utility failures, major infectious diseases, food and drug safety incidents, terrorism, mass incidents, and other urban-security risks.

1.2 Urban Population Sensitivity and Shelter-Demand Analysis

Urban populations are the direct bearers of disaster impacts. Their spatial distribution and social attributes form the core basis of response pressure in shelter systems. Under multi-hazard coupled scenarios, shelter demand is no longer determined by population size or density alone. It is instead a systemic outcome driven by the interaction among risk causality, population sensitivity, and rescue effectiveness [13] (Figure 2). Risk-source distribution determines hazard intensity and scope; population sensitivity determines the degree to which individuals are vulnerable to disasters; and rescue effectiveness affects whether resources can arrive in time and whether functions can be activated accurately.

To ensure scientific and reproducible modeling, the indicators for these three dimensions are drawn from Beijing's historical disaster-event database, the Seventh National Population Census, and infrastructure spatial-information data. After normalization and significance testing, the study uses principal component analysis to extract the main composite factors and determine weights, and then applies the coupling coordination model to reveal the interactions among disaster exposure, population sensitivity, and rescue effectiveness, forming an integrated quantitative model of urban shelter demand. Given the significant differences among hazards in loss scale, action mechanisms, and refuge modes, this study treats hazard type as a prior constraint in demand identification. It uses multi-hazard scenarios to differentiate and correct the compound impacts of different hazards, avoiding scenario omissions that would result from relying only on population and infrastructure data. Key hazards such as earthquakes, floods, fires, and hazardous-chemical accidents differ in shelter-trigger intensity, refuge mode, and spatial conditions. Scenario-based demand coefficients can therefore be introduced to correct the calculation results and reflect differences in shelter scale, shelter duration, and spatial adaptability (Table 1).

In Beijing, population distribution and social sensitivity show clear spatial differentiation. The central city contains many old residential communities and elderly residents, with a relatively high social-vulnerability index. Emerging functional areas such as Tongzhou and Yizhuang are dominated by floating populations and employment-intensive groups, producing concentrated shelter-response pressure. Plain new towns and ecological-conservation areas have lower population density but poorer transport accessibility, resulting in strong shelter-access constraints. Based on spatial data for Beijing's actual population, floating population, and highly vulnerable groups, including older adults, children, and low-income groups, this study constructs a population-sensitivity evaluation model. The results show that older residents are concentrated in old communities and central urban districts, while floating populations cluster along rail corridors and urban-fringe areas. This forms multiple "high-density - high-sensitivity - low-security" shelter-pressure zones. The superposition of population sensitivity and urban functional space gives Beijing a typical pattern of high pressure in the core and fluctuating demand in peripheral areas.

Combining these population characteristics with hazard features such as earthquakes, fires, floods, and epidemics, the study constructs a two-dimensional matching framework of "hazard type x shelter cycle" to identify the spatial structure and response timing of different shelter demands. Calculations show that under extreme scenarios, Beijing's maximum sheltering population may account for about 30% of the service population, with a spatial distribution characterized by "high pressure in the core and fluctuation in the periphery." This demand map can provide quantitative support for identifying high-priority areas, refining facility-configuration standards, and formulating resource-dispatch strategies.

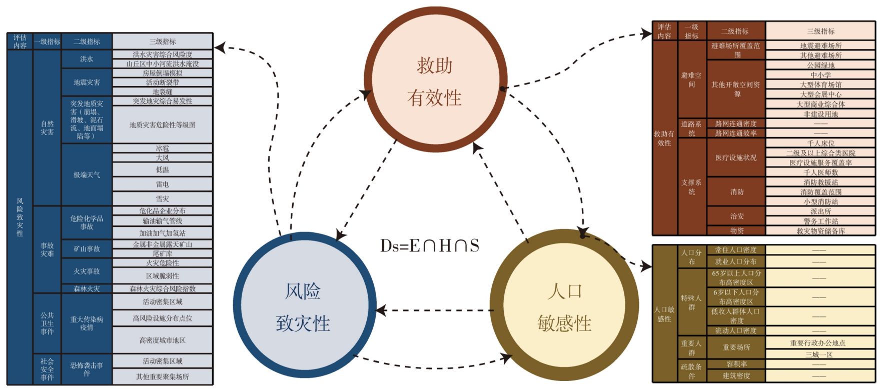

Figure 2. Three-Dimensional Coupled Model for Demand Identification of Urban Shelters

The model includes three dimensions: risk causality, population sensitivity, and rescue effectiveness. Risk causality covers floods, earthquakes, geological hazards, extreme weather, hazardous chemicals, mining accidents, fires, forest fires, public-health events, and social-security events. Population sensitivity includes resident population, employment population, older adults, children, low-income groups, floating population, important places, floor-area ratio, and building density. Rescue effectiveness includes shelter coverage, open-space resources, road-network connectivity and efficiency, medical facilities, fire rescue, policing, and disaster-relief material reserves.

Table 1. Differentiated Evacuation Trigger Thresholds and Spatial Requirements for Common Disaster Types

Disaster type	Shelter-trigger intensity	Key spatial-demand characteristics	Correction direction
Earthquake	High	Open and safe assembly space.	Demand weight.
Flood	Medium	Avoid low-lying land; ensure safe elevation and drainage capacity.	Local validity in affected areas.
Fire	Low (local)	Fire separation distance and smoke isolation.	Local correction.
Hazardous-chemical accident	Medium (local)	Safe isolation distance and enclosure according to wind direction.	Local correction.
Extreme weather, such as heat or air pollution	Low	Indoor refuge and ventilation systems.	Usually does not generate large-scale centralized shelter demand.

1.3 Shelter-System Response Capacity and Spatial Supply-Demand Diagnosis

The response capacity of emergency shelter systems depends not only on the number and density of facilities, but more importantly on their spatial fit with population distribution, hazard characteristics, and functional nodes. Beijing's existing shelters are mainly built on public facilities such as green spaces, parks, and schools, forming a three-level response network at municipal, district, and subdistrict levels.

Under multi-hazard scenarios, however, the system still faces structural mismatch and supply-demand imbalance.

To reveal these spatial differences, this study constructs a "shelter supply-demand matching index" based on shelter service radius, population density, and facility capacity. The results show significant differences in the supply-demand ratio across Beijing (Figure 3). The Capital Functional Core Area has a ratio of 1:0.6, indicating adequate shelter supply and even some resource redundancy. The central city has a ratio of 1:1.8, showing high shelter pressure caused by dense population. The urban sub-center has a ratio of 1:1.4, indicating a moderately tight condition. The multiple plain new-town areas have a ratio of 1:1.3, showing relative balance. The ecological-conservation area has a ratio of 1:1, indicating basic supply-demand matching. Overall, Beijing's shelter system presents a spatial pattern of "core redundancy - sub-center tightness - plain-area balance - moderate peripheral capacity." This pattern reflects structural differences in shelter-resource distribution across functional areas and regions, and it calls for more rational layout and multi-level response mechanisms to address supply-demand mismatch.

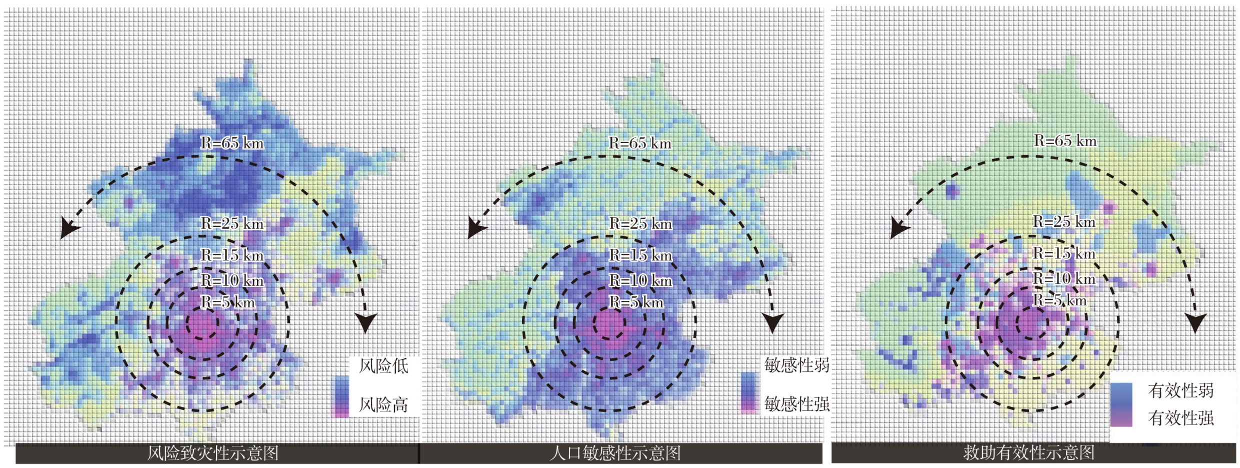

Figure 3. Spatial Heterogeneity of the Emergency Shelter System in Beijing

The figure compares three spatial layers: risk causality, population sensitivity, and rescue effectiveness. It illustrates the differentiated shelter pressure generated by overlapping risk, sensitive population, and rescue-resource conditions across Beijing.

2. Structural Response Mechanisms of Shelter Systems Under Multi-Hazard Coupled Scenarios

Facing the superposed effects of multiple hazards and the high-density concentration of urban space, Beijing's shelter system, as part of a national political center and a typical megacity, exposes multiple structural constraints in type setting, spatial layout, and operational mechanisms. These constraints make it difficult to support rapid response and safe transfer under dynamic scenarios. To identify constraints and bottlenecks, analysis should proceed from three dimensions: whether functions adapt to hazard demands, whether layout covers key areas, and whether mechanisms support efficient coordination. This provides targeted support for subsequent system reconstruction.

2.1 Functional Fit of Shelter-Type Structure

Under frequent compound risks and diversified shelter demands, Beijing's existing shelter system is mainly composed of three types of spaces: emergency refuge, temporary resettlement, and transitional resettlement. Together they form a functional system covering the full disaster process. However, because Beijing faces diverse hazards and complex disaster chains, different shelter types still show obvious deficiencies in functional layering and hazard correspondence. Sudden hazards such as earthquakes and fires require high timeliness and accessibility, whereas slow-onset hazards such as floods and epidemics depend more on protective and sustainable spaces. These two sets of demands are often difficult to reconcile in urban space.

In Beijing's central city, for example, old residential areas lack sufficient shelter space, and some schools and parks, because of early construction and weak infrastructure, cannot meet the dual requirements of earthquake protection and flood drainage. In emerging functional areas such as Tongzhou and Yizhuang, many new public green spaces and comprehensive shelters have been built, but facility conversion and material support still lack compound-response design for multiple hazards. This creates a problem in which shelters are visible as sites but absent as functions when different disaster scenarios occur. The type structure should therefore shift from administrative classification toward an integrated response logic of "hazard - cycle - function," strengthening the functional adaptation of the system under multiple scenarios.

2.2 Spatial Coordination of Shelter-Layout Structure

Shelter layout carries the functions of population evacuation and resource aggregation across different urban areas during disasters. Its structural rationality directly affects the pressure-bearing capacity and linkage-response level of the entire system. Beijing's spatial layout has a clear ring-and-radial structure. The piedmont plain, high-density functional areas, and peripheral ecological-conservation areas together form a typical "multi-ring, multi-constraint" urban structure. This structure subjects shelter distribution, balance, and accessibility to multiple natural and social constraints.

Overlaying shelter-population prediction with service-capacity assessment shows marked spatial imbalance in Beijing's shelter system. The central city has high shelter density, but limited accommodation capacity and heavy population-evacuation pressure. The Tongzhou sub-center and plain new towns are experiencing rapid aggregation of shelter populations, while facility supply lags behind. Peripheral areas such as Fangshan and Miyun have poor shelter accessibility because of terrain barriers and transport conditions. This "high pressure in the center - delayed response in the periphery" pattern is a typical spatial-structure problem in Beijing. It reflects the uneven development of shelter systems between the urban core and edge areas, especially in urban-rural fringe zones, key functional areas, and transport-corridor intersections, where layout fragmentation, poor access routes, and single-function sites make rapid assembly and response difficult during disasters. Overall, Beijing's current shelter distribution shows a pattern of "dense center and sparse periphery," with a low match among population distribution, risk levels, and accessibility conditions.

2.3 Mechanism Response in Shelter Operations

The operational structure of shelter systems is the practical foundation for space activation, resource dispatch, and population transfer. The systematic and coordinated nature of response mechanisms directly determines the efficiency and effectiveness of disaster-time linkage. Beijing has initially established a three-level operating mechanism based on municipal, district, and subdistrict structures, but problems such as overlapping functions, fragmented information systems, and delayed interdepartmental coordination remain widespread. These problems make it difficult to respond to rapid conversion needs during disaster-chain evolution.

As the capital, Beijing's shelter operations must also consider political security, public safety, and social stability, making mechanism design more complex than in other cities. During major events, extreme weather, or public-health emergencies, for example, the shelter system must both evacuate people and guarantee smooth transport and safety in key areas, producing a typical problem of multi-objective coordinated response. A responsibility system guided by scenario status should therefore be established, along with an organization mechanism integrating ordinary and emergency operations. Digital platforms should be used to build an integrated closed loop of "sensing - dispatch - linkage." By setting population service-support coefficients for emergency shelters, short-term shelters, and long-term shelters, and dynamically connecting meteorological, hydrological, transport, and energy data, the shelter system can provide efficient, safe, and intelligent response support under complex disaster conditions.

3. Reconstruction Pathways for Shelter Systems Oriented to Megacity Risk Characteristics

Against the background of compound disasters, Beijing's emergency shelter system faces adaptive shortcomings and organizational barriers. As a typical megacity and national political center, Beijing has complex terrain, dense population, and diverse hazards. Its shelter-system construction is therefore both representative and complex. Based on the problem identification and response diagnosis above, this section proposes an integrated reconstruction pathway involving type, space, and mechanism. It focuses on three aspects: reconstructing type systems adapted to multi-hazard characteristics, optimizing spatial networks according to local conditions, and reshaping mechanisms based on scenario orientation. The aim is to explore a resilience-transformation pathway grounded in Beijing's practice and potentially applicable nationwide [14-15].

3.1 Adaptive Reconstruction of Shelter-Type Systems for Multi-Hazard Characteristics

Different hazards vary significantly in disaster-chain formation, spatial scope, and population refuge pathways. This leads to structural differentiation in shelter behavior and spatial demand. Earthquakes, for example, often trigger regional structural damage and generate large-scale centralized emergency evacuation demand. Floods are elevation-sensitive and fluctuate over short periods, often producing dispersed temporary transfers dependent on topographic difference. Fires and hazardous-chemical accidents mainly involve local diffusion and generally require rapid isolation and short-term spatial transfer. It is therefore necessary to build a type-classification system using risk type, response cycle, and service function as logical supports, and to treat disaster scenarios as an important basis for reconstructing shelter types.

First, a shelter grading and classification system should be reconstructed according to the three-dimensional mapping relationship of "hazard type - response duration - functional demand." Emergency shelters mainly respond to high-intensity sudden events and should emphasize nearby, short-duration, high-response local evacuation. Short-term emergency shelters correspond to medium-intensity regional disasters and undertake staged tasks such as population transfer, centralized resettlement, and resource aggregation. Long-term emergency shelters serve post-disaster recovery and relocation, and should provide integrated capacities such as life support, medical services, and material supply. Given Beijing's triple spatial structure of high-density built-up areas, broad plains, and piedmont ecological zones, geographical zoning weights should be introduced into type layering. The central city should prioritize rapid-response spaces, while plain and mountain areas should strengthen relocation and reserve-support functions, forming a multi-level system of progressive response, gradual functional escalation, and spatial-temporal linkage.

Second, the classification framework should be expanded into a compound structure of "comprehensive - specialized - specific" shelter types. Different areas of Beijing face different hazards. Comprehensive emergency shelters should primarily address earthquakes while also covering hazardous-chemical accidents, fires, mining accidents, terrorist attacks, and other disaster incidents. Specialized emergency shelters can be classified according to specific shelter demands during disasters, including flood control, extreme weather, sudden geological disasters, forest fires, and major infectious-disease epidemics. Specific emergency shelters refer to spaces serving older adults, infants, pregnant women, persons with disabilities, and injured or ill people. They should meet barrier-free design requirements and reflect the capital's social inclusiveness and precise-service capacity.

Finally, a dynamic coupling system between type hierarchy and operational mechanisms should be established. Beijing has a solid foundation in disaster-prevention drills, disaster simulation, and material reserves. Its "city brain" platform should be used to establish dynamic matching between shelter types and disaster conditions, forming an operational logic of ordinary preparedness, disaster-time conversion, and post-disaster reuse. Through pre-positioned configuration and scenario-based drills, the emergency conversion capacity and response elasticity of different shelter spaces can be improved. Legal standards, technical guidelines, and evaluation mechanisms should support institutionalized operation and response compliance.

Overall, adaptive reconstruction of shelter types should focus on differences in urban risk profiles and population needs. Based on functional differentiation and scenario dynamism, the shelter system should shift from broad categories to refined classification and from single-hazard response to multi-hazard adaptation, strengthening the human-space coordination and spatial resilience needed for compound disasters.

3.2 Optimizing Shelter-Space Layout Through Coordinated Linkage

As a core support for resilience governance, Beijing's current shelter resources show a ring-like imbalance of central concentration and peripheral weakness. This spatial pattern is highly typical of megacities. To build a spatial system with elastic dispatch capacity and interdistrict coordination, layout optimization should proceed through three dimensions: ring coordination, dual-ring linkage, and urban-rural integration. This can move the system from segmented administration to networked linkage.

In terms of ring organization, a multi-level shelter-support system should be built according to the hierarchy of capital functional areas. It should include the central city, Beijing's urban sub-center, plain new towns, and cross-boundary areas. In the Capital Functional Core Area, emergency shelters should be fully guaranteed according to functional positioning, shelter demand, and available resources. Layout should be based on 1.7-1.8 times the planned population, while short-term and long-term shelter needs that cannot be fully supported by local spatial resources should be coordinated within the central city. In the urban sub-center and plain new towns, the responsibilities for medium-term transfer and off-site resettlement should be clarified, and the buffering effects of transport hubs and green belts should be effectively used. In cross-boundary node areas such as Tongzhou, Pinggu, and Changping, regional linkage mechanisms can be coordinated to form a three-dimensional support structure of main and auxiliary nodes.

In terms of network structure, large-scale green spaces, transport corridors, and emergency nodes should be integrated to build a three-in-one shelter linkage network of ecological corridors, transport axes, and emergency nodes. The first and second green isolation belts can function as pressure-transition zones. Transport nodes and green belts in areas such as Fengtai, Chaoyang, and Changping can be jointly developed into ecological-emergency dual-function corridors, with cross-district long-term shelters and emergency logistics nodes. Through railway and highway axes, a three-level response corridor of local sheltering, nearby evacuation, and off-site resettlement should be established to strengthen spatial accessibility and material-reach capacity.

In terms of urban-rural spatial coordination, emergency shelters should extend in an orderly way to urban-rural fringe areas, town and village nodes, and mountain valleys. Beijing's terrain is characterized by "three mountain systems and five gardens encircling one city"; mountainous areas account for about two-thirds of the municipal area, and the urban spatial gradient is clear. A compound shelter system should therefore be built for the urban center, plain hinterland, and mountain periphery. The urban center should strengthen local sheltering and rapid evacuation in high-density built-up areas, relying on community green spaces, cultural and sports venues, and underground spaces to form an efficient assembly network. The plain hinterland should use the transport and spatial advantages of Tongzhou, Yizhuang, and Shunyi to adopt clustered and grid-based embedded layouts, improving medium-term resettlement and off-site transfer. The mountain periphery, focusing on Yanqing, Fangshan, and Miyun, should combine terrain conditions and road accessibility with distributed layouts to ensure emergency-response accessibility in high-risk areas.

Service radius, accessible time, per capita protected area, and corridor quantity can be incorporated into spatial-optimization assessment, statutory planning, and risk-evaluation procedures. This will promote a shift from static overlay to dynamic coupling and from administrative allocation to functional coordination.

3.3 Systemic Reconstruction of Shelter-Operation Mechanisms Based on Scenario Conversion

Under frequent multi-hazard disturbances and high-pressure megacity operations, Beijing's emergency shelter operation mechanism must be upgraded from "static designation - single response" to "dynamic conversion - multiple adaptation." This study proposes a multi-hazard scenario-based hierarchical linkage mechanism suited to Beijing's conditions. It builds a closed-loop operational logic of sensing, identification, response, and feedback, forming a digitally driven and multi-departmental resilient operating system.

First, a dual normal-abnormal operating mechanism should be improved to support institutional conversion and functional switching under different scenarios (Figure 4). In the normal-operation stage, Beijing's emergency command information system and urban digital-twin platform should be used for shelter reserve management, risk monitoring, resource dispatch, and training drills. Multi-source data on meteorology, hydrology, transport, population, energy, and shelter facilities should be integrated. By clarifying activation standards, control rules, and responsibility boundaries, dynamic management of disaster monitoring and shelter-resource reserves can be realized. In the abnormal-operation stage, response-level classification, route-dispatch procedures, and information-release mechanisms should be improved. During disasters, a four-level response mode of red, orange, yellow, and blue can be triggered according to hazard type and impact scope. Intelligent deduction modules can quickly generate evacuation and resource-allocation schemes, ensuring rapid activation, closed-loop tasks, and clear responsibilities during sudden disasters.

Second, the functional integration of indoor and outdoor spaces should be strengthened. In the central city, indoor safe spaces, such as cultural and sports venues, underground commercial facilities, and metro passages, should be activated first to strengthen protection against earthquakes, rainstorms, air pollution, and other hazards. In the plain hinterland and ecological-conservation areas, open and semiopen shelter spaces should perform diversion and buffering functions, forming an operational pattern of spatial diversity and functional complementarity. High-rise buildings and civil-defense engineering systems should enhance three-dimensional response capacity under extreme disasters through a coordinated mechanism of vertical refuge and underground buffering. Through cooperation among regions, a spatial system with diverse forms, zonal fit, and complementary functions can be built to meet refuge needs under earthquakes, rainstorms, heat waves, and other hazards. At the same time, Internet of Things sensing terminals should monitor crowd density, energy supply, and corridor smoothness in real time, supporting dynamic activation and automatic dispatch of shelter spaces.

Third, a public-resource conversion mechanism for ordinary and emergency use should be established to promote emergency conversion and functional expansion of existing public resources. For regular-use places such as parks, school playgrounds, and community squares, a three-element checklist of conversion conditions, activation procedures, and resource support should be developed. This ensures rapid identity conversion and functional transition when disasters occur, enabling efficient reuse as "ordinary service for residents and emergency refuge in disasters." Beijing's urban sub-center and plain new towns should further use their spatial carrying advantages to improve cross-district linkage and time-sharing response, forming a multi-level coordination system of central evacuation, sub-center reception, and peripheral support. This can increase redundancy and dynamic dispatch capacity of shelter resources.

Finally, high-rise building refuge spaces and urban civil-defense engineering should be systematically included to build a three-dimensional emergency support network. In core functional areas and high-density districts, refuge floors and escape platforms in high-rise buildings should be promoted and connected with metro passages and underground parking civil-defense systems. This can form a three-dimensional shelter network of rapid above-ground assembly and safe underground buffering, improving spatial redundancy and operational resilience in extreme megacity scenarios.

Overall, through multi-dimensional linkage among normal-abnormal conversion, indoor-outdoor integration, ordinary-emergency dual use, high-rise refuge, and civil-defense engineering, Beijing can realize efficient shelter dispatch, precise resource supply, and closed-loop response chains under multi-hazard coupled scenarios. This will promote the transformation of shelter operations from passive emergency response to proactive governance.

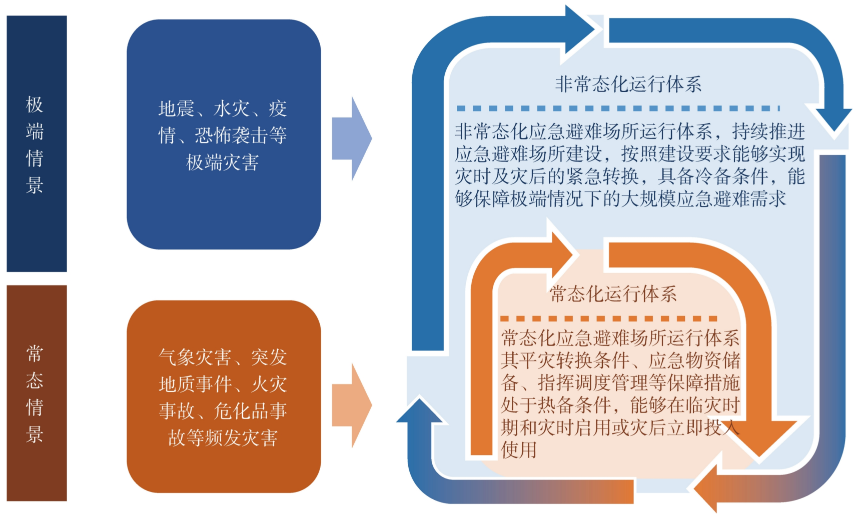

Figure 4. Normal-to-Emergency Conversion Mechanism of Emergency Shelter Spaces

The figure distinguishes abnormal emergency-shelter operation systems, which should remain in cold standby and support large-scale emergency refuge under extreme conditions, from normal emergency-shelter operation systems, whose conversion conditions, material reserves, and command-dispatch measures should remain in hot standby for immediate use before, during, and after disasters.

4. Conclusions and Prospects

4.1 Main Conclusions

Using Beijing as a typical case, this study examines the response resilience of urban emergency shelter systems under multi-hazard coupling. It systematically reviews the logical needs and real-world constraints of shelter systems in terms of hazard adaptation, population transfer, and resource matching, and proposes targeted optimization pathways within a framework of multidimensional identification and mechanism reconstruction. The main conclusions are as follows.

First, the evolution logic of shelter systems urgently requires a paradigm update oriented to multi-hazard adaptation. As urban disaster risks become more compound and extreme, shelter systems centered on single hazards and static configuration cannot adapt to high-intensity disturbance environments. As a megacity, Beijing needs to extend its shelter system from post-disaster emergency response toward a full-process system covering pre-disaster preparedness, disaster-time transfer, and post-disaster recovery, achieving a paradigm shift from type classification to capability coordination.

Second, the functional structure of the shelter system has clear matching gaps. Beijing's current shelter-type configuration shows insufficient coverage of hazard-specific functions and poor temporal conversion mechanisms. Spatially, it exhibits uneven distribution across districts and prominent blind spots at the urban edge. Operationally, it faces fragmented responsibilities and incomplete response loops. These three core dimensions jointly constrain the overall resilience of the shelter system.

Third, system optimization should follow an integrated path of "type - space - mechanism." Functionally, shelter types should be reshaped according to multi-hazard adaptation to cover response cycles and precisely match service groups. Spatially, a zonal coupling system based on layout coordination should be built to strengthen multi-scale, multi-node, and multi-district network integration. Mechanistically, coordinated linkage and resilient reconstruction should be advanced by improving dynamic operations with clear responsibilities, data sharing, and closed-loop response.

Fourth, "structure identification - response diagnosis - system reshaping" constitutes the core research logic. By identifying the basic structure of the urban shelter system, analyzing its response difficulties under compound disaster disturbances, and proposing countermeasures of system reshaping, spatial optimization, and mechanism reconstruction, this study forms a complete research chain from problem identification to system redesign. It therefore has strong theoretical significance and practical adaptability.

4.2 Research Prospects

This study develops an analytical framework for urban emergency shelter systems under multi-hazard coupled scenarios and proposes targeted pathways. However, because of limits in data availability and practical verification, several issues require further research.

First, the deep coupling of cross-hazard response logic needs to be expanded. The transmission relationships among hazards, their superposition mechanisms, and their effects on shelter-resource mobilization still lack detailed modeling. Future research can introduce disaster-chain evolution models and urban dynamic-simulation technologies to extend the analysis from compound disturbance to strategy simulation.

Second, the dynamic dispatch mechanism for spatial allocation of shelter resources remains immature. This article mainly discusses layout optimization from the perspective of static spatial patterns. Future work should combine real-time population distribution, transport accessibility, and disaster prediction data to build a shelter-resource matching platform with real-time dispatch capacity, enabling elastic response and dynamic evolution of shelter spaces.

Third, collaborative governance mechanisms involving multiple actors require further empirical verification. In actual operation, shelter systems involve cooperation among governments, subdistrict offices, communities, enterprises, public institutions, and other actors. How to embed executable mechanisms of joint construction, joint governance, and joint management into institutional design is a key issue for implementing shelter systems in the future, and it is also an important component of resilient-city construction.

Notes

[1] The source text marks the event-chain principle with note symbol ① at this point, but no separate explanatory note is printed in the extracted PDF text.

References

[1] WEI Y X, JIN L Z, XU M W, et al. Instructions for planning emergency shelters and open spaces in China: lessons from global experiences and expertise[J]. International Journal of Disaster Risk Reduction, 2020, 51: 101813.

[2] HUNG C H, HUNG H C, HSU M C. Linking the interplay of resilience, vulnerability, and adaptation to long-term changes in metropolitan spaces for climate-related disaster risk management[J]. Climate Risk Management, 2024, 44: 100618.

[3] LIU B, LI Y B, ZHANG Y, et al. Multi-criteria decision-making method for emergency shelter site selection considering flood risk: a case study of Zhuhai, China[J]. Cleaner Engineering and Technology, 2025, 24: 100892.

[4] AHMED I, GUYTON S T. The shelter recovery trajectory of typhoon Yolanda survivors: a critical synthesis review[J]. Progress in Disaster Science, 2024, 24: 100378.
[5] RAN Jing, LIU Xiangyi, HE Lei, et al. Disaster-prevention zoning in central urban areas based on the community life circle: a case study of Huayuan County, Hunan Province[J]. Planners, 2024, 40(9): 98-106.
[6] WANG Yixin, ZHANG Shuo, LIU Delin. Spatial zoning of ordinary-emergency dual-use urban shelters: a case study of the main urban area of Luoyang[J]. City and Disaster Reduction, 2025(3): 42-50.
[7] ZHU Anfeng, FAN Xiufang, DU Wenrui, et al. Comprehensive evaluation of disaster-prevention and disaster-reduction capacity of emergency shelters from a resilience perspective: a case study of Ouhai District, Wenzhou[J]. China Safety Science Journal, 2024, 34(5): 223-230.
[8] DAI Shenzhi, LIU Tingting, GAO Xiaoyu, et al. Compilation system and implementation mechanism for territorial spatial disaster prevention and reduction planning[J]. Urban Planning Forum, 2023(1): 48-53.
[9] WANG Wei, XIA Chenhong, MA Donghui, et al. Multi-hazard comprehensive risk assessment method under a coupled incentive mechanism[J]. China Safety Science Journal, 2019, 29(3): 161-167.
[10] WANG Wei, QU Zinuo, GUO Xiaodong, et al. Framework and method for constructing urban multi-hazard correlation and chain networks[J]. Journal of Safety Science and Technology, 2023, 19(11): 5-12.
[11] WANG Wei, ZHUANG Yuanyuan, ZHANG Luemiao, et al. Optimized layout of urban emergency shelters under compound disaster scenarios[J]. Journal of Beijing University of Technology, 2025, 51(4): 375-385.
[12] YANG Bing, HE Yong, ZHAO Dan. Comprehensive multi-hazard urban risk assessment: a case study of Beijing[C]//Sharing and Quality: Proceedings of the 2018 Annual National Planning Conference (01 Urban Safety and Disaster-Prevention Planning). Urban Planning Society of China; Hangzhou Municipal People's Government, 2018.
[13] WEI Miling, WANG Wei, RONG Qingwen, et al. Risk assessment model for compound-disaster shelter evacuation considering uncertainty[J]. China Safety Science Journal, 2023, 33(7): 203-212.
[14] YANG Xuanmei. Territorial spatial resilience: conceptual framework and implementation pathways[J]. Urban Planning Forum, 2021(3): 112-118.
[15] PENG Chong, ZUO Peiwen, LI Yuewen, et al. Multi-risk coupling in urban space and resilient planning responses[J]. Urban Planning Forum, 2024(5): 88-97.

AI-assisted translation