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Research on Three-Dimensional Analysis and Systematic Optimization of Urban Peacetime-Emergency Dual-Use Public Infrastructure

Yanan Shi

School of Emergency Management, Henan Polytechnic University, Jiaozuo Henan 454003, China

ABSTRACT

To address the theoretical and practical challenges of 'dual-use for normal and emergency situations' public infrastructure from concept to implementation, this study is based on the reality of the regularized urban risks in China. Using an integrated 'structure–process–function' analytical framework, it systematically reviews the development trajectory of dual-use facilities from the germination of ideas, the establishment of concepts, to systematic promotion, and comprehensively diagnoses their construction status and core issues across the three dimensions of structure, process, and function, using multi-source data and cases. By analyzing innovative practices at home and abroad to extract experiential insights, the study proposes a system optimization path aimed at high-quality development, covering key aspects such as institutional foundations, transformation mechanisms, resilience efficiency, and sustainable operation, with the aim of providing theoretical support and practical reference for promoting the high-quality development of dual-use public infrastructure beyond large-scale construction.

KEYWORDS

Dual-use for normal and emergency situations; Public infrastructure; Three-dimensional framework; Resilient city; Systematic optimization.

1. INTRODUCTION

In recent years, the intensification of global climate change and the acceleration of urbanization have formed a double superposition, and China's major cities are encountering increasingly complex risks and challenges, and urban safety governance is facing severe tests. According to the "China Climate Change Blue Book (2025)" released by the China Meteorological Administration, China's climate risk index will climb to a historical peak since 1961 in 2024, with high temperature and flood risks being particularly prominent, posing a serious threat to the normal operation of cities and the safety of residents' lives and property. The occurrence of a series of extreme weather events has intuitively exposed the vulnerability of cities in response to sudden disasters. The "7.20" heavy rainstorm in Zhengzhou caused severe waterlogging in the urban area, causing subway operations to be suspended and residents trapped; Zhuozhou, Hebei Province, due to the superposition of upstream floods and local heavy rainfall, led to large-scale water accumulation and traffic interruptions in the urban area, and shops along the streets became temporary shelters. A flash flood raided an elderly care center in Miyun, Beijing, and 31 elderly people were killed because the center was not included in the emergency support network and lacked flood control design. These incidents show that the traditional emergency facilities with a single function and scattered layout are difficult to adapt to the new requirements for urban safety in the context of risk normalization.

In this context, "dual-use" public infrastructure has emerged as the times require, becoming an innovative solution for coordinating urban development and safety. According to the "Guiding Opinions on Actively and Steadily Promoting the Construction of "Dual-use" Public Infrastructure in Megacities, "dual-use" facilities are defined as: undertaking people's livelihood and economic functions such as tourism, health care, and warehousing to meet the daily development needs of the city; in case of emergency, it can become a safety support carrier for emergency isolation, temporary resettlement and material support, and realize the compound value of "one facility for multiple purposes". The core advantage of this model is that it realizes resource intensification through functional compounding, which not only solves the waste of resources caused by long-term idle special emergency facilities, but also makes up for the shortcomings of the lack of emergency capacity of conventional people's livelihood facilities. As a key starting point for improving urban resilience, the "dual-use" facility effectively enhances the city's rapid response and recovery ability in the face of risks through the operation mechanism of "saving energy in peacetime and exerting force in emergencies". From a strategic perspective, it also meets the requirements of high-quality development, and provides an important path for optimizing the spatial layout of the city, improving the modern governance system, and realizing the dynamic balance between urban security and development.

This paper takes the "dual-use" public infrastructure as the research object, and is committed to constructing a systematic analysis framework and carrying out a panoramic investigation. This paper first constructs an integrated theoretical framework of "structure-process-function" as the analytical paradigm throughout the whole text. On this basis, the evolution of China's "dual-use" facilities from concept germination, policy establishment to systematic promotion is systematically sorted out. Then, from the three dimensions of structure, process and function, the construction progress and problems are comprehensively diagnosed. Finally, on the basis of systematically summarizing the practical experience of innovation at home and abroad, the optimization implementation path is proposed from multiple levels such as system design, implementation mechanism and efficiency improvement.

2. CORE CONCEPTS, RESEARCH CONTEXT, AND CONSTRUCTION OF ANALYTICAL FRAMEWORK

By defining the core concepts and characteristics of "dual-use for normal and emergency situations" public infrastructure, systematically reviewing and commenting on existing related research, the theoretical foundation and entry point of this paper are clarified. On this basis, a "structure-process-function" analytical framework running throughout the paper is proposed to provide methodological support for subsequent research.

2.1. Concept Connotation: Evolution from Single Function to Composite Function Paradigm

"Dual-use public infrastructure for both normal and emergency situations" refers to infrastructure systems that, under normal circumstances, serve public service functions such as tourism, wellness, leisure, entertainment, culture, and technology, but can be immediately converted to emergency functions such as evacuation, medical rescue, and material support in the event of major emergencies. The establishment of this concept marks an important shift in China's public infrastructure construction philosophy from 'single-function' to 'multi-functional.' Its essence lies in achieving an organic unity of development and safety through functional integration and resource coordination.

In terms of connotation, 'dual-use' facilities have three core characteristics: first, functional integration, meaning the same facility carries different functions under different time and space conditions; second, rapid convertibility, requiring the facility to have the physical conditions and management

mechanisms to complete function switching within a specified time; and third, resource synergy, which is reflected in maximizing multiple benefits under limited space and resource constraints.

In terms of extension, 'dual-use' facilities cover five main application scenarios: integration of normal health and epidemic management, integration of normal and disaster functions, integration of normal and holiday use, integration of normal and competitive/event use, and integration of peace and wartime use. Specific facilities include, but are not limited to, tourism and residential facilities, medical rescue facilities, material storage facilities, and transportation facilities, forming a comprehensive and hierarchically organized facility system (as shown in the figure 1 below).

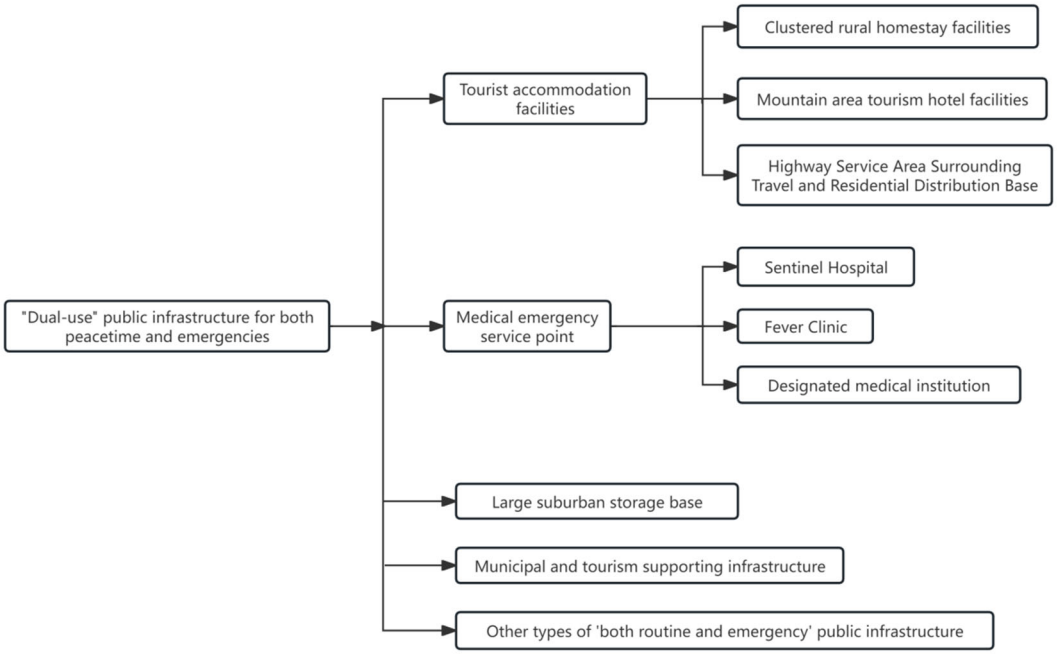

Figure 1. Classification of "Peacetime-Emergency Dual-purpose" Public Infrastructure

2.2. Main Advances, Multiple Perspectives, and Lack of Systematization in Existing Research

At present, the academic community has carried out in-depth discussions on the public infrastructure of "dual-use" from multiple dimensions such as concept classification, system construction and spatial layout.

In terms of conceptual definition and facility classification, there are two main perspectives: narrow list and broad integration. The narrow definition is strictly based on the "Guiding Opinions on Actively and Steadily Promoting the Construction of "Dual-use" Public Infrastructure in Megacities (hereinafter referred to as the "Guiding Opinions"), which is clearly divided into four types of facilities[1]. The broad perspective pioneers the functional intersection of urban disaster prevention facilities and general infrastructure, and advocates that all facilities that operate normally under normal conditions and can be quickly converted in emergencies are included in the category of "dual-use", so as to expand the types of facilities to various urban systems[2]. This delineates a clear and flexible category for subsequent research.

In terms of system construction research, scholars generally recognize that the core of this system lies in realizing the paradigm transformation from "isolation and decentralization" to "system integration"[3]. This study not only discusses the top-level logic that the system should follow from the macro level, emphasizing integrity, collaboration, and hierarchy[4]; it also answers how the system can be realized through planning transmission and community governance from the micro

practical level, highlighting the key role of regulations, standards and grassroots governance in transforming concepts into physical space and concrete actions[5,6].

At the level of spatial layout research, existing research shows the characteristics of multi-scale deepening and expansion. In the urban core area, the research focuses on solving the bottleneck of spatial resources, exploring the development of the "dual-use" potential of underground space, and the construction of a vertical dynamic coupling mechanism to enhance elasticity[7]. In the grassroots unit, the study sinks to the community living circle, and explores how the existing buildings represented by community complexes can quickly respond to local emergency needs through functional transformation, so as to weave a dense emergency network at the end of the city[8]. In rural areas, the research focuses on solving the contradiction between single facility function and idle resources, and proposes a low-cost and replicable construction model based on "spatial adaptation-facility co-construction-operation and maintenance", aiming to make up for the shortcomings of urban and rural emergency systems[9,10].

In general, the existing research has formed a preliminary system, but there are still the following three shortcomings: first, there is a lack of systematic sorting out of the development context of "dual-use" facilities, and the evolution logic is not clear enough[11,12]; second, the research on the construction status mostly focuses on specific regions or specific types of facilities, and lacks the overall picture at the national level or across regions[13]; third, the analysis of problems is mostly scattered in specific links such as layout optimization and functional transformation, and there is a lack of systematic attribution[14,15,16]. Therefore, this study will systematically explore the development context, construction status and core problems of "dual-use" facilities to make up for the shortcomings of existing research in terms of systematization and integrity.

2.3. 'Structure-Process-Function' Three-Dimensional Integrated Analysis Framework

In order to systematically analyze the evolutionary logic and practical challenges of "dual-use" public infrastructure from conceptualization to implementation, and to address the shortcomings of existing research in terms of holism and dynamics, this study constructs an integrated 'structure-process-function' analytical framework. The aim is to go beyond static descriptions of the physical form of facilities or a single system, and to conduct a comprehensive review and mechanistic analysis of 'dual-use' facilities from three mutually constitutive and dynamically interconnected core dimensions (as shown in the figure 2 below).

2.3.1. The Basic Role of Structural Dimensions

The structural dimension constitutes the foundational conditions and stability framework upon which 'dual-use for peacetime and emergencies' facilities rely for their creation and operation. It primarily encompasses two levels: institutional structure and spatial structure, both of which jointly provide rules and physical carriers for governance practices. The institutional structure is reflected in the laws and regulations, policy systems, standards, and embedded cross-departmental allocation of responsibilities that regulate the planning, construction, and management of facilities. Its completeness and coordination form the regulatory boundaries for the legitimacy and standardization of project advancement. The spatial structure refers to the physical layout, typology, hierarchical system of facilities in urban and rural spaces, and the network topology formed by their interweaving across different scales, fundamentally determining the geographic efficiency of emergency resource allocation and service coverage levels. The core function of the structural dimension is to provide order and support for the entire 'dual-use for peacetime and emergencies' system.

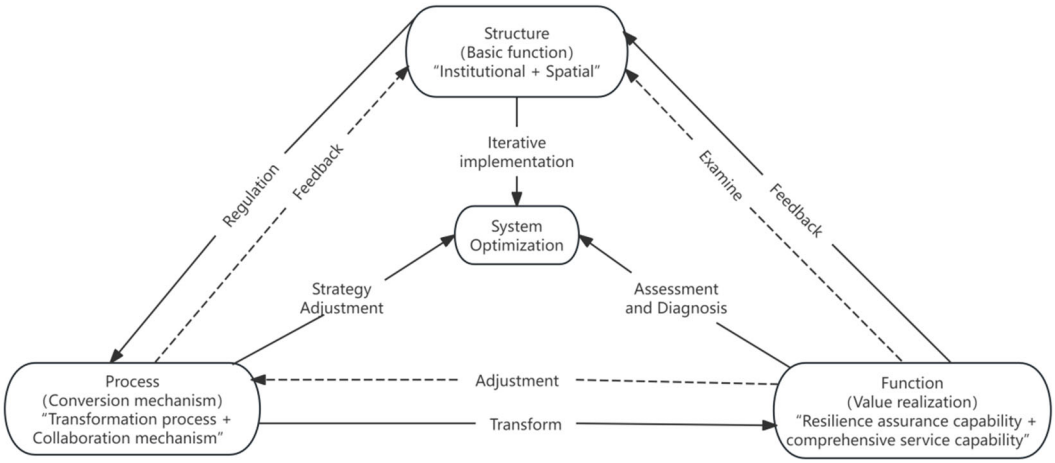

Figure 2. Three-dimensional integrated analytical framework of "Structure–Process–Function"

2.3.2. Conversion Mechanism of Process Dimension

The process dimension focuses on how to transform 'dual-use for normal and emergency' facilities from static reserves into actual operational effectiveness through management and coordination methods. It serves as a bridge connecting structure and function, running through the entire lifecycle management of the facilities, as well as the full process of switching between 'normal' and 'emergency' states. Its core includes two aspects: first, a standardized conversion process, which refers to the procedural chain from routine operations to emergency response, covering steps such as activation, scheduling, transition, and recovery, to ensure that the conversion process is orderly and efficient. Second, a diversified coordination mechanism, which refers to the rules and collaborative networks established among stakeholders such as government, enterprises, social organizations, and community members in emergency situations, centered on information sharing, resource allocation, joint decision-making, and coordinated actions. The effectiveness of the process dimension is directly related to whether institutional design and spatial planning can be translated into actual governance actions and service provision, and it is also a practical link to test whether the structure is reasonable.

2.3.3. Value Realization in the Functional Dimension

The functional dimension reflects the ultimate value and practical role of 'dual-use for normal and emergency situations' facility construction. Consideration of this dimension mainly revolves around two aspects: first, the facility's resilience capability, that is, the ability to maintain critical services, absorb disturbances, and achieve rapid recovery in the face of sudden shocks, which constitutes the core of its public safety value; second, the facility's comprehensive service capability, which requires assessing its effectiveness and operational efficiency in serving social development under normal circumstances, as well as the adequacy and accuracy of emergency resource supply in urgent situations. The degree to which functions are realized is not only the ultimate benchmark for evaluating the success of the system but also generates key feedback signals that in turn drive adjustments and optimizations in structure and processes, thereby forming a closed loop of continuous system improvement.

3. THE CONSTRUCTION HISTORY AND POLICY DEEPENING OF 'DUAL-USE FOR PEACE AND EMERGENCY' FACILITIES

The rise and development of 'dual-use for peacetime and emergencies' public infrastructure is an inevitable product of responding to complex public safety challenges against the backdrop of China's urbanization entering a risk society. Its evolution process is not linear, but a dynamic process in which the continuous deepening of conceptual understanding and the increasingly完善 construction of the

system are realized through the complex interaction of policy-driven initiatives and practical feedback. To clearly present this process, this section divides it into three key historical stages.

3.1. Early Practice and Conceptual Origins of Simple Functional Reuse (2010-2021)

This stage was the incubation period for the concept of 'dual use for peacetime and emergencies,' characterized mainly by the spontaneity of grassroots practices and the simplicity of conceptual understanding. At the policy and practical level, early explorations primarily arose from leveraging the functions and extending the efficiency of existing facilities. The most representative examples were the commercial development and utilization of civil air defense projects under the guidance of the 'integration of peacetime and wartime' idea, such as transforming air-raid shelters and underground bunkers into underground shopping malls, parking lots, or storage facilities, thereby converting national defense preparedness resources into economic benefits during peacetime, reflecting the preliminary notion of 'one investment, double benefits.' At the same time, practices where large public buildings like stadiums and convention centers were temporarily used as emergency shelters or material transfer sites during non-event periods also occasionally occurred. However, these practices were generally fragmented and localized, mostly temporary measures responding to specific needs, reflecting a lack of stable institutional support, forward-looking spatial planning, standardized emergency conversion procedures, and effective coordination mechanisms.

At the theoretical and cognitive level, the stage was marked by a rudimentary concept of functional reuse. The practical ideas of this period were mainly rooted in the long-standing tradition of 'integration of peacetime and wartime' and the preliminary application of 'integration of peacetime and disaster response' in the field of natural disaster prevention. Its core logic was to improve the ability to respond to known and certain risks through simple overlay of physical spaces and temporary functional adjustments at relatively low marginal costs. However, the understanding at this stage had obvious limitations: 'peacetime' and 'emergency' remained essentially separate, resulting in both the service efficiency of facilities in peacetime and their protective effectiveness in emergencies being rather limited, without achieving organic integration and maximized value. Overall, deeper issues such as suitability under emergency conditions, conversion standards, operational management mechanisms, and long-term maintenance costs were not systematically considered.

3.2. Policy Establishment and Cognitive Deepening in the Process of Strategic Conceptualization (2021-2023)

Building on the aforementioned spontaneous exploration, this phase achieved a critical leap in transforming the "dual-use for peacetime and emergencies" concept from local experience to national strategy. This milestone was marked by the formal proposal of the concept and the preliminary construction of national top-level design, achieving substantial progress in institutional development and mechanism exploration.

At the policy and practice level, the release of the "Chengdu-Chongqing Economic Circle Construction Planning Outline" in 2021 for the first time distilled the concept of "dual-use for peacetime and emergencies" in a national strategic document. Subsequently, the global COVID-19 pandemic acted as a strong external catalyst. Practices such as the rapid large-scale construction and efficient conversion of facilities like Fangcang hospitals and centralized quarantine sites not only exposed the fragility of the traditional emergency system but also provided rich empirical cases for the "dual-use for peacetime and emergencies" concept. Against this backdrop, the Central Political Bureau meeting in 2023 explicitly called for the promotion of this construction, and in July of the same year, the General Office of the State Council officially issued the "Guiding Opinions," providing key institutional bases and policy guidance for comprehensive development.

With the clarification of policies, there was also a qualitative leap at the theoretical and cognitive level. Through systematic reflection on previous practical experiences in "peace-to-war," "peace-to-

disaster," and "peace-and-epidemic integration," the connotation of "dual-use for peacetime and emergencies" was profoundly refined and expanded. Its core characteristics were clearly defined as scenario diversity, modular functional design, and normalized operational management. This deepening of understanding marks a shift in research focus from mere spatial utilization to a comprehensive pursuit of efficient conversion processes, sustainable operating models, and deeper resilience assurance capabilities. Consequently, the concept of public safety has shifted from specialized defense against specific disasters to building comprehensive resilience to cope with uncertain risks.

3.3. Comprehensive Advancement and Resilience Building Since Systematization (2023 to Present)

Marked by the release of the "Guiding Opinions," the construction of "dual-use for normal and emergency" public infrastructure has entered a new stage of accelerated, systematic advancement with continuous theoretical deepening. Its institutional system, implementation mechanisms, and value objectives all show trends of coordinated deepening and comprehensive expansion.

At the policy and practice levels, its strategic position has been further elevated, forming together with urban village redevelopment and the construction of affordable housing the "three major projects" for high-quality urban development and safety in the new era. The policy promotion exhibits characteristics of systematization and refinement, with multiple national ministries and commissions issuing more than 20 supporting policies in total, forming a "1+N+X" policy system. Documents such as the "Guidelines for Resilient Urban Planning and Land Policy with Dual Normal and Emergency Functions" provide key support for the spatial implementation of facilities. This indicates that the institutional environment and planning foundation supporting infrastructure development are becoming increasingly mature. At the practical level, project construction demonstrates large-scale and grid-like characteristics, evolving from "points" to "areas." According to statistics, the first batch of 54 major cities nationwide has planned approximately 3,000 projects, with a total investment exceeding one trillion yuan. Local innovative practices are diverse, for example, Beijing's Pinggu District has created five application scenarios focused on "eating, living, commuting, medical services, and centralized capacity," while Hangzhou has built a "1+1+4+N" policy system and was the first to issue local construction standards.

At the same time, theoretical understanding has reached a new height. Comprehensive resilience has become the overarching core concept. "Dual-use for normal and emergency" is regarded as an indispensable physical pillar for building resilient cities. Its scope of application has systematically expanded to five areas: normal epidemic, normal disaster, normal vacation, normal competition, and normal war, with value objectives elevating from single emergency security to integrated public values that coordinate development and safety while balancing efficiency and equity. Against this background, theoretical research has also deepened to focus on mechanism and governance issues such as "how to achieve efficient conversion and sustainable operation," reflecting a shift in the practice focus from hardware construction to soft mechanism innovation and governance capacity enhancement. This marks the transition of China's public infrastructure construction from the traditional "specialized response and fragmented management" to a modern approach of "comprehensive resilience and collaborative governance."

4. THREE-DIMENSIONAL DILEMMA DIAGNOSIS BASED ON THE 'STRUCTURE-PROCESS-FUNCTION' FRAMEWORK

Currently, the construction of 'dual-purpose for routine and emergency' public infrastructure is moving from conceptual pilot projects to a mature system, but it still faces profound systemic challenges. This section uses the 'structure-process-function' integrated analysis framework to

examine the core problems that exist, aiming to reveal the inherent contradictions that constrain its sustainable development and provide a basis for subsequent optimization.

4.1. Insufficient Institutional Provision and Imbalanced Spatial Layout at the Structural Level

The structural dimension encompasses the static foundations that support system operation, including institutional structures and spatial structures. Currently, both areas have obvious deficiencies, forming the fundamental bottleneck to enhancing system resilience.

4.1.1. Institutional Structures Exhibit Legal Gaps, Fragmented Standards, and Weak Coordination

Although a preliminary policy framework has been established, systematic, full-life-cycle institutional provision is still lacking. In terms of legal protection, existing bases mainly consist of departmental regulations and normative documents, lacking high-level laws or administrative regulations. This results in key stages such as planning, construction, property rights, operation, transition, and compensation being weakly constrained and unpredictable. Ambiguities in the authority and responsibility relationships among departments also make project advancement highly dependent on ad hoc coordination, making it difficult to form long-term mechanisms and thereby affecting social capital participation confidence. The technical standards system is fragmented; due to the absence of top-level design at the national level, different regions have inconsistent standards for facility classification, design specifications, and technical parameters. This not only leads to uneven construction quality but also undermines the standardization of emergency networks and their potential for future cross-regional coordination. In addition, the issue of weak cross-departmental coordination mechanisms is also prominent. Routine coordination platforms and clear delineation of authority among multiple departments are generally lacking, with "multiple management heads" and "responsibility vacuums" coexisting, significantly reducing the overall efficiency of planning integration, project approval, operational supervision, and emergency dispatch.

4.1.2. Spatial Structure Shows Regional Imbalance, Urban-Rural Segregation, and Type Bias

In terms of spatial layout, there are currently deep structural contradictions in construction. Regional allocation is uneven, with facilities highly concentrated in the developed eastern coastal city clusters, while coverage in the central and western regions and underdeveloped areas is obviously insufficient. This exacerbates regional gaps in national emergency support capacity and weakens the ability for cross-regional collaborative assistance. There is also significant segregation between urban and rural areas, as facility layout naturally tends toward urban built-up areas, with weak coverage in county towns, townships, and rural areas, affecting the equalization of public safety services and the overall quality of system coverage. In terms of facility types, existing projects overly focus on tourism and residential facilities that are easy to commercialize, while the construction of professional facilities critical in emergencies, such as medical rescue, material reserves, and specialized rescue training, lags behind. This results in a facility network with a single function, making it difficult to meet the specialized needs of complex disaster scenarios.

4.2. Process-Level Conversion Flow Bottlenecks and Failures in Collaborative Governance

The process dimension focuses on the core mechanisms of dynamic conversion between "normal" and "emergency" functions and the collaboration of multiple stakeholders. Currently, both aspects face deep-seated bottlenecks, resulting in facilities' operational efficiency and emergency response capabilities not being fully realized.

4.2.1. Conversion Flows Face Design Deficiencies, Lack of Standards, and Insufficient Testing

Although some advanced regions have conducted conversion drills and formulated local guidelines, from a national perspective, the "normal-to-emergency" conversion generally still encounters multiple practical difficulties from design to operation. The level of standardization and normalization needs urgent improvement. Many current renovation projects only involve simply adding emergency equipment without systematically reconstructing building spatial flows, structural loads, or equipment system compatibility, leading to chaotic processes, low efficiency, and safety risks during emergency activation. Due to the lack of top-level standards, each region implements its own criteria regarding conversion trigger conditions, operational procedures, and time requirements, making it difficult to achieve coordinated linkage among different regions and types of facilities. Moreover, the conversion functions of the vast majority of facilities have not undergone full stress testing under extreme conditions such as network or power outages, leaving their system reliability and continuity in doubt.

4.2.2. Collaborative Mechanisms Encounter Information Barriers, Conflicting Interests, and Ambiguous Responsibilities

An effective collaborative governance framework involving multiple stakeholders has yet to be established. Information barriers between departments are severe, data standards are inconsistent, and platforms are not interconnected, making it difficult to grasp resources in real time under emergency conditions, with resulting inefficiencies in decision-making and resource allocation. The interests of governments, enterprises, communities, and other parties are in tension, yet there is a lack of institutionalized consultation platforms and clear risk compensation mechanisms, which suppresses market and social participation incentives. Meanwhile, facility ownership, operational rights, maintenance rights, and emergency activation rights are dispersed, but corresponding key responsibilities such as routine maintenance accountability and sharing of emergency activation costs are not clearly defined. This directly affects the long-term usability and emergency readiness of facilities.

4.3. Shortcomings in Resilience Effectiveness at the Functional Level and the Crisis of Operational Sustainability

The functional dimension is the ultimate measure of a facility's value. Currently, it faces severe challenges in both core resilience effectiveness and sustainable operation.

4.3.1. Resilience Protection Manifests as Weak Scenario Adaptability and Insufficient Professional Capability

The functional design of existing facilities mainly targets a predetermined single emergency scenario, lacking modularity and reconfigurable flexibility, making it difficult to adapt to non-traditional or complex situations such as new public health emergencies and compound disaster chains. Facilities converted from hotels, stadiums, and other venues possess inherent shortcomings in strict hospital infection control, medical waste management, and professional rescue support, often proving inadequate when faced with scenarios demanding high professional standards. In addition, the entire system lacks regular, practical stress testing for extreme disaster situations, and its ability to operate continuously under harsh conditions and the societal capacity to withstand pressure have not been effectively verified.

4.3.2. Operational Sustainability Hindered by Usage Rate Polarization, Cost Dilemmas, and Maintenance Gaps

"Being useful in normal times" is the socio-economic foundation supporting system operation, but this foundation is not solid. Facility usage rates are polarized: tourism and residential facilities can be maintained, while professional facilities with specific functions in suburban areas remain idle for long

periods, causing resource waste and financial burdens. Higher initial construction and daily maintenance costs lack a stable revenue model and a reasonable cost-sharing mechanism to cover them, leading to unsustainable government subsidies and a lack of willingness for continuous social capital investment. Moreover, the absence of dedicated maintenance standards, funding guarantees, and dynamic technology update mechanisms for the "dual-use for normal and emergency situations" feature results in functional degradation over time and a continuous decline in emergency reliability.

5. LESSONS AND INSIGHTS FROM DOMESTIC AND INTERNATIONAL INNOVATIVE PRACTICES OF DUAL-USE FOR ROUTINE AND EMERGENCY

Based on diagnosing, within the "structure-process-function" framework, the systemic challenges facing the construction of dual-use facilities in China—such as institutional gaps, coordination bottlenecks, and operational crises—this section aims to seek solutions from relevant innovative practices at home and abroad. These practices are not isolated incidents but proactive explorations addressing the specific difficulties mentioned above. Their successful experiences and underlying logic provide crucial empirical evidence and guidance for moving from "problem diagnosis" to "path optimization."

5.1. Localized Exploration and Practice Models in Pilot Domestic Regions

Some pioneering regions in China have confronted the deep-seated conflicts in construction and carried out targeted innovations across institutional, spatial, procedural, and functional dimensions, forming valuable local experiences.

To address the challenges of insufficient institutional structure supply and fragmented standards, Zhejiang Province responded through systematic standard construction and innovative coordination mechanisms. By formulating provincial technical guidelines and establishing cross-departmental special working groups, Zhejiang built an integrated institutional system of "policy-standard-supervision." The core of the “Zhejiang Model” lies in actively reshaping the institutional environment, promoting regulation through standardization, and breaking administrative barriers via tangible coordination mechanisms, providing a replicable example for establishing a stable and predictable construction management order.

To tackle spatial structural imbalances and scattered layouts, Yinchuan city explored a full-region grid layout and full-cycle refined management approach. Through developing special plans, Yinchuan systematically constructed a four-level network of emergency shelters covering both urban and rural areas, implementing an integrated "planning-construction-management-use" model. The key to its practice is systematically optimizing the spatial network through top-level planning and realizing precise management through smart platforms, effectively improving facility coverage, accessibility, and overall network resilience.

Addressing process-based coordination failure and delayed response bottlenecks, Hangzhou built an agile response mechanism relying on smart logistics and grassroots governance innovation. By creating an intelligent material allocation network and the "1-3-N" grassroots governance model, Hangzhou achieved data-driven resource deployment and government-society coordinated emergency mobilization. The essence of the "Hangzhou Plan" is using digital technology to streamline processes and socialized mechanisms to activate the endpoints, significantly optimizing the agility and reliability of the emergency response chain.

Regarding functional operational crises and poor sustainability, Pinggu District in Beijing contributed ideas for market-oriented functional integration driven by scenario-based applications. To address high facility idleness and difficulty forming commercial loops, Pinggu guided the transformation of

idle rural houses into dual-use homestays, creating an integrated model of "routine operation and emergency accommodation." The core of the "Pinggu Experience" lies in building a value cycle between market-based operation and public emergency, providing innovative ideas for social capital participation and the integration of facility economic and social benefits.

5.2. Developed Countries' Diverse Paths Dominated by Rule of Law, Market, and Planning

Developed countries and regions such as Japan, the United States, and Europe have formed relatively mature resilient infrastructure development models through different dominant paths, including the rule of law, market mechanisms, and planning, providing multidimensional perspectives for China to learn from.

Japan has established a system of deep coordination between legalized regulations and community governance. Through laws such as the Basic Act on Disaster Countermeasures, it fully legalizes facility standards, responsibilities, and procedures, fundamentally resolving the issue of unclear responsibilities. At the same time, community organizations like the ‘‘Chonai-kai’’ are deeply embedded in daily maintenance and emergency response, forming a solid grassroots support network. This offers important insights for China in systematically building an authoritative legal framework and activating social capital to ensure the effective operation of the system.

The United States has developed a mobilization model that integrates social resources through market-based agreements. The Federal Emergency Management Agency (FEMA) clearly defines responsibilities and compensation through standardized ‘‘pre-arranged agreements,’’ efficiently converting commercial logistics networks and accommodation resources into emergency capabilities. This model, where the government acts as a system integrator leveraging market forces through contractual design, provides China with a market-oriented solution for innovating public-private cooperation and building a resilient, efficient resource mobilization and dispatch system.

Europe, represented by the Netherlands, has developed a proactive integration path centered on spatial planning guidance and multifunctional resilience design. By mandating resilience requirements in national spatial planning and building regulations, it ensures that infrastructure possesses physical potential for normal-emergency transition and adaptive flexibility from the design stage. This offers fundamental insights for China to move the concept of ‘‘dual-use for normal and emergency times’’ from post-construction retrofitting to proactive planning, achieving systemic integration with urban development.

5.3. Comprehensive Insights from Domestic and International Experiences for System Optimization

At the structural level, it is necessary to establish a legal standards system and coordination mechanism that balances rigidity and flexibility, while building a balanced, multi-level facility network through scientific planning to lay a solid foundation of rules and space for system operation. At the process level, digital technology should be fully utilized to break information barriers and optimize decision-making processes, while market-oriented contracts integrate social resources to build a resilient and efficient mobilization and collaboration model, ensuring smooth normal-emergency conversion processes and effective coordination. At the functional level, it is necessary to explore sustainable operation models that integrate market mechanisms and public value, enhance the resilience of facilities in responding to diverse and complex scenarios through modular and adaptive designs, and ultimately achieve the core value of being useful in normal times and effective in emergencies.

6. SYSTEM OPTIMIZATION PATH FOR THE HIGH-QUALITY DEVELOPMENT OF "DUAL-USE" FACILITIES

Based on the diagnosis of the current situation and problems in the framework of "structure-process-function" and the enlightenment of domestic and foreign practice, this study believes that the key to promoting the "dual-use" public infrastructure from large-scale construction to high-quality development lies in systematic reconstruction. The optimization path must closely correspond to and systematically solve the structural shortcomings, process obstructions and functional crises revealed in the previous article, so as to achieve the overall upgrading of the system.

6.1. Build a solid institutional foundation and reshape the balanced network

In view of the insufficient supply of institutional structural systems and the deep imbalance of spatial structure, the optimization path needs to be strengthened from both top-level design and planning layout to build a stable and balanced system foundation. The primary task is to accelerate the process of rule of law and fill the gaps in authoritative laws. It is necessary to promote the formulation of special regulations such as the "dual-use" public infrastructure management regulations, fundamentally clarify the legal attributes, property ownership, management responsibilities and emergency requisition compensation standards of facilities, provide stable long-term expectations for social capital, and solve the synergy problem caused by the ambiguity of rights and responsibilities. On this basis, efforts should be made to build a rigid and elastic standard and specification system. It is recommended that the national standardization management agency take the lead in issuing national technical guidelines covering the whole life cycle of "planning, design, construction, conversion, operation and maintenance". At the same time, it is necessary to further establish a unified national basic mandatory standard, and encourage local governments to formulate supporting implementation rules and flexible guidelines according to the differences in disaster risk, economic level and facility type, especially to refine the technical standards for functional conversion in different emergency scenarios, so as to solve the current standard fragmentation dilemma.

The optimization of spatial layout must shift from discrete project points to a balanced resource network, and the "dual-use" facility system should be deeply integrated into the territorial spatial planning at all levels, and a mandatory connection mechanism with national economic planning and emergency system planning should be established. The focus is to change the current imbalance between regions, urban and rural areas and types through regional collaborative planning, and build a network of facilities with complementary functions and resource sharing in urban agglomerations. At the urban and rural levels, combine urban renewal and rural construction to promote the extension of facilities to grassroots communities and counties and townships. At the same time, through planning guidance and land use policies, optimize the proportion and layout of tourism and residential facilities, medical care, material reserves and other professional facilities, and form a resilient network with complete functions and covering the whole area.

6.2. Promoting Standardized Conversion and Intelligent Collaborative Governance

To overcome the practical difficulties in the conversion process and the governance failures of collaborative mechanisms, it is necessary to strengthen the standardization and intelligence of process management, and to build a multi-party governance structure with aligned incentives. Achieving smooth, rapid, and efficient conversion relies primarily on promoting standardization and operational readiness of the conversion process. It is essential to develop and promote modular, menu-style facility conversion plans and operation manuals based on national technical guidelines, clearly specifying the full-chain operational norms, time requirements, and responsible parties—from emergency warning issuance, function switching initiation, spatial flow adjustments, to equipment system activation. More importantly, regular drills and stress tests must be established to simulate

extreme conditions such as network or power outages, regularly testing and optimizing the reliability and robustness of the conversion process.

The key to activating multi-party collaborative effectiveness lies in breaking down barriers through digital technology and designing effective market and social participation mechanisms. Efforts should be accelerated to build national or regional “dual-use emergency facilities” intelligent management platforms, unify data standards, and integrate dynamic information such as facility status, material reserves, and human resources, achieving real-time monitoring and intelligent scheduling across departments and regions during emergencies. At the same time, drawing from international experience, the pre-arranged agreement model between government and market entities should be widely promoted, specifying the procedures for resource mobilization, cost compensation, and liability exemptions in emergency activation through standardized contracts, thereby orderly incorporating social resources such as commercial logistics, accommodation, and catering into the emergency mobilization system.

6.3. Strengthening Source Resilience and Innovative Operation Models

In response to the structural limitations of resilience assurance effectiveness and the crisis of operational sustainability, optimization pathways need to focus on the integration of functional design from the outset and the closed-loop innovation of business models, ensuring that facilities are "useful in normal times and effective in emergencies." Enhancing the functional resilience of facilities requires a shift from retrofit-oriented thinking to source-integrated design. During the planning and architectural design phases of new or renovated facilities, it is necessary to mandatorily include "dual-use for normal and emergency situations" resilience assessments, actively adopting modular and adaptive designs such as movable partitions, multifunctional interfaces, and flexible structural loads, so that facility spaces and equipment systems possess inherent capabilities and adaptability to cope with diverse and uncertain risk scenarios, going beyond merely responding to a single predetermined disaster.

The core to ensuring long-term operation of facilities lies in exploring a sustainable model that balances "public welfare and commercial interests." On the one hand, it is necessary to innovate market-based operation mechanisms, encouraging professional institutions to operate through service purchases, franchising, performance subsidies, etc., and to develop the compound commercial value of facilities in normal times. On the other hand, a cost-sharing and dynamic update mechanism covering the entire lifecycle should be established, clearly defining the responsibilities and funding channels of the government and operators in construction, maintenance, and upgrades, setting up special maintenance funds, and establishing regular evaluation and technical renovation systems to ensure that the technical performance and service capabilities of facilities evolve over time, avoiding functional degradation.

6.4. Improve Implementation Support and Dynamic Feedback Mechanism

The implementation of the system optimization pathway cannot be achieved without strong support guarantees and continuous feedback adjustments. In terms of organizational and capability support, it is recommended to establish a tangible cross-departmental coordination body at the central level, responsible for policy coordination and supervision assessment, while strengthening the planning execution and emergency management capabilities of local governments. At the same time, implement a special talent development program to build a composite talent system covering planning and design, engineering management, and emergency operations.

It is crucial to establish and improve a dynamic management closed loop of "monitoring-assessment-optimization." By continuously collecting facility operation data through an intelligent management platform, build a comprehensive performance evaluation system centered on resilience enhancement and operational efficiency, linking assessment results directly to policy incentives and financial

subsidies. Conduct systematic evaluations regularly and dynamically revise and optimize standards, plans, and policies in a timely manner based on practical feedback, risk changes, and technological advancements, ensuring that the "dual-use for normal and emergency" system maintains its evolutionary capability and effectively supports high-quality urban development and high-level safety.

7. CONCLUSIONS AND LIMITATIONS

This study, based on the 'Structure-Process-Function' analytical framework, systematically explores the development trajectory, practical challenges, and optimization paths of China's 'dual-use for normal and emergency' public infrastructure. The main conclusions are as follows:

The construction of 'dual-use for normal and emergency' facilities has evolved from early spontaneous functional reuse to a systematic resilience project that coordinates urban development and safety. Currently, the promotion of these facilities still faces threefold challenges in structure, process, and function: insufficient institutional authority and unbalanced spatial layout restrict the foundational system; the lack of transition processes and obstacles in coordination mechanisms affect operational efficiency; shortcomings in resilience assurance and crises in operational sustainability weaken long-term effectiveness. These problems are interrelated and require systematic responses.

For high-quality development, the optimization path should focus on systemic reconstruction: by improving legal standards and optimizing spatial networks to strengthen structure; relying on smart platforms and market agreements to facilitate processes; leveraging resilience-oriented design and sustainable business models to enhance function. Simultaneously, it is necessary to establish a dynamic evaluation and continuous optimization management loop to ensure the system adapts to the ever-changing risk environment.

This study is limited by data from emerging fields, and some conclusions rely on typical cases, with their generalizability needing further verification; the differentiated paths for facilities of different regions and types can still be explored in greater depth. Future research can continue to deepen in the following directions: first, expand the research scope to strengthen differentiated studies on various regional contexts and facility types; second, deepen theoretical exploration to further improve the theoretical framework and methodological system for 'dual-use for normal and emergency' facility construction; third, reinforce empirical research through systematic data collection and case analysis to verify and refine existing theoretical findings. As practical implementation advances, continuous tracking of facility operational effectiveness is needed, with dynamic optimization of development paths to provide stronger theoretical support and practical guidance for promoting the high-quality development of 'dual-use for normal and emergency' public infrastructure.

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