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Unlocking Physical Resilience Capacities of Building Systems: An Enhanced Network Analysis Approach

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Abstract: Fostering the physical resilience of building systems and ensuring their functionality during disasters is paramount. To unlock the physical resilience capacities of building systems, this study applied an enhanced network-based approach comprising four steps: (1) classifying the building systems and developing a comprehensive building system network can be achieved by treating building components as nodes and their functional, resource, information, and physical interdependence as connections; (2) characterizing the physical resilience capacities of building systems through robustness and redundancy; (3) setting up both deliberate and random attack scenarios and revealing the robustness of building systems by using the relative size of maximum connected subgraphs and global network efficiency; and (4) proposing a novel redundancy index to reveal the capacities to maintain function in the face of disruptions. A real-world case study was conducted to analyze the physical resilience of a building system under disruptions, illustrating the feasibility of the proposed approach. The case study identified several key systems and operation strategies for enhancing the resilience of building systems. In summary, the proposed approach contributes to a comprehensive understanding of the building system and quantitatively reveals its robustness and redundancy capacities. Practically, these findings offer valuable insights and practical strategies for facility managers to foster resilient and sustainable operations during building operations.

Keywords: physical resilience; building systems; complex network theory; network analysis

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1. Introduction

Buildings serve as essential spaces for people to live, work, and socialize [1], deliver crucial lifeline services (e.g., equipment monitoring, timing and scoring, and television and commentary) [2], and provide integrated services (e.g., rest service, catering service, game watching service) [3]. The frequency and intensity of natural disasters (such as earthquakes, tsunamis, volcanic eruptions, floods, storms, and epidemics) and man-made disasters (such as power failure) are increasing, and buildings are extremely vulnerable to this multiple disturbance environment [4,5]. These multiple disruptions will cause the functional loss of the building and easily cause new secondary and derivative disturbances in the process of generation and propagation, leading to major safety accidents and even evolving into public crises [6]. Nevertheless, with the high level of comfort and safety requirements

of buildings, integrating all systems (power, telecommunications, water supply, safety equipment, etc.) is required [7]. Because of this, contemporary building systems are growing more sophisticated and intelligent, and a cascade effect among systems makes them even more vulnerable—particularly in the event of extreme occurrences. Therefore, it is imperative to enhance the resilience of the buildings to interruptions.

Previous studies devoted efforts to critical infrastructure resilience at the urban level, including the assessment of infrastructure (i.e., transportation systems, power systems, and water supply systems) resilience [8,9], identification and assessment of the interdependencies between critical infrastructures [10,11], factors influencing infrastructure resilience [12,13], and the modeling of integrated infrastructure systems [14,15]. Despite these studies offering insightful information, the resilience analysis at the single-building level is ignored. Buildings are the basic units of a city or community, and their resilience is vital to both the infrastructure and the city. A building system encompasses the functional spaces (i.e., office meeting area, coach area, and press area) and lifeline systems (i.e., power supply, sewage, and water supply). The functionality of building systems relies on the support of individual systems and their interactions. These individual systems and their interactions collectively form the Building System Network (BSN).

Quantitative evaluation of network resilience offers vital benchmarks [16,17], along with the necessary corrections for resilience enhancement [18]. Network analysis is an effective method for resilience assessment, as it can clearly represent the complex interactions within systems through the construction of a network model and dynamically analyze changes in the system under disruptions. Complex network theory (CNT) is a useful instrument for network analysis. CNT provides a promising approach to establishing BSNs by accounting for multiple types of systems and their various interactions [19]. Typically, a building system consists of numerous components (i.e., lighting system, power supply system, domestic water supply system) with intricate connections (i.e., physical connections, resource exchange). The network structure abstracts the components of the building system as nodes and their interactions as edges, thereby facilitating a more comprehensive understanding of the overall structure and interactions within the building system. The dynamic changes within the network during an outage provide a more precise assessment of physical resilience.

Several basic topology indicators (i.e., betweenness centrality and closeness centrality) are frequently employed in assessments of network robustness [20]. Nevertheless, the majority of research only measures the indicators in a static network, failing to take into account the network's dynamic characteristics. Building on these insights, this paper assesses the robustness of the network under attack scenarios [21,22]. In the quantification of robustness, the Edge Coupling Robustness can also be used [23]. However, it cannot be broadly applicable to networks with varying sizes and structures [24]. Nevertheless, the relative size of maximum connected subgraphs (RSMCS) and global network efficiency (GNE) can fully reflect the disruption tolerance of the network structure [25]. Therefore, RSMCS and GNE under random and deliberate attacks are selected in this research to quantitatively characterize the robustness of the building system network.

Nevertheless, redundancy was less of a focus in most earlier studies on resilience evaluation, which mostly concentrated on robustness [26]. In the existing research on redundancy, there is more research on structural redundancy and less attention on functional redundancy [27]. The functional redundancy of complex networks is generally characterized by the number of alternative paths remaining after the failure of the partially connected paths between any nodes in the network [28,29]. However, compared to networks such as traffic and water supply systems, BSN is heterogeneous since each node represents a different system. It is not appropriate to calculate the number of alternate paths between

any node in the BSN [30]. Consequently, there are few appropriate methods for assessing the functional redundancy of BSN.

To address the aforementioned research gaps, this study applied an enhanced network-based approach to unlock the physical resilience capacities of building systems. First, the building systems were classified and a comprehensive building system network was developed, which can be achieved by treating building components as nodes and their functional and physical interdependence as connections. Second, the physical resilience capacities of building systems were characterized through robustness and redundancy. Third, both deliberate and random attack scenarios were set up and revealing the robustness of building systems by using the relative size of maximum connected subgraphs and global network efficiency. Finally, a novel redundancy index revealed the capacity to maintain function in the face of disruptions through backup resources or repetitive functions.

To be more precise, a comprehensive building system network is created by treating building components as nodes and their functional and physical interdependence as connections. The resilience of BSN is measured by assessing suitable network indicators (robustness and redundancy). The proposed framework was then fully examined in a real-world case building—the Nanjing Olympic Sports Center (NOSC). Following that, the physical resilience metrics were analyzed, and strategies for BSN physical resilience improvement were identified. This study has some guiding implications for investigating resilience in various contexts. Managers can better understand the intricacy and susceptibility of large stadium physical systems, according to the research. This research gives them the ability to create the policies that are required to improve safety management in dynamic operating environments—especially in times of emergency.

2. Literature Review

2.1. Building System and Physical Resilience

The building system provides the basic living, working, and activity space for urban residents and is the basis for the normal operation of urban functions. In addition, building systems, through design and management, can significantly enhance the resilience of cities, enabling them to better recover and adapt in the face of disruptions [1]. Understanding building systems is critical in modern infrastructure research since they play a vital role in urban resilience and functionality. As cities continue to develop, the complexity of building-related systems has increased enormously. Modern architecture often integrates multiple functions—such as living, working, commerce, and entertainment—into a single building, thereby increasing the complexity of its internal systems. Additionally, the widespread adoption of intelligent building systems, including intelligent lighting, security, and energy management, has further complicated these systems.

Given the increasing complexity of building systems, complex networks offer a robust framework for analyzing the physical toughness and resilience of these systems [31]. In light of the characteristics of the complex networks and frequent disasters, much effort has been devoted to the networks for disaster resistance. Specifically, most of these efforts have been focused on the level of urban infrastructure, including transportation systems [32,33], power systems [34,35], water supply systems [36], and interrelated infrastructure systems [37]. Typical studies include (1) identifying and modeling the relationships (physical, cyber, geographic/spatial, and logical) among critical infrastructures and analyzing their interdependence [10,11], (2) examining the stability and disaster resistance of the network from the perspective of structure [38,39], and (3) investigating the network performance via network measures [40,41]. Despite these studies providing insightful information, the research was conducted at the macro level and failed to investigate individual building systems at the micro level. Nevertheless, individual buildings contain complex interior

structures and function as stand-alone systems. As a result, from a microscopic perspective, this article represents each system and its interrelationship in the building as a BSN. Furthermore, frequent and multiple disturbances severely impede the system's capacity to operate normally, highlighting the vital importance of resilient physical systems [42]. As a result, the public sector and academia are increasingly focusing on the physical resilience of BSN. Nevertheless, the majority of studies have concentrated on physical structures (such as beams, plates, and columns) in the field of physical resilience [43,44]. Functional support systems (such as water supply systems and power supply systems), which provide the primary support for building functioning, are overlooked. Being a complex system, a building's ability to function depends not only on its physical structure but also on the support of functional support systems (including lifeline systems and functional spaces) [45]. Thus, a significant addition to this study is the examination of the physical resilience of the building's functional support system. The characteristics, including robustness, redundancy, connectedness, adaptability, and resourcefulness, are extensively researched in the context of resilience evaluation. Nevertheless, robustness and redundancy are the most important characteristics affecting physical resilience [46]. In this study, the authors will focus on quantifying robustness and redundancy.

2.2. Network Robustness and Redundancy

Robustness refers to the strength or ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function [17,47]. For a building system network, robustness refers to the ability of the building system to resist disruptions and maintain the system's function. Many models and methods have been implemented to study the robustness of systems, such as agent-based modeling (ABM) [48], System Dynamics (SD) [49], the Petri-net method [50], and CNT [51]. By abstracting highly interconnected units into graphs, where nodes represent the units and edges represent their interactions, CNT can more accurately model each component of the building system and their interdependencies. Through modeling, the resistance of the network to disruptions can be more accurately quantified. Therefore, CNT is an effective way to reveal the robustness of the network.

Network robustness measures are mainly categorized into two classes: topological network measures [52,53] and network function-related measures [54,55]. Given the research scope of this paper, the measurement of network robustness mainly discusses network topology measurement [53]. Several basic topology indicators, including the degree, the betweenness centrality, and the average path length of the network, are frequently employed in assessments of network robustness [20]. Nevertheless, the majority of research only measures the indicators in a static network, failing to take into account the network's dynamic characteristics. Based on this, removing some nodes and edges randomly or deliberately is more in keeping with the real-world network's changing trend that is being targeted [21,22]. The Edge Coupling Robustness can also be used to measure network robustness, which can effectively analyze the influence of edge failure on network structure and load capacity [23]. However, the robustness of some coupling modes decreases as the average degree or number of nodes increases. This implies that it might not be broadly applicable to networks with varying sizes and structures [24]. At present, the relative size of maximum connected subgraphs (RSMCS) and global network efficiency (GNE) are widely used as an intuitive and effective method [25,56]. RSMCS represents the robustness of the network by quantifying the critical threshold of network collapse. GNE measures the robustness of a network by quantifying the average distance between nodes. These indicators can fully reflect the disruption tolerance of the network structure [25]. This brings the study closer to real-world situations that are subject to disruptions. Therefore,

RSMCS and GNE under random and deliberate attacks are selected in this research to quantitatively characterize the robustness of the building system network.

Redundancy is the degree to which replaceable elements, systems, or other units of analysis exist; that is, the degree to which functional requirements can be met in the event of disruption, degradation, or loss of function [17]. For a BSN, redundancy represents the extent to which replaceable systems meet functional requirements in the event of disruption, degradation, or loss of functionality. While earlier research predominantly focused on robustness, recent studies have increasingly recognized the importance of redundancy in enhancing system resilience [26]. Redundancy has garnered significant attention in various critical infrastructure domains, including transportation [28], communication [57], water distribution systems [58], supply chain and logistics [59], etc. This shift reflects a growing understanding that redundancy can mitigate the impact of subsystem failures, which often lead to service interruptions in building systems. The key to reducing service outage time and improving resilience lies in the timely and effective restoration of system functionality. This can be achieved through functional redundancy [60], where multiple components with similar functions can restore service and limit the spread of faults [61]. Previous studies paid more attention to the structural redundancy of systems and less attention to the functional redundancy [61,62]. In addition, in the quantification of redundancy, the redundancy of complex networks is generally characterized by the number of alternative paths remaining after the failure of the partially connected paths between any nodes in the network [28,29]. In particular, Xu et al. characterize transportation network redundancy from two perspectives: travel alternative diversity and network spare capacity, and assessment of transportation network redundancy quantitatively [28]. Kalungi et al. employ the existence of alternative pathways from the sources to demand nodes or excess capacity to characterize redundancy and assess redundancy through head-driven analysis (HDA) [58]. BSNs, however, are heterogeneous, in contrast to networks like traffic and water supply systems. It is not appropriate to calculate the number of alternate paths between any node in the BSN [30]. As a result, the redundancy index is suggested as a way to gauge how well a building system continues to work in the face of disruption.

3. Methodology

3.1. Research Framework

A thorough review of the literature identifies three research gaps that need to be addressed. First, existing research was conducted at the macro level and failed to investigate individual building systems at the micro level. Second, the majority of studies have concentrated on physical structures (such as beams, plates, and columns) in the field of physical resilience [43,44]. Functional support systems (such as water supply systems and power supply systems) are overlooked. Finally, redundancy was less of a focus in most earlier studies on resilience evaluation, which mostly concentrated on robustness [26]. Furthermore, in the existing research on redundancy, there is more research on structural redundancy and less attention on functional redundancy [27].

To fill the above knowledge gaps, this study aims to evaluate the physical resilience of the building system through network analysis. The research framework is shown in Figure 1. The network is generated first. This step includes (1) collecting data from architectural drawings and academic publications; (2) identifying the nodes and links of the network; (3) establishing an adjacency matrix according to node relationship; and (4) generating the network according to the adjacency matrix. The next step is the assessment of physical resilience, which includes (1) the assessment of the three basic topological indicators—degree centrality, betweenness centrality, and average path length—and inves-

tigates the characteristics of the BSN; (2) the assessment of redundancy using the proposed redundancy index; and (3) the assessment of robustness using GNE and RSMCS.

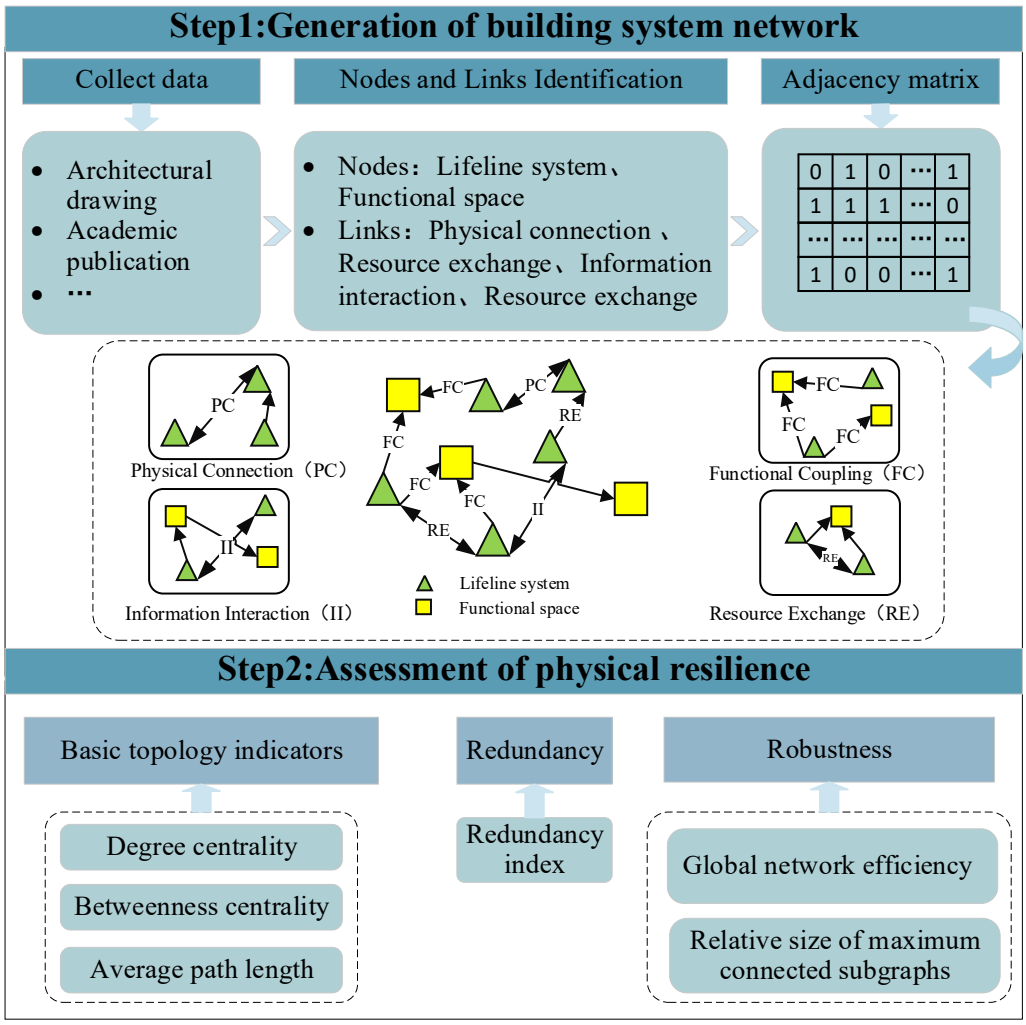


Figure 1. Research framework.

3.2. Complex Network Modeling

The building system contains lifeline systems and functional spaces, which are interrelated and interact with each other [63]. On this basis, disruptions usually do not occur in isolation. Safety hazards or failures of one subsystem may interact with an existing sociotechnical structure and finally result in a sequence of incidents [64,65]. Network analysis provides a systematic view of the building system by abstracting the functions of the physical system and explores the characteristics of the building system. CNT is a powerful tool for studying the independence and interdependence of subsystems in the physical resilience of building systems [66].

The building system is conceptually modeled as a complex network with nodes and links. Specifically, two types of building systems are selected to represent the nodes: lifeline systems and functional spaces. In a given building, lifeline systems (i.e., equipment monitoring system, timing and scoring system, and television and commentary system) are a collection of lifeline services that are supplied for the implementation of a function. [67]. The functional spaces (i.e., office meeting area, coach area, and press area) are the systems that meet people's basic physiological demands, promote social activities, and provide a comfortable environment [68].

The next step for developing the BSN is to establish the links between the nodes. The interactions between nodes can be divided into four types: physical connection (i.e., the building's air conditioning system is connected to the ventilation system by pipes.); resource exchange (i.e., a building's electrical system provides power resources for lighting, air conditioning, elevators, and other systems.); functional coupling (i.e., the function of the laboratory depends on the good ventilation conditions provided by the ventilation system.); and information interaction (i.e., the outside dry sprinkler system is automatically activated when the automatic fire alarm system detects a fire). These interactions between nodes are conceptualized as links. This conceptualization is based on the following rules: (1) the operation of some systems depends on physical connections to other systems; (2) the operation of the lifeline systems requires other lifeline systems to provide resources for it; (3) the normal operation of the functional spaces depends on the functional coupling with the lifeline systems; (4) the systems realize cooperative work through information transfer.

Mathematically, a building system network is defined as an undirected and unweighted graph $G = (V; E)$, where V (i.e., a set of vertices) represents systems and $E \subseteq V \times V$ (i.e., a set of edges) represents systems interactions. Let $N = |V|$ be the total number of systems and $M = |E|$ be the total number of systems interactions. Let $A(G) = (a_{ij})_{n \times n}$ denote the adjacency matrix of G. When $a_{ij} = a_{ji} = 1$, system v_i interacts with system v_j; and when $a_{ij} = a_{ji} = 0$, they do not have interactions. After the adjacency matrix is determined based on all nodes and their links, this study adopts the PAJEK software 6.01 program to develop the BSN. When reflected in the diagram, the connections between systems can be represented by arrows. The arrow at the edge indicates the direction of interaction between the two systems and shows that the node at the end is influenced by the other node. As illustrated in Figure 2, if arrows are present at both ends of the line, this indicates that these two vertices directly influence each other. If only the end of the line contains an arrow, the node being pointed at is influenced by another node.

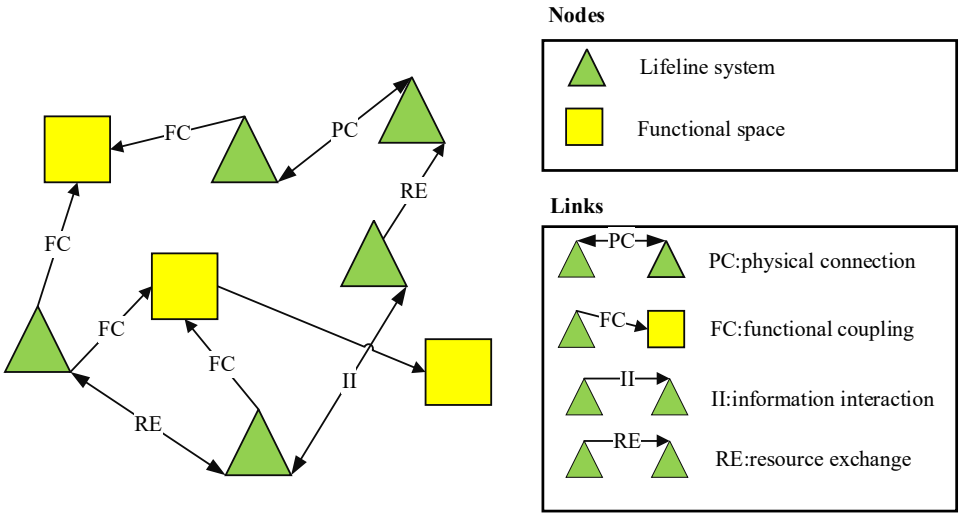


Figure 2. Example of system connection.

3.3. Physical Resilience Measurement

3.3.1. Basic Topology Indicators

In order to identify important network nodes and obtain an extensive understanding of the network's structural features, this study analyzed some basic topology indicators, including degree centrality, betweenness centrality, and average path length.

A. Degree centrality

In an undirected network, degree centrality is defined as the number of all edges connected to a node. In a directed network, degree centrality can be divided into in-degree and out-degree. In-degree is the number of incoming edges connected to the node, and out-degree is the number of outgoing edges from the node [69]. The average degree centrality of a network is then the sum of the node's degrees divided by the number of nodes that exist in the network. Degree centrality is a fundamental metric used to quantify nodes' significance; nodes with a high degree of centrality are more important for the transmission of information and the distribution of resources. In addition, the network's overall structural features can be uncovered by examining the distribution of node degrees, which is crucial for robustness analysis. The calculation method is shown in Formula (1):

$$C_D(N_i) = \sum_{j=1}^{n} x_{ij}(i \neq j), \tag{1}$$

B. Betweenness Centrality

Betweenness centrality is to measure one node undertaking 'mediation's role in a network. If a node is on a path that many nodes pass through, then the node should be important and likely to have high mediation centrality [70]. Betweenness centrality measures the probability that a node is in the shortest path between any two other nodes. Its value belongs to [0, 1]; the larger the value, the stronger the mediation. The analysis of betweenness centrality may help in identifying essential nodes and weak points, optimizing resource allocation, and increasing network resilience. Furthermore, investigating the distribution of betweenness centrality also helps to reveal information about the network's overall structure and organization. The calculation method is shown in Formula (2):

$$C_B(N_i) = \sum_{j<k} \frac{Gjk(N_i)}{Gjk}, \tag{2}$$

In this equation, $\sum_{j<k} \frac{Gjk(N_i)}{Gjk}$ means the number of nodes N located between any other two nodes in the network [71].

C. The average path length of the network

The average path length of the network is defined as the average distance between all pairs of its nodes. The average path length of the network determines the effective scale of the network and measures the transmission performance and efficiency of the network [72]. In addition, it represents the degree of separation between nodes in the network, reflecting the global nature of the network. The average path length of the network can be used to investigate the network's structural properties as well as to assess its robustness. Let $d(V_1, V_2)$, where $V_1, V_2 \in V$ denote the shortest distance between V_1 and V_2. Assume that $d(V_1, V_2) = 0$, then $V_1 = V_2$ or V_2 cannot be reached from V_1. Then, the average path length of the network L_G is:

$$L_G = \frac{1}{n \times (n-1)} \sum_{ij} d(V_i, V_j), \tag{3}$$

3.3.2. Redundancy

Redundancy is the extent to which replaceable elements, systems, or other units of analysis exist; that is, the extent to which functional requirements can be met in the event of disruption, degradation, or loss of functionality [73]. Based on the analysis of the basic topological indicators, we use qualitative and quantitative methods to study redundancy.

Since the normal operation of functional spaces relies on lifeline systems, the redundancy of these spaces translates into the redundancy of the underlying lifeline systems. In other words, it reflects the extent to which replaceable lifeline systems meet functional

requirements in the event of disruption, degradation, or loss of functionality. In this paper, the redundancy of the functional spaces is represented by the proportion of the lifeline systems that can continue to work when encountering disruptions. The calculation method is shown in Formula (4):

$$R_i = \frac{n}{N}, \tag{4}$$

where R_i represents the redundancy of the functional space of i, n represents the number of systems that can maintain functions in the functional space of i under disruptions, and N represents the number of all systems in the functional space of i.

3.3.3. Robustness

Robustness is the strength or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function [47,73]. In a BSN, when the network is attacked or fails, some nodes in the network are removed, and then the nodes and edges connected to those nodes are removed as well. After nodes and edges are deleted, the connectivity of the network decreases. However, the new network can still be connected, and the original function is not lost. At this point, the network shows its robustness. Therefore, the ability of a physical system to retain connectivity in the face of deliberate or random attacks is how robustness will be measured in this study. The random attack is realized by randomly removing any nodes in the network, while the deliberate attack is realized by removing the corresponding nodes from high to low according to the degree centrality. Based on this, the RSMCS and GNE are selected to characterize the robustness of the network in this study.

The maximum connected subgraph is the subgraph that connects all nodes of the graph with the least number of edges. The RSMCS refers to the ratio between the number of nodes of the maximum connected subgraph in the network after the attack and the number of all nodes in the whole network [25]:

$$S = \frac{N'}{N}, \tag{5}$$

In the formula, N' represents the maximum number of nodes connected to the subgraph after the network is attacked randomly or deliberately. N indicates the number of nodes in the entire network. In the initial state, the value of N and N' is the same. After being attacked, the number of nodes of the maximum connected subgraph of the network N' decreases continuously, so the RSMCS also decreases continuously. This indicator reflects the change in the network after the attack, and the damage degree of the network can be judged by observing it.

GNE is a robustness index that quantifies the connectivity and communication efficiency between nodes [56]. It is the average value of the reciprocal of the shortest path distance between any two nodes in the network:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j \in V} \frac{1}{d_{ij}} \tag{6}$$

where N represents the number of nodes in the network,d_{ij} represents the shortest path between nodes i and j, $E_{ij} = \frac{1}{d_{ij}}$ is the efficiency between nodes i and j in the network, is the inverse of the shortest path, but when nodes i and j are disconnected, d_{ij} is equal to infinity and E_{ij} is equal to 0.

4. Case Study

4.1. The Building System Network Generation

To demonstrate the feasibility and validity of the proposed approach, physical resilience in the NOSC was analyzed. The NOSC can be found in Jianye District, Hexi New Town, Nanjing. It is a multi-functional national stadium. The stadium (which includes a training ground), the gymnasium, the swimming pool, the tennis hall, the sports science and technology center, and the sports and entrepreneurship center are the "four venues and two centers" that make up the primary buildings.

As summarized in Table 1, the original and authoritative data, including architectural drawings and actual information, were collected from official documents, websites, and academic publications. According to the information provided by these documents, the physical system of the NOSC and the relationship between the systems can be identified. The construction of the complex network was a collaborative process involving six researchers. Each researcher contributed their unique insights and data, which were then integrated through a series of collaborative sessions. The team reached a consensus on the network's architecture, ensuring that it reflected the reliability of the system. Based on this collaborative effort, the established Building System Network (BSN) is deemed both reliable and accurate, as it integrates diverse perspectives and robust data and has been validated through collective expertise.

Table 1. Representative data sources.

Types	Data Title	Sources	Used for Network Development
Architectural drawings	Nanjing Olympic Sports Center deepening design drawings	Nanjing Olympic Sports Center construction headquarters	Identify the functional spaces
	A brief introduction to the design and construction of the Nanjing Olympic Sports Center	Nanjing Olympic Sports Center's official website	Identify the functional spaces
Actual information	Nanjing Olympic Sports Center main stadium building intelligent system design	Engineering cases	Identify the subsystems of the intelligent system
	Introduction to Water Supply and Drainage System and Fire Protection Design of Nanjing Olympic Sports Center Stadium	Water and wastewater engineering	Identify the subsystems of the water supply and drainage system, the fire protection system, and their connections
	Construction Scheme of Heating and Ventilation Engineering of a Stadium Project in Nanjing	Nanjing Olympic Sports Center gymnasium construction organization design report	Identify the subsystems of the heating and ventilation system and their connections

Under the lifeline system, there are the low-voltage distribution system, water supply and drainage system, HVAC system, elevator system, and intelligent system. Each system operates independently and collaboratively to ensure the normal operation of the NOSC. The subsystems of each system are recognized as nodes in a complex network, and the associations between the systems are identified as edges connecting the nodes. They are nodes V1–V5 in the low voltage distribution system, V6–V15 in the water supply and drainage system, V16–V18 in the HVAC system, V19 in the elevator system, and V20–V36

in the intelligent system. The node of the functional spaces is determined by the design plan of the NOSC. According to the spatial function, it is divided into several functional areas V37–V54, and two functional rooms V55–V56 under the control area. The composition of the building system is shown in Figure 3. The corresponding subsystems are shown in Table A2 (see Appendix A for details).

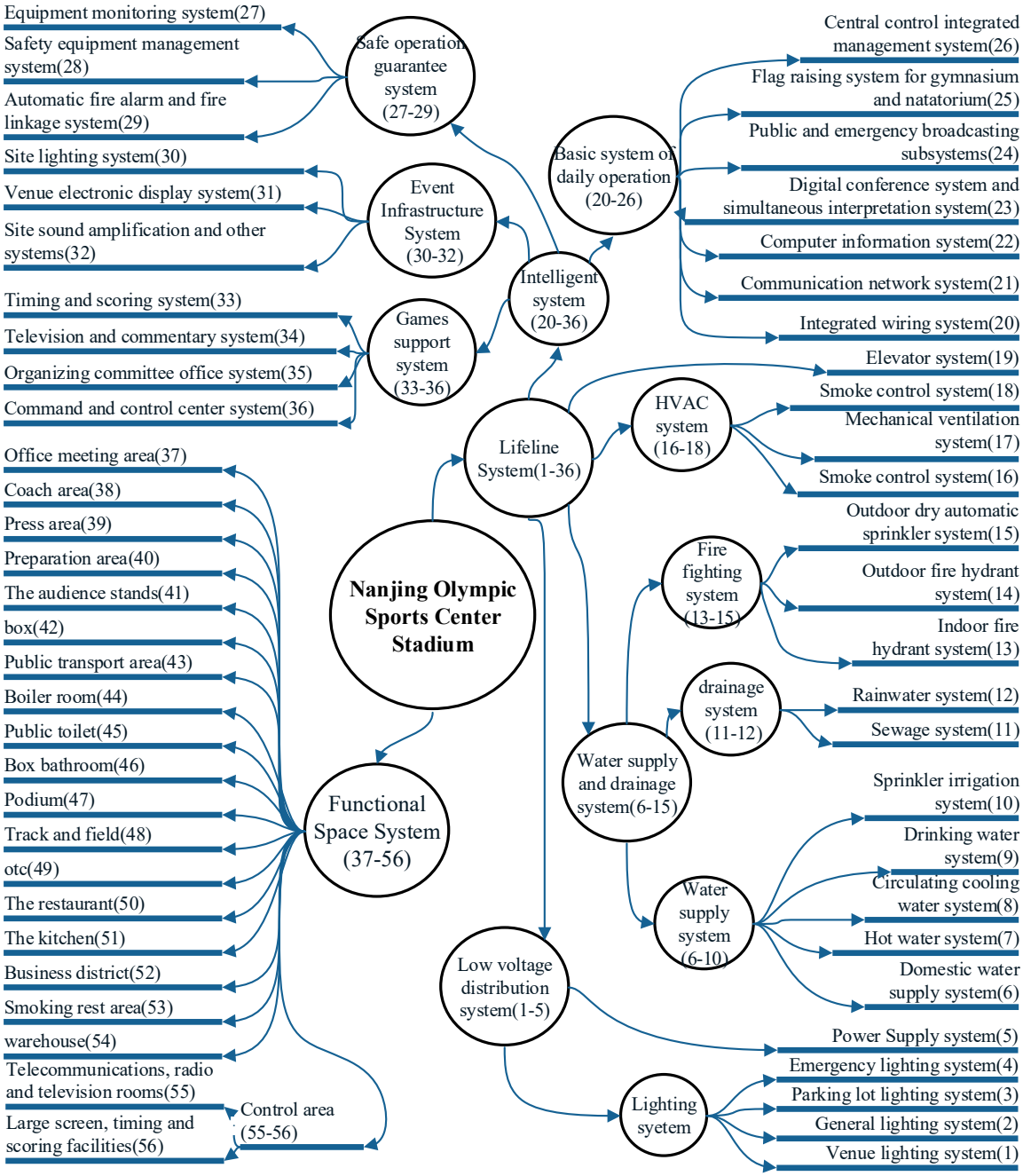


Figure 3. System diagram of the NOSC.

Based on the function modules and their interaction relationship, the building system of the NOSC is modeled by a network. The constructed PAJEK networks format data file is imported into PAJEK software, and the visual physical network model of the NOSC is obtained by using the software's drawing tool, as shown in Figure 4. The purple node represents the functional space system, the pink node represents the intelligent system, the yellow node represents the low-voltage distribution system (including lighting and power subsystem), the blue node represents the water supply and drainage system (including

water supply, drainage, and fire-fighting subsystem), and the orange node represents the intelligent system. The green nodes represent the HVAC system, and the red nodes represent the elevator system.

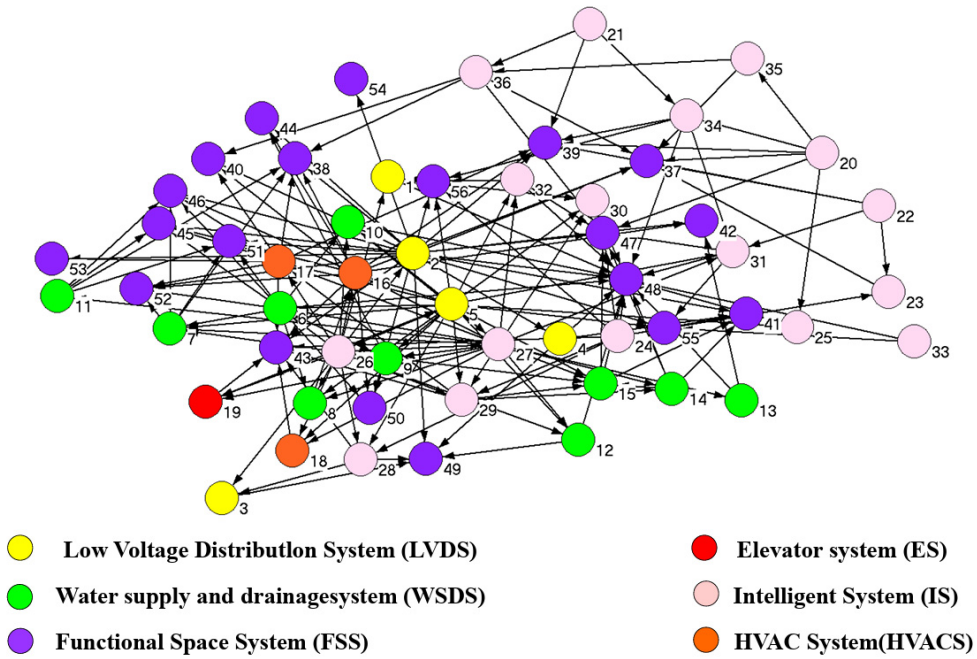


Figure 4. Complex network model of the building system of the NOSC.

4.2. Physical Resilience Analysis

4.2.1. Basic Topology Indicators Analysis

The degree centrality can fully reflect the importance of a system in the whole building system. The greater the degree centrality of a node, the more important the node is, and the greater the impact on the network after its failure. The average degree centrality of a network is the arithmetic average of all the degree values in the network. According to the calculation formula, the average degree centrality of nodes in the network is 6.82, indicating that each subsystem in the network is related to the other seven subsystems on average.

From the building system point of view, as indicated in Table A1 (see details in Appendix A), the nodes with the highest degree centrality are the GLS and PSS, followed by the equipment monitoring system (EMS) and CCIMS. At the same time, the degree of the air conditioning system (ACS) and smoke control system (SCS) is higher than that of other nodes. This means these six subsystems have relatively higher interdependence with other subsystems. PSS and GLS provide the most fundamental power supply and lighting support for NOSC and are considered to be the most critical systems in building systems.

From the function space point of view, the node with the highest degree centrality is the track and field, followed by the podium, and then the public transport area. This shows these areas are more important in the functional space system of the NOSC. Track and field provides venues for competition and training. The podium is the core link to connect with the media audience during the competition. The public transport area is the space area in which staff, referees, spectators, athletes, and coaches will all be involved. The relationship between these three areas and sports competitions is extremely close and important.

If a network has serious heterogeneity, the connection status (degree centrality) between its nodes has serious non-uniform distribution; such a network is called a scale-free network. A scaleless network is an inherent property of describing the serious non-uniform distribution of a large number of complex systems as a whole. From Figure 5, it can be

seen that the degree centrality of nodes in the NOSC building system network varies greatly, which indicates that only a few nodes have more connections, while most nodes only have a few connections. In this case, if the node with a high degree of centrality is disturbed, the network will show bad robustness and be easy to crash, which is a typical scale-free network.

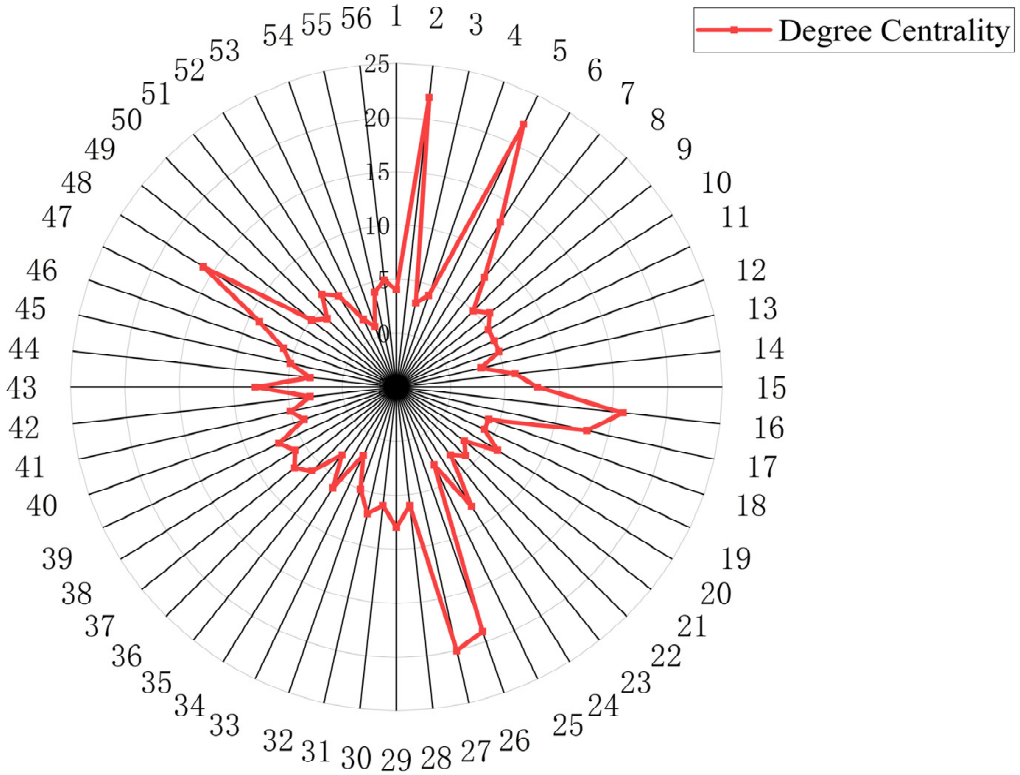


Figure 5. Degree centrality.

Betweenness centrality is used to evaluate the role and impact of a node in the whole network. The larger the betweenness centrality of a node, the greater the role of the node as an intermediary. The betweenness centrality of a network can be defined as the average of the betweenness centrality of all nodes in the network. According to the formula, the betweenness centrality of the network model of the NOSC is 0.00099, and the numerical range of the betweenness centrality shown in Table A1 is from 0 to 0.011. As can be seen from Table A1, there are 26 nodes whose betweenness centrality is 0, which indicates that these nodes do not play the role of transmission media and are at the edge of the network. As illustrated in Figure 6, the betweenness centrality of the ACS is the largest, indicating that the number of shortest paths through the node is the largest. It shows that when the system with high betweenness centrality fails and cannot play its due function normally, many channels in the network will be disconnected, which will certainly have an important impact on the operation of the entire building system. If the safety of these critical systems can be effectively guaranteed, the cascade reaction of the building system can be weakened, and the robustness of the building system can be increased.

Third, in the network model of a building system, the distance between the PSS and large screen, timing, and scoring facilities is the largest, and three edges are needed to connect these two nodes. This means that the interdependence between the two nodes is the worst. On the other hand, the average path length of the network is 0.32, which means that the building system can be connected through a short path, with strong correlation and high transmission and efficiency. If the key system has problems, the system connected

with it is more vulnerable to involvement, which increases the difficulty of robust control of the whole network.

The analysis of basic topological indicators reveals that the BSN exhibits characteristics typical of a scale-free network. Key nodes within the BSN, such as the GLS and the PSS, have the highest degree centrality. Most nodes in the BSN do not function as bridges. Among all systems, the ACS demonstrates the highest mediation centrality, thereby playing a crucial role in the network. The network's short average path length indicates robust connectivity and high transmission efficiency.

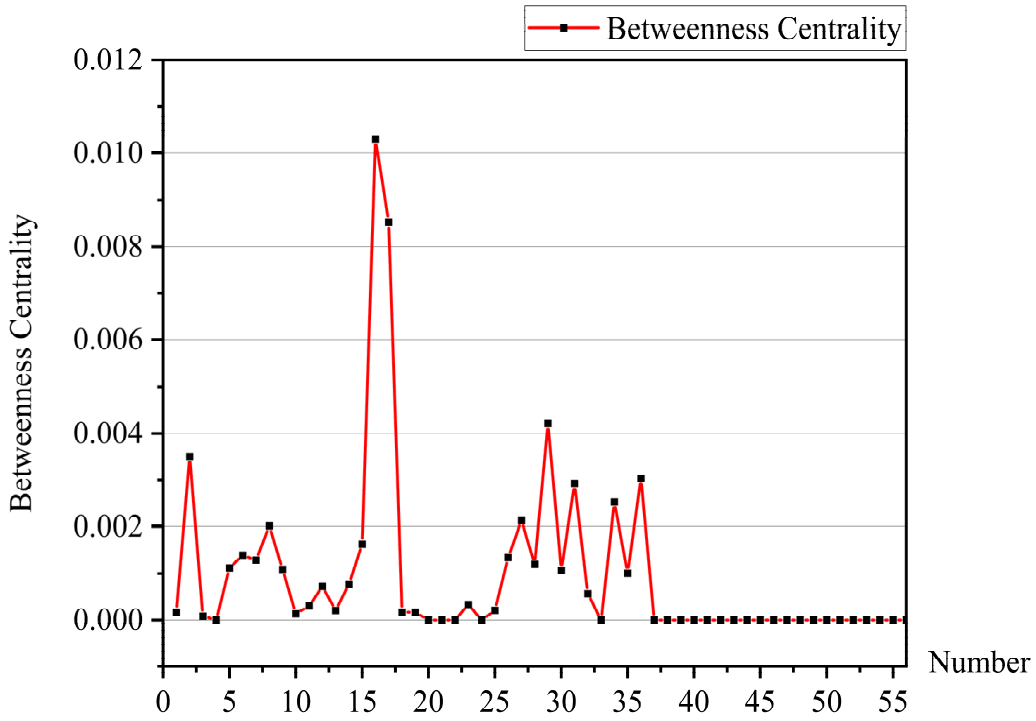


Figure 6. Betweenness centrality.

4.2.2. Redundancy Analysis

Power outages are one of the most prevalent emergencies that sporting venues may encounter. As a result, this study uses a power outage scenario to investigate redundancy, with the goal of assisting venue management in improving their ability to deal with emergencies. Only systems with backup power can operate normally in the case of a power outage. According to the drawings and data, the backup power supply for the lifeline system can be obtained. Lifeline systems with emergency power supply (EPS), uninterruptible power supply (UPS), or connections to generator P are regarded to have electrical redundancy, as indicated in Figure 5, which is highlighted in dark hues. As depicted in Figure 7, during power failure disruptions, 20 out of 36 lifeline systems exhibit power redundancy. These 20 systems are equipped with backup power sources, ensuring uninterrupted operation during short-term outages. Conversely, the remaining 16 systems, including the venue lighting system (VLS), GLS, parking lot lighting system (PLLS), PSS, domestic water supply system (DWSS), hot water system (HWS), circulating cooling water system (CCWS), drinking water system (DWS), sprinkler irrigation system (SIS), sewage system (SS), rainwater system (RS), indoor fire hydrant system (IFHS), outdoor fire hydrant system (OFHS), ACS, digital conference system and simultaneous interpretation system (DC&SIS), and organizing committee office system (OCOS), lack backup power but necessitate electrical support during operation. Notably, the VLS, GLS, and PLLS can be substituted by ELS post-power failure. However, the remaining 13 systems lack power

redundancy and cannot be substituted by alternative lifeline systems, thereby requiring continual power support for operation. Nevertheless, the majority of these 13 systems are non-critical and can be artificially compensated, resulting in minimal impact on the NOSC following power outages.

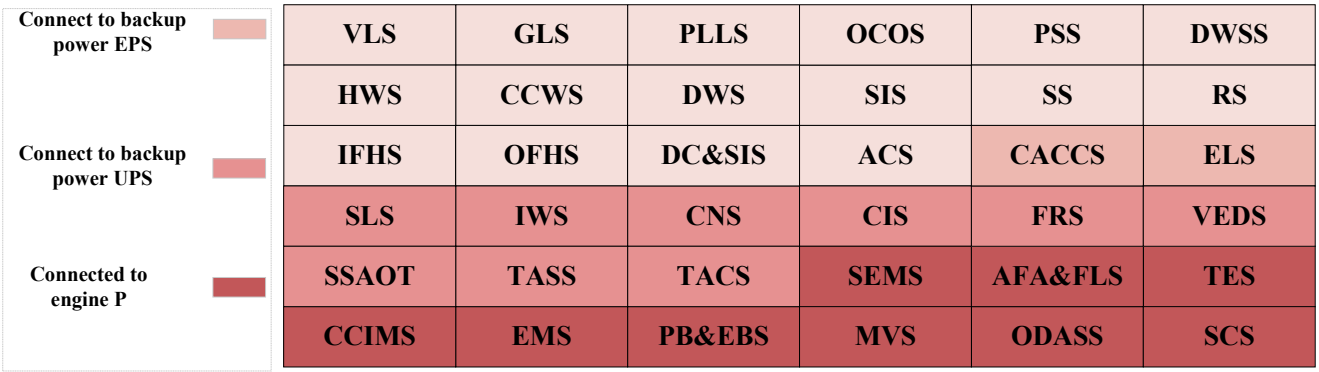


Figure 7. The composition of the lifeline system.

The functional space consists of lifeline systems. According to the data obtained, the equipment composition and backup power supply of each functional space can be determined, as depicted in Figure 8. Eight systems, specifically the HVAC system, event infrastructure system, basic system of daily operation, games support system, low voltage distribution system, fire-fighting system, safe operation guarantee system, and elevator system, exhibit power redundancy. It is worth noting that all systems in the event infrastructure system, safe operation guarantee system, and elevator system have power redundancy. Furthermore, aside from the office meeting area, power redundancy is present in the basic system of daily operation and the game support system across other areas. These systems demonstrate superior redundancy performance.

The redundancy index formula is employed to quantify the redundancy of the building system, with the resultant values illustrated in Figure 9. Specifically, among the 20 functional spaces V37–V56, the redundancy index values of 9 functional spaces (including the press area, preparation area, audience stands, public transport area, podium, track and field, smoking rest area, large screen, time and scoring facilities, and telecommunications, radio, and television rooms) closely associated with the event are greater than or equal to 0.5. Combined with Figure 8, it can be observed that more than half of the subsystems within these systems are equipped with backup power EPS and UPS or connected to generator P. Additionally, there are 7 functional space systems with a redundancy index of less than 0.5, indicating that the number of subsystems with power redundancy in these functional space systems is less than half of the total subsystems. However, as evident from Figure 6, subsystems critical to the event possess power redundancy. The remaining four functional spaces lack power redundancy but are not closely tied to the event. These systems comprise the boiler room, restaurant, warehouse, and box.

Hence, it is preliminarily assessed that in the event of power failure disruptions, the power redundancy of the NOSC is relatively robust, whereas the redundancy of the lighting system appears to be lacking. ELSs (emergency lighting systems) are only present in the track and field, OTC, and audience stand areas.

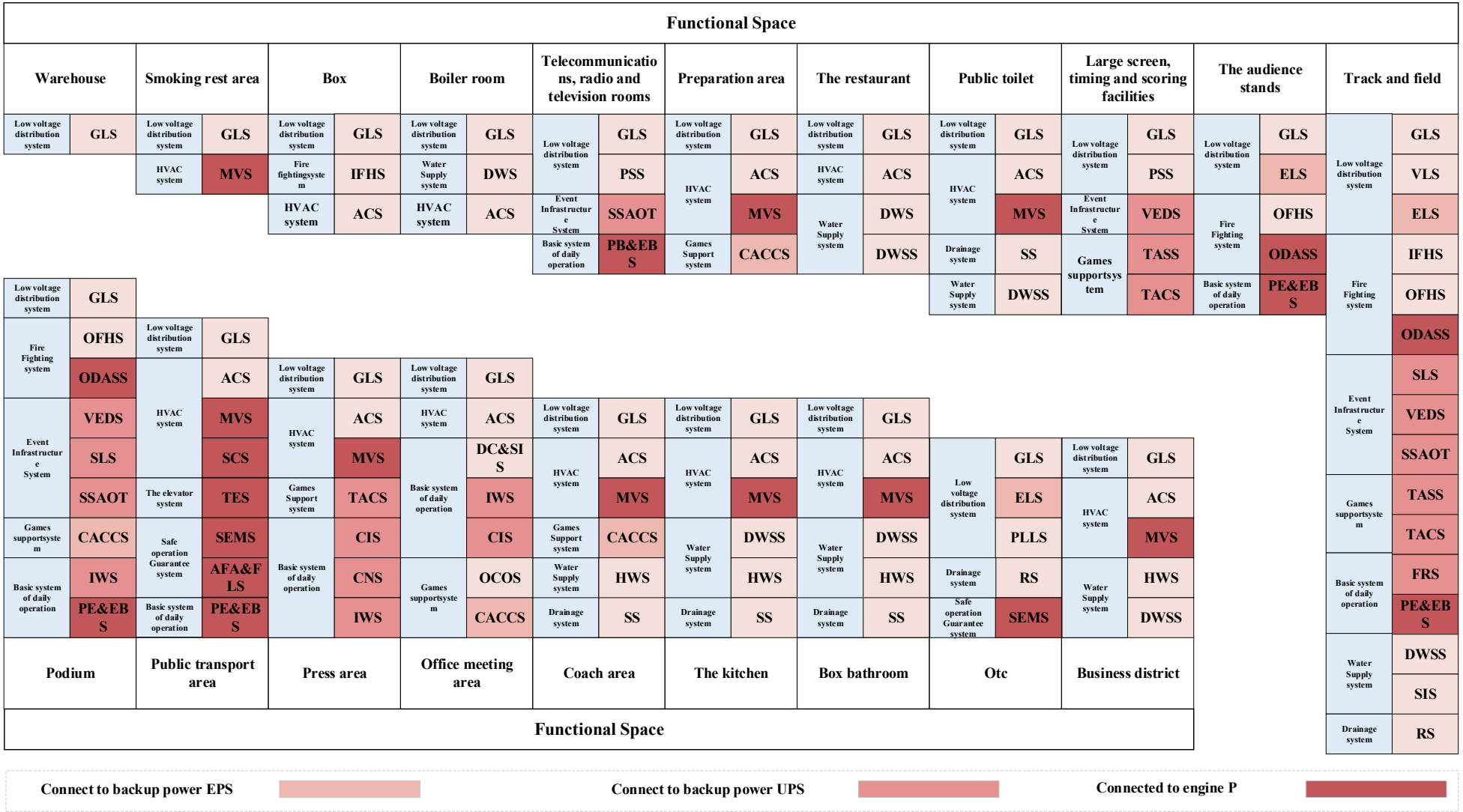


Figure 8. The composition of the functional space system.

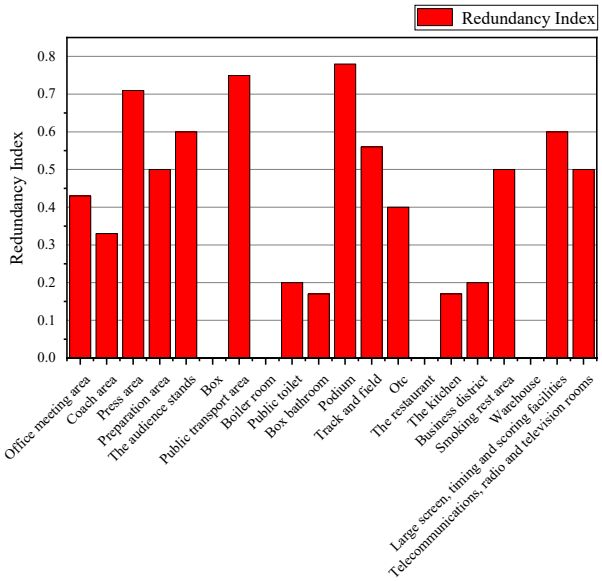


Figure 9. The proportion of systems equipped with backup power.

4.2.3. Robustness Analysis

Deliberate attacks and random attacks were executed based on the degree centrality order, and the average value from 50 simulation experiments was obtained. The RSMCS and GNE of the 50 simulation results, along with the expected curves under deliberate and random attacks, are illustrated in Figure 10. It is observed that the GNE of the network at a static state is 8.4%, with RSMCS at 1. Upon the failure of the first node in the network, the edge connected to the node will break, leading to many nodes entering a discrete state. Consequently, both RSMCS and GNE begin to decrease.

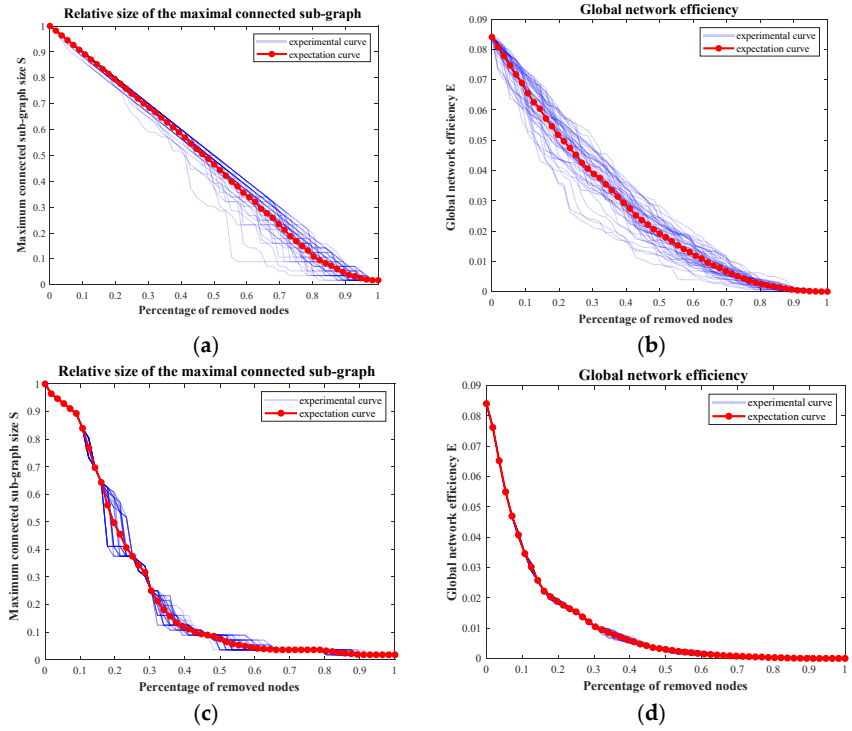
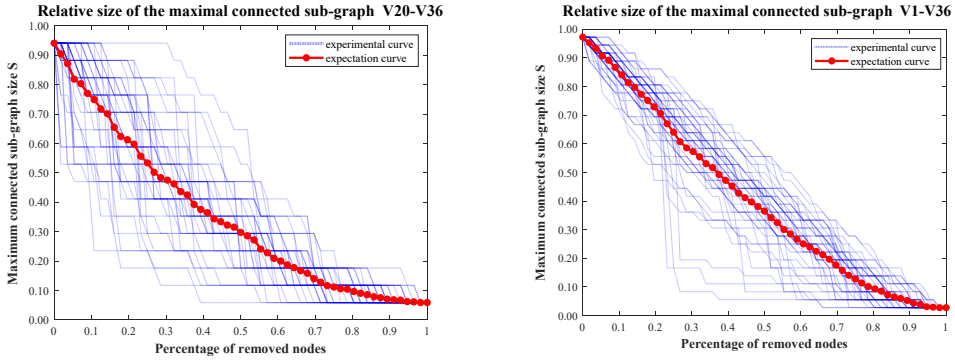


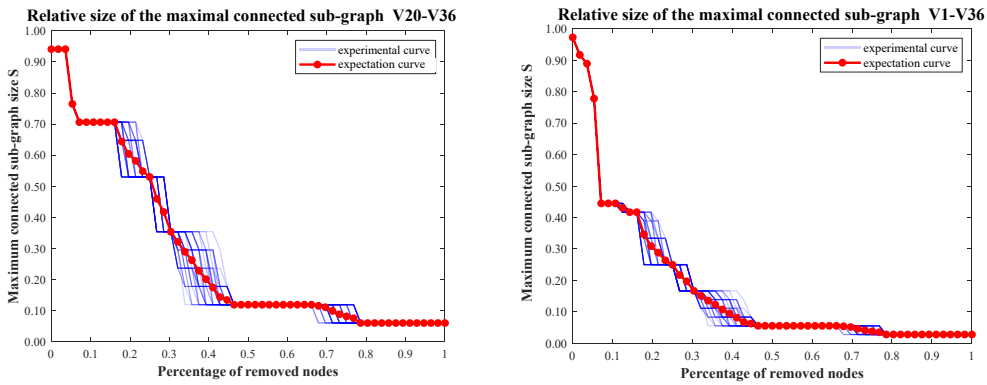
Figure 10. Robustness under deliberate and random attacks. (**a**) RSMCS under random attacks; (**b**) GNE under random attacks; (**c**) RSMCS under deliberate attacks; (**d**) GNE under deliberate attacks.

RSMCS serves as an indicator of network connectivity. When RSMCS is sufficiently small, it implies that most nodes in the network have entered a discrete state, approaching network paralysis. As depicted in Figure 10a, under random attacks, RSMCS exhibits a consistent downward trajectory as the number of failed nodes increases. When the proportion of node failure approaches 100%, RSMCS approaches zero, signifying network collapse. However, as illustrated in Figure 10c, during deliberate attacks, RSMCS experiences a rapid decline once the failure node rate reaches approximately 10%. With only 60% of nodes failing, RSMCS approaches zero, leading to network paralysis. Furthermore, apart from the overall network, both Figures 11 and 12 demonstrate that the RSMCS of individual subsystems and the entire lifeline system exhibit similar variation trends under random and deliberate attacks.



(**a**) (**b**)

Figure 11. RSMCS of the subsystem under random attack. (**a**) RSMCS of the intelligent system under random attack; (**b**) RSMCS of the lifeline system under random attack.



(**a**) (**b**)

Figure 12. RSMCS of the subsystem under deliberate attack. (**a**) RSMCS of the intelligent system under deliberate attack; (**b**) RSMCS of the lifeline system under deliberate attack.

As depicted in Figure 13b, RSMCS exhibited a significant decrease following deliberate attacks on nodes 7, 8, and 10. During 50 simulation experiments, the 7th and 8th attacked nodes were identified as domestic water supply systems or mechanical ventilation systems. However, the situation surrounding the 10th compromised node is more intricate. In this instance, the RSMCS experienced the most pronounced change after the failure of the public broadcast and emergency broadcast subsystems, reaching 23.4%. This underscores the criticality of these three systems in NOSC operation. Failure of these critical systems leads to a substantial reduction in the relative size of the maximum connected subgraph, potentially resulting in widespread paralysis of the building system network. Enhancing

the ability to prevent the failure of key systems during NOSC operations can significantly improve its resistance to disruptions.

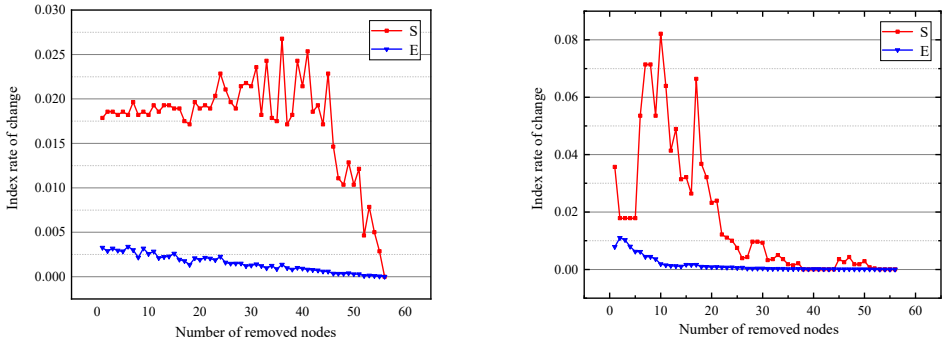


Figure 13. Rate of indicator change under deliberate and random attacks. (**a**) Rate of indicator change under random attacks; (**b**) Rate of indicator change under deliberate attacks.

The GNE metric serves as a gauge of the network's overall transmission capacity. Similarly, when GNE approaches zero, it suggests that a majority of the network's edges are fractured, leading to network paralysis. As depicted in Figure 10b, during random attacks, GNE exhibits a consistent decline with an increasing number of failed nodes. When the percentage of node failures nears 100%, GNE tends towards zero, resulting in network breakdown. However, as observed in Figure 10d, GNE experiences a rapid decline initially, but this rate of decline slows when the failure node count reaches approximately 15%. Upon reaching 50% of failed nodes, GNE approaches zero, indicating network breakdown. Additionally, Figures 14 and 15 reveal that, akin to the relative size of the maximum connected subgraph, the global efficiency of subsystems and lifeline systems under random and deliberate attacks mirrors the trend observed in complete networks. As evident in Figure 13a,b, under attack scenarios, there is no significant disparity in the impact of node failure on GNE, exhibiting a gradual downward trend.

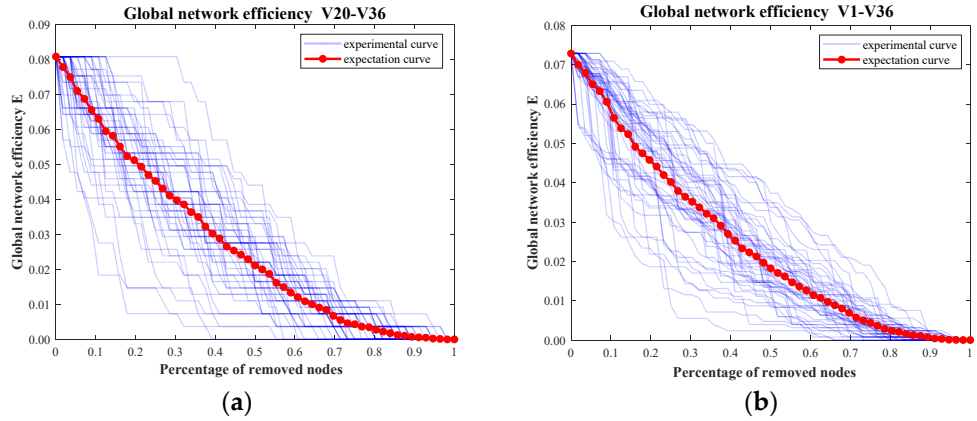


Figure 14. GNE of the subsystem under random attack. (**a**) GNE of the intelligent system under random attack; (**b**) GNE of the lifeline system under random attack.

In comparison, it can be inferred that the physical system network of the NOSC exhibits robustness against random attacks but demonstrates considerable vulnerability to deliberate attacks. When a critical node within the network is targeted, the likelihood of network failure increases substantially. Enhancing the maintenance and upkeep of key systems can effectively mitigate the stadium's losses resulting from emergencies.

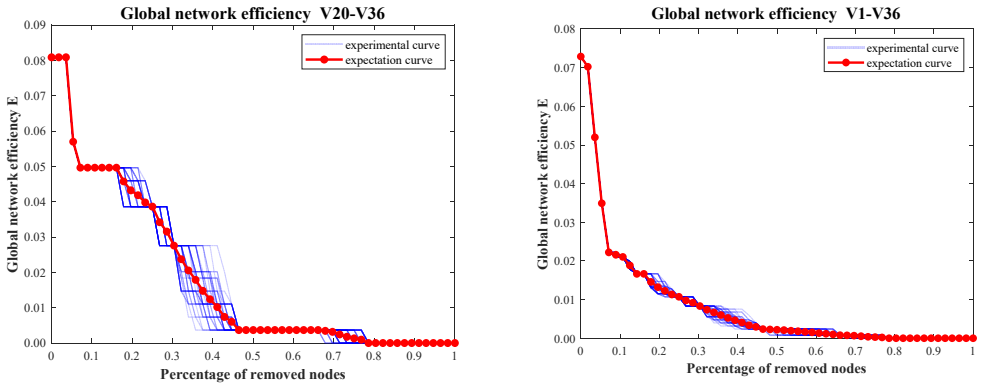


Figure 15. GNE of the subsystem under deliberate attack. (**a**) GNE of the intelligent system under deliberate attack; (**b**) GNE of the lifeline system under deliberate attack.

5. Discussion

5.1. Optimization of Redundancy in Building Systems

After the analysis of the redundancy, the majority of the lifeline systems related to sporting events and tightly related to the operation of the sports venues have power redundancy. All subsystems within the event infrastructure system, the safe operation guarantee system, and the elevator system exhibit power redundancy, thereby enhancing overall redundancy performance. Furthermore, functional spaces that are strongly associated with the event exhibit higher redundancy. In contrast, functional spaces lacking redundancy have a minimal impact on the event and do not influence overall redundancy performance.

The findings indicate that the lifeline system's redundancy is determined by whether or not it has a backup power source. Similarly, in other circumstances (i.e., communication system failure, fire), to guarantee the regular functioning of the lifeline system, a backup system must be set up for the primary lifeline system first [74]. This will guarantee that the backup system can immediately perform a replacement role if the lifeline system stops functioning because of disruptions. Also, the functional connections between the two lifeline systems will be impacted by an interruption in the links. Adding alternate links between the lifeline systems is currently the best course of action [75]. Thus, even if a portion of the network's link is broken, resource transfer can still be guaranteed [76]. Furthermore, the redundancy of the building's functional space is intimately tied to the redundancy of the lifeline system. The regular operation of the functional space depends on the lifeline system, so the redundant design of the lifeline system has a direct impact on the resilience of the functional space [75]. For instance, in residential buildings, the water supply system's redundant design can continue to supply residents with water resources normally and guarantee their comfort even in the event that some equipment fails. In addition, increasing building redundancy can also improve the robustness of the building system [77]. In line with the views of this study, Yang et al. also aim to enhance the structural robustness of the subway network by adding transfer stations to give suitable options for the subway system in the event of an attack [78]. From the perspective of network analysis, increasing network redundancy is to add additional nodes or lines to the original network as backup support. If a node fails, the standby node in the network can replace the faulty node to work, and the original function of the system can still be realized, thus improving the robustness of the building system.

5.2. Optimization of Robustness in Building Systems

Similarly to previous research [79,80], the findings indicate that the network exhibits significant resilience to random attacks but is more susceptible to deliberate ones. This is due to the fact that the BSN is a scale-free network, and a scale-free network's degree distribution is power-law, meaning that most nodes have a low degree while a few have a very high degree. Due to the severe heterogeneity of scale-free networks, nodes with high degrees are more likely to be the target of deliberate attacks [79,81]. At the same time, the connectivity of the overall network will be considerably diminished after the nodes with high degrees are attacked. This demonstrates the significant alterations to the network structure caused by the removal of significant nodes [82]. Furthermore, the higher the decline in the network robustness indicator after removing a node, the more important it is to the overall operation of the building system [83]. This demonstrates how important the public and emergency broadcasting subsystems are to the stadium's running. The organization and coordination of athletes, officials, and personnel during events are directly impacted by the caliber of the public broadcasting system at large sports arenas. Apart from conventional voice broadcasting, such devices play a crucial role in precisely locating and informing all staff members of the location and gravity of situations. Failure of the public and emergency broadcasting subsystems can interfere with the transmission of instructions, which could cause mass casualties in the case of a disaster in addition to impeding the orderly conduct of activities. Therefore, it is critical to ensure the normal operation of the public and emergency broadcasting subsystems. In addition, betweenness centrality is the indicator to measure one node undertaking 'mediation's role in a network [70]. In this study, the betweenness centrality of ACS, MVS, and AFA&FLS is relatively high, showing that these systems not only connect numerous important areas within the building but also have close interdependence with other systems.

Based on the association between the calculated robustness and corresponding network measures, a series of strategies can be formulated to enhance the robustness capacity specific to the case scenario. Optimizing BSN's resilience is critical because of the need to learn from this attack and be fully prepared for future emergency responses [84]. Thus, it is crucial to identify the key systems in a building system and come up with a resilient strategy to handle network failures quickly to minimize service interruptions and slow down the spread of failures across the entire system. Building service disruptions are usually caused by long service life, material aging, or mechanical failure [85]. It is possible to maximize the building system's robustness through the creation of an appropriate work plan, routine troubleshooting, maintenance, and replacement of essential equipment systems [75]. Similarly, enhancing robustness can also be achieved by augmenting the number of redundant pathways through the increased backup of vital systems [86]. Another crucial concept for preserving high robustness is being proactive in limiting or even stopping the propagation of errors. Subsystems that act as intermediaries within the building systems should therefore be given priority when it comes to robustness optimization because they are important points for the spread of faults throughout the system. By focusing on increasing the maintenance of these intermediary systems during routine upkeep, the spread of defects can be considerably prevented, matching the concept of robust optimization.

6. Conclusions

Following disasters, maintaining the building's operations is critical to the occupants' security. Resilient buildings require resilient physical systems. To unlock the physical resilience capacities of building systems, this study applied an enhanced network-based approach. First, classifying the building systems and developing a comprehensive building system network can be achieved by treating building components as nodes and their func-

tional and physical interdependence as connections. Second, characterizing the physical resilience capacities of building systems through robustness and redundancy. Third, setting up both deliberate and random attack scenarios and revealing the robustness of building systems by using the relative size of maximum connected subgraphs and global network efficiency. Finally, a novel redundancy index reveals the capacity to maintain function in the face of disruptions through backup resources or repetitive functions.

This method's viability and efficacy were demonstrated by the resilience analysis of the Nanjing Olympic Sports Center. The analysis demonstrates that administrators can effectively boost redundancy by establishing links between systems or adding important system backups. Moreover, enhancing the system's redundancy contributes to improving its robustness. Furthermore, enhancing robustness requires guaranteeing the regular operation of intermediary and crucial systems. Lastly, the building system relies heavily on the public and emergency broadcasting subsystem.

Theoretically, it offers a fresh viewpoint by performing micro-level structural analysis and resilience evaluation of individual buildings as nodes in the infrastructure network. This method offers a new perspective on resilience research and departs from the macro-level resilience analysis of infrastructure used in previous studies. Methodologically, this paper applied an enhanced network-based approach for resilience analysis. Additionally, innovative approaches to redundancy and robustness quantification are put forth. Practically, the applicability of the above method is confirmed. This concept has some guiding implications for investigating resilience in various contexts. Managers can better understand the intricacy and susceptibility of large stadium physical systems, according to the research. This research gives them the ability to create the policies that are required to improve safety management in dynamic operating environments—especially in times of emergency.

However, the research has certain shortcomings. In the robustness analysis, this study employs a node-based attack method. But in this study, like in most others, nodes that were attacked deliberately or at random were just eliminated and deemed totally disabled. In practice, the system might not break down entirely. To make system failures more realistic, failure modes can be divided into partial and whole function losses. Compared to simple random attacks and deliberate attacks, more accurate failure modes can be applied in future research, which has greater practical value. Finally, redundancy intervention scenarios are not extensive enough. The impact of different damage types on buildings varies greatly. Future research should take into account different crisis scenarios and real-world failure scenarios.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Degree centrality and betweenness centrality.

Num.	Name	Degree Centrality	Betweenness Centrality
1	Venue lighting system	4	0.0001684
2	General lighting system	22	0.0035049
3	Parking lot lighting system	3	0.0000842
4	Emergency lighting system	4	0
5	Power supply system	22	0.0011223
6	Domestic water supply system	13	0.0013982
7	Hot water system	8	0.0012907
8	Circulating cooling water system	5	0.0020202
9	Drinking water system	6	0.0010943
10	Sprinkler irrigation system	5	0.0001356
11	Sewage system	5	0.000303
12	Rainwater system	5	0.0007248
13	Indoor fire hydrant system	3	0.0002058
14	Outdoor fire hydrant system	6	0.0007782
15	Outdoor dry automatic sprinkler system	8	0.0016339
16	Air conditioning system	16	0.0103006
17	Mechanical ventilation system	13	0.0085329
18	Smoke control system	4	0.0001716
19	The elevator system	4	0.0001716
20	Integrated wiring system	6	0
21	Communication network system	3	0
22	Computer information system	4	0
23	Digital conference system and simultaneous interpretation system	3	0.0003367
24	Public and emergency broadcasting subsystems	8	0
25	Flag raising system for gymnasium and natatorium	3	0.0002104
26	Central control integrated management system	19	0.0013468
27	Equipment monitoring system	20	0.0021324
28	Safety equipment management system	6	0.0011985
29	Automatic fire alarm and fire linkage system	8	0.004212
30	Site lighting system	6	0.0010728
31	Venue electronic display system	7	0.0029246
32	Site sound amplification and other systems	5	0.0005677
33	Timing and scoring system	2	0
34	Television and commentary system	6	0.0025253
35	Organizing committee office system	3	0.0010101
36	Command and control center system	6	0.0030303
37	Office meeting area	7	0
38	Coach area	6	0
39	Press area	7	0
40	Preparation area	4	0
41	The audience stands	5	0
42	Box	3	0
43	Public transport area	8	0
44	Boiler room	3	0
45	Public toilet	5	0
46	Box bathroom	6	0
47	Podium	9	0
48	Track and field	16	0
49	Otc	5	0
50	The restaurant	4	0
51	The kitchen	6	0
52	Business district	5	0
53	Smoking rest area	2	0
54	Warehouse	1	0
55	Large screen, timing, and scoring facilities	4	0
56	Telecommunications, radio, and television rooms	5	0

Table A2. The system composition of the Nanjing Olympic Sports Center.

Num.	Name	Abbr.	Num.	Name	Abbr.
1	Venue lighting system	VLS	29	Automatic fire alarm and fire linkage system	AFA&FLS
2	General lighting system	GLS	30	Site lighting system	SLS
3	Parking lot lighting system	PLLS	31	Venue electronic display system	VEDS
4	Emergency lighting system	ELS	32	Site sound amplification and other systems	SSAOT
5	Power supply system	PSS	33	Timing and scoring system	TASS
6	Domestic water supply system	DWSS	34	Television and commentary system	TACS
7	Hot water system	HWS	35	Organizing committee office system	OCOS
8	Circulating cooling water system	CCWS	36	Command and control center system	CACCS
9	Drinking water system	DWS	37	Office meeting area	-
10	Sprinkler irrigation system	SIS	38	Coach area	-
11	Sewage system	SS	39	Press area	-
12	Rainwater system	RS	40	Preparation area	-
13	Indoor fire hydrant system	IFHS	41	The audience stands	-
14	Outdoor fire hydrant system	OFHS	42	Box	-
15	Outdoor dry automatic sprinkler system	ODASS	43	Public transport area	-
16	Air conditioning system	ACS	44	Boiler room	-
17	Mechanical ventilation system	MVS	45	Public toilet	-
18	Smoke control system	SCS	46	Box bathroom	-
19	The elevator system	TES	47	Podium	-
20	Integrated wiring system	IWS	48	Track and field	-
21	Communication network system	CNS	49	Otc	-
22	Computer information system	CIS	50	The restaurant	-
23	Digital conference system and simultaneous interpretation system	DC&SIS	51	The kitchen	-
24	Public and emergency broadcasting subsystems	PB&EBS	52	Business district	-
25	Flag raising system for gymnasium and natatorium	FRS	53	Smoking rest area	-
26	Central control integrated management system	CCIMS	54	Warehouse	-
27	Equipment monitoring system	EMS	55	Large screen, timing, and scoring facilities	-
28	Safety equipment management system	SEMS	56	Telecommunications, radio, and television rooms	-

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