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Evaluating Spatial Allocation of Resilient Medical Facilities in Megacities: A Case Study of Shanghai, China

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Abstract: In response to public health emergencies, the importance of resilient medical facilities—such as large exhibition centers and sports venues that can be rapidly converted into temporary emergency hospitals—has become increasingly evident. This study focuses on these potential medical resources within megacities, using Shanghai as a case study. Employing advanced analytical tools including the kernel density two-step floating catchment area method, Lorenz curves, and *Gini* coefficient, we systematically evaluated the spatial allocation of 36 resilient medical facilities in Shanghai. The findings indicate that Shanghai's resilient medical facilities ensure 4.5 emergency beds per thousand residents, with large exhibition centers and sports venues demonstrating exceptional conversion capabilities far surpassing those of ordinary public venues. However, the study also uncovers significant disparities in spatial allocation: these facilities are predominantly concentrated in the city center, leading to notable deficiencies in accessibility and equity for suburban areas. The opportunity for residents to access emergency medical services decreases progressively from the city center outward, a trend consistent across various travel time scenarios. The calculated *Gini* coefficient underscores an extremely uneven spatial configuration of resilient medical facilities, well beyond the warning threshold, suggesting substantial service disparities between different regions during emergencies, which poses potential risks to public health. Our research provides valuable insights for megacities aiming to more effectively address future public health challenges and enhance societal resilience.

Keywords: peacetime–pandemic integration; resilient medical facilities; spatial allocation; accessibility; Shanghai

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1. Introduction

Megacities, as complex and special socio-economic ecosystems [1], have been facing various disturbances and impacts from either the external environment or the internal structure since their formation. Natural geological disasters such as tsunamis and earthquakes and extreme weather conditions triggered by global climate change as well as the rampant spread of infectious diseases and economic crises and fluctuations all pose severe challenges to the stable operation of megacities [2]. Nowadays, major influential public health events are mainly caused by infectious diseases, such as SARS, Ebola, and COVID-19 [3]. The COVID-19 pandemic that broke out at the end of 2019 was like a global storm, dealing a heavy blow to human society. People's lives and safety were directly threatened, the

normal order of life was completely disrupted, the global economy fell into an unprecedented recession abyss, and society also fell into a turbulent and unstable situation. Due to their highly dense population, frequent economic activities, and strong agglomeration and diffusion effects [4], megacities have become "hotbeds" for virus transmission during this pandemic, but at the same time, they also bear the crucial mission of blocking the spread of the epidemic and stabilizing the social situation. Therefore, constructing a normalized urban public health crisis prevention and control system has become an urgent matter. This is not only a necessary measure to guarantee the life and health of urban residents and social stability but also the core essence of the construction of a "resilient city" [5,6]. Through establishing and improving this prevention and control system, megacities are expected to enhance their ability to respond to all kinds of sudden public health events and improve their resilience and adaptability in adversity, thereby demonstrating stronger resilience and vitality in the face of future uncertainties.

The concept of a "resilient city" stands as a pivotal framework in urban governance, focusing on ensuring urban safety and achieving sustainable development [7,8]. Originating from the realms of engineering resilience and ecological resilience, the notion has evolved to encompass evolutionary resilience [9–11]. Under the guidance of this theory, resilient cities possess the capacity for continuous adjustment, adaptation, and transformation, maintaining normal functionality even in the face of diverse disasters. It is itself a complex system with multiple components, closely and flexibly connected internally, rapid feedback and adjustment mechanisms, and high redundancy in important functions and reserve facilities [12]. Currently, the research on resilient cities mainly concentrates on the socio-economic level, covering aspects such as economic growth [13], social culture [14], institutional arrangements [15], etc., and the physical space level, mainly focusing on urban infrastructure [16] and emergency shelters [17], which are mostly used for specific natural disasters such as tsunamis, earthquakes, droughts, floods, and climate change [18–20].

However, it is noteworthy that for megacities, research on emergency medical service facilities during public health emergencies, particularly field hospitals, remains underexplored. Even less attention has been paid to large public venues repurposed as emergency medical facilities, which significantly affects discussions on comprehensive risk management in megacities. Compared to newly constructed temporary emergency hospitals, repurposed large public venues like sports venues and exhibition centers better align with the principles of "peacetime–pandemic integration" and minimal modification. These venues represent crucial resilient medical facilities (RMFs) for megacities in responding to major pandemics, effectively alleviating shortages of medical facilities during crises. Therefore, precise spatial configuration evaluations of these repurposed temporary emergency hospitals are essential [21]. Such assessments will aid urban planners, policymakers, and managers in understanding the service provision capabilities and spatial distribution disparities of RMFs within megacities during public health emergencies. Moreover, these evaluations provide valuable guidance for the selection and construction of RMFs in future public health crises.

In summary, the establishment of RMFs through the repurposing of large public venues is not only a practical solution for addressing immediate medical needs but also an integral component of enhancing the overall resilience of megacities. By integrating these facilities into urban planning and emergency preparedness strategies, cities can better withstand and recover from unexpected challenges, ensuring the well-being and sustainability of their populations.

This paper, supported by the kernel density two-step floating catchment area (KD2SFCA) method, Lorenz curves, and *Gini* coefficient, has established an analysis framework for evaluating the scale of emergency medical beds that RMFs such as exhibition

centers and sports venues within megacities can offer, as well as their spatial accessibility and spatial equity of services. The basic analysis unit is refined to a 1 km×1 km grid, providing a high-resolution evaluation. Taking Shanghai, a megacity, as a case, it reflects the problems existing in the spatial allocation of RMFs intuitively and accurately from the perspective of supply and demand matching. Based on the evaluation results, targeted planning strategies are proposed to promote the balance of supply and demand of such facilities in order to enhance the response capacity of megacities when facing sudden public health events.

The article is organized as follows: Section 2 begins with a literature review that offers an in-depth survey of existing studies relevant to our topic. In Section 3, we introduce Shanghai as the study area and outline the comprehensive analytical framework employed, detailing the methodologies and data processing steps that underpin our study. Section 4 then explores the spatial distribution of RMFs, examining issues of spatial accessibility and equity. Here, we analyze how these facilities are laid out across space and assess their reachability and fairness in distribution. Finally, the article concludes with a synthesis of our findings, summarizing key insights gained from the research and suggesting implications for future work.

2. Literature Review

The RMFs discussed in this paper differ from the centralized quarantine facilities used since 2020 for medical observation. These emergency hospitals are designed to provide basic medical care for patients with mild symptoms and have more stringent requirements for suitable buildings. Suitable structures must meet the following criteria:

(1) Enclosed standalone buildings: located in relatively open areas, these buildings can effectively control virus transmission and facilitate patient treatment [22].
(2) Large-space characteristics: ample space is essential for adequate ventilation and ease of construction modifications [23].
(3) Public ownership: government-led initiatives can expedite administrative procedures and ensure the efficient allocation of public resources, aligning with the need for rapid adaptation during emergencies [24].
(4) Good internal fire safety conditions: buildings with existing fire safety measures require less modification, lower costs, and shorter construction times [25].

Current discussions on potential repurposed buildings focus primarily on exhibition centers, medium-to-large sports venues, vacant industrial factories, school dormitories, and exhibition halls. However, school dormitories must prioritize the needs of students during a pandemic and are often located in densely populated communities. Vacant industrial factories, due to their simple internal finishes, incur higher renovation costs and longer timelines. Therefore, these options are not ideal for converting into temporary field hospitals. In contrast, public sports venues and exhibition centers offer several advantages: they are situated in relatively open areas, have complete internal structures and fire safety systems, and typically feature multiple distinct spatial zones. These characteristics align closely with the standards required for emergency hospital conversions, making them the most common choices in actual renovation projects. Public exhibition centers and sports venues can be rapidly converted into temporary emergency hospitals at low cost to address the isolation and treatment needs of large numbers of mildly symptomatic patients. Post-pandemic, they can be quickly and cost-effectively restored to their original functions. Thus, public exhibition centers and sports venues serve as unique physical space examples for studying resilient medical facilities [26]. They exemplify how urban infrastructure can be efficiently adapted to enhance a city's resilience during public health crises while maintaining flexibility for future use.

Since Teitz et al. [27] first introduced the theory of location for public service facilities, numerous scholars have explored theoretical models and empirical methods to study the spatial configuration of such facilities. These studies combine quantitative geography with empirical research to deepen our understanding of optimal placement strategies. For instance, Murray et al. [28] developed spatial optimization models for the location coverage of public service facilities. Morrill et al. [29] focused on the equity of location selection for public services, examining both the fairness and efficiency implications. Orloff et al. [30] established models for the location choice of NIMBY (Not In My Back Yard) facilities, addressing community resistance. In the context of building a "peacetime–pandemic integration" emergency medical facility system, evaluating the spatial configuration of resilient healthcare facilities is critical, providing foundational support for the entire system. Numerous studies have highlighted the shortcomings of existing urban medical facilities during the COVID-19 pandemic, identifying issues in the spatial allocation of medical resources and seeking optimization pathways [31]. Additionally, some research has delved into the principles and planning strategies for siting large-scale emergency medical facilities, aiming to enhance their effectiveness from the outset [32,33]. For potential emergency resources like sports venues and exhibition centers, past studies have predominantly concentrated on engineering modifications. This also explores the feasibility of converting these venues into temporary emergency hospitals and meticulously designing specific renovation plans, thereby laying the groundwork for their emergency conversion at the hardware level [34].

During the pandemic outbreak, emergency medical facilities played a crucial role due to their high accessibility. On one hand, they enabled triage and treatment for mild cases within the region, significantly alleviating the pressure on comprehensive hospitals. This allowed for more efficient allocation of limited medical resources during emergencies [35]. On the other hand, these facilities leveraged their proximity advantage to receive a large number of suspected cases. This not only improved patient transport efficiency but also effectively reduced the risk of virus transmission during long-distance medical visits, contributing significantly to curbing the spread of the pandemic [36]. Thus, spatial accessibility has been widely recognized by scholars as a core element in optimizing the spatial layout of emergency medical facilities and promoting equitable distribution of emergency medical resources [37–39]. The concept of accessibility was first introduced by Hansen in the 1950s, emphasizing "potential opportunities for interaction" [40]. It encompasses key elements such as origin, destination, and spatial impedance. In the context of emergency medical facilities, spatial accessibility refers to the relative ease of obtaining emergency medical services from a given facility location [41], highlighting the importance of the spatial separation between supply (emergency medical facilities) and demand (population), and how they are interconnected.

Currently, various models exist to measure the spatial accessibility of medical services, including buffer analysis [42], nearest neighbor analysis [43], the two-step floating catchment area (2SFCA) method [44], and potential models [45]. These methods reflect researchers' efforts to incorporate more factors into models to better align analysis results with reality. However, each model has its limitations and specific applicability, necessitating optimization based on the intended application. Among these methods, the 2SFCA method has become a commonly used approach due to its comprehensive consideration of supply–demand interactions and its intuitive presentation of accessibility results through supply-to-demand ratios. To more accurately simulate spatial interactions between supply and demand points, enhancing the alignment of model results with actual healthcare supply–demand conditions, researchers have developed several enhanced versions of the 2SFCA method. These include enhanced 2SFCA [46], gravity-based 2SFCA [47], kernel

density-based 2SFCA [48], and Gaussian-based 2SFCA [49]. The primary distinction between these enhanced 2SFCA models lies in the different trends of their distance decay functions. Selecting an appropriate distance decay function can enhance the precision and practicality of research, providing a more scientific and robust methodological foundation for optimizing the spatial allocation of RMFs.

Spatial equity is also considered a critical component in evaluating the spatial configuration of emergency medical facilities, essential for formulating effective intervention strategies to improve the fairness of healthcare resource distribution in megacities. The concept of spatial equity originates from theories of social justice and focuses on the fairness of resource allocation and service accessibility within geographic space. As research has advanced, some scholars advocate that the distribution of public resources, including healthcare resources, should consider individual social attributes and needs, rather than merely pursuing spatial equality. To address this, concepts of horizontal and vertical equity have been proposed [50]. Horizontal equity emphasizes equal treatment for individuals under identical conditions. Vertical equity advocates for differentiated treatment based on varying conditions, using compensatory resource allocation to mitigate social inequalities. This distinction aids in more accurately understanding and addressing issues of inequality and unfairness [51].

The equity of medical resource allocation is an important goal of public health management and a basic principle advocated by the World Health Organization (WHO). The research on the spatial equity of medical resource allocation initially focused on the time required to travel from the place of residence to the nearest medical facility [52] and then expanded to the evaluation of the quality and service capacity of medical institutions. With the development of GIS technology, the research scale covers small scales such as kilometer grids and communities to national and even global ranges [53,54]. The research on the spatial equity of medical resource allocation is often based on the evaluation results of accessibility. In megacities like Beijing, Shanghai, Guangzhou, and Shenzhen, medical facilities show uneven spatial allocation. They are more accessible in city centers, with suburban areas having lower accessibility and distribution imbalance [33,55–57]. The *Gini* coefficient and Theil index are commonly used indicators for evaluating equity, used to measure the degree of equity of accessibility or resource allocation at the spatial level. The *Gini* coefficient is obtained by depicting the Lorenz curves [37,49]. The Theil index analyzes the difference of data from the perspective of information quantity and entropy and can measure the contribution of intra-group and inter-group differences to the total difference, and has a certain complementarity with the *Gini* coefficient [58].

The COVID-19 pandemic has starkly revealed the serious deficiencies in existing urban emergency land use and facilities, emphasizing the importance of RMFs as a crucial element supporting resilient city construction. In the event of sudden public health emergencies, RMFs must possess multifunctionality, high adaptability, and flexibility to swiftly transform and adapt to new requirements. However, a review of the literature uncovers several limitations: Few scholars have conducted specialized studies on the spatial allocation of RMFs. Comprehensive research that integrates multiple dimensions—spatial distribution, spatial accessibility, and spatial equity—is especially scarce. Furthermore, most existing studies typically analyze population statistics at the administrative district level, resulting in analyses conducted at excessively large geographic scales. This leads to simplistic and rough measurements of the supply–demand characteristics of emergency medical facilities, significantly limiting the accuracy of the research outcomes. In the era of big data, conducting large-sample empirical studies based on smaller evaluation units (such as grid-scale cells) has become feasible [59]. This advancement holds substantial application

value for the precise evaluation of RMF spatial allocation in megacities, offering a more refined understanding and enhancing the effectiveness of urban resilience strategies.

3. Research Design, Methodology, and Data

3.1. Analytical Framework

This study systematically evaluates the spatial configuration of resilient healthcare facilities in Shanghai from three key perspectives. Firstly, we conducted a detailed statistical analysis of two critical types of RMFs within Shanghai's municipal boundaries—exhibition centers and sports venues—focusing on their capacity to provide emergency medical beds. We also examined the spatial distribution characteristics of these facilities. By overlaying these data with high-resolution population raster data, we explored the spatial correlation between facility distribution and population density. Secondly, employing the kernel density two-step floating catchment area (KD2SFCA) method, we calculated both the supply-to-demand ratios and coverage rates of emergency medical beds provided by these facilities under various travel time scenarios, thereby assessing their spatial accessibility. Moreover, we analyzed the spatial equity of access to RMFs using Lorenz curves and the *Gini* coefficient based on the accessibility metrics obtained. Finally, informed by the aforementioned evaluations, we proposed targeted policy recommendations aimed at enhancing the construction of RMFs and improving megacities' emergency response capabilities in handling public health emergencies. The analytical framework is illustrated in Figure 1.

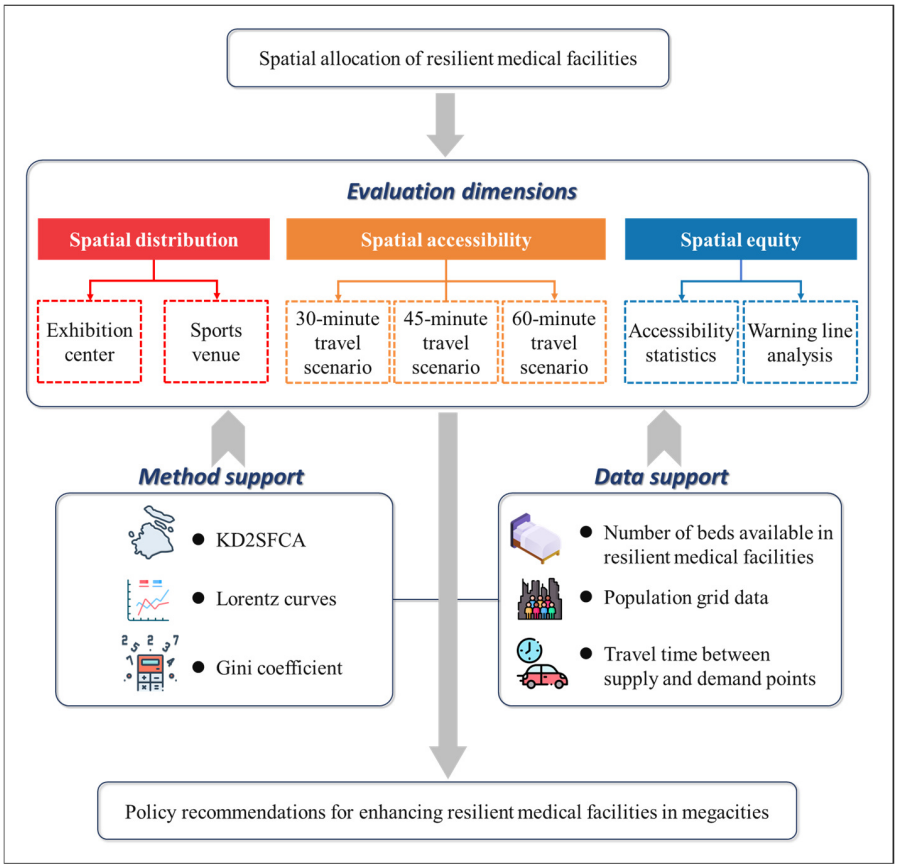


Figure 1. Analytical framework.

3.2. Study Area

Shanghai, as the specific regional scope of this study, has 16 districts under its jurisdiction, with a land area of approximately 6340.5 km^2. According to the data of the

seventh national census released in May 2021, the total resident population amounts to 24.87 million. The central urban area of Shanghai includes the districts of Huangpu, Jing'an, Xuhui, Changning, Hongkou, Yangpu, and Putuo, as well as the areas within the outer ring road of Baoshan, Jiading, Minhang, and Pudong New Area. This central urban area spans about 749.9 km^2 (Figure 2). Considering the two key dimensions of spatial scope and population size comprehensively, Shanghai is undoubtedly a highly typical megacity. This provides a unique and complex urban sample basis for the subsequent study and also makes the relevant analysis based on Shanghai in this study highly representative and referential, capable of providing useful references and inspiration for the studies of similar megacities.



Figure 2. Research area.

3.3. Study Methods

3.3.1. Kernel Density Two-Step Floating Catchment Area Method

The investigation into the accessibility of RMFs primarily hinges on the discussion of whether supply and demand can be matched, both in terms of quantity and spatial distance. The two-step floating catchment area (2SFCA) method effectively addresses this issue. Initially proposed by Radke and Mu [60], this method involves two rounds of floating searches centered first on supply points and then on demand points, hence its name. Given the specific nature of our research question, we have enhanced the basic 2SFCA model. To account for the impact of distance between supply and demand points on patient travel probability, a distance decay function has been introduced. This modification overcomes the original model's limitation of handling spatial distance effects dichotomously.

Both the kernel density function and the gravity model are commonly used distance decay functions, but our choice of the former over the latter was primarily driven by the specific characteristics of public health emergencies, especially during pandemics. The gravity model, while widely used in accessibility studies, assumes a continuous decay of interaction probabilities with increasing distance, typically following a power-law or exponential function. However, during a pandemic, the risk of disease transmission increases exponentially with travel time, especially in densely populated urban areas like Shanghai. This necessitates a distance decay function that more accurately reflects

the rapid decline in the probability of patients traveling to medical facilities as travel time increases. The kernel density function, with its sharper decay curve, better captures this dynamic, as it assigns higher weights to shorter travel times and rapidly diminishes the influence of longer travel times. This aligns with the goal of minimizing the risk of virus transmission during patient movement, ensuring that the accessibility model more realistically simulates the spatial interactions between supply (RMFs) and demand (population) during a public health crisis. Furthermore, the kernel density function allows for a more nuanced representation of spatial impedance, which is critical for accurately assessing the accessibility of emergency medical resources in a high-risk environment. Thus, we chose a kernel density function (Equation (1)) [48] as the distance decay function.

$$G(d_{ij}) = \begin{cases} \frac{3}{4}\left[1 - (\frac{d_{ij}}{d_0})^2\right], d_{ij} \le d_0 \\ 0, d_{ij} > d_0 \end{cases} \quad (1)$$

The resulting kernel density two-step floating catchment area (KD2SFCA) model is formulated as follows:

$$R_j = \sum_{j \in \{d_{kj} \le d_0\}} \frac{S_j}{\sum_{k \in \{d_{kj} \le d_0\}} D_k G(d_{kj})} \quad (2)$$

$$A_i^F = \sum_{j \in \{d_{kj} \le d_0\}} R_j G(d_{ij}) \quad (3)$$

where i and k represent medical demand points, j represents medical supply points (locations of RMFs), S_j denotes the supply scale at point j (number of beds), D_k denotes the demand scale at point k (population size), R_j is the supply-to-demand ratio at point j, d_0 is the search radius threshold, d_{kj} and d_{ij} represent the cost (time) of obtaining medical services from points i or k to point j, $G(d_{ij})$ and $G(d_{kj})$ are the distance decay functions, and A_i^F represents the accessibility of RMFs at point i.

Based on the above model, the measurement of accessibility can be achieved through two steps: The first step is to capture all accessible demand points within the search radius centered on each RMF and calculate the supply–demand ratio of each RMF, specifically the bed-to-population ratio. The second step is to search for all accessible RMFs within the search radius centered on each demand point and take the sum of the supply–demand ratios of RMFs as the accessibility index of this demand point. Meanwhile, multiple search radii are set for sensitivity analysis. The search radius represents the maximum travel time acceptable to patients and its size will affect the scarcity of medical resources (supply–demand ratio) and the actual calculation range of accessibility. Increasing the search radius, on one hand, makes the beds of a single RMF scarcer; on the other hand, it also increases the number of resilient medical facilities that patients can access, thereby affecting the accessibility results. Considering that temporary emergency hospitals do not have fixed service areas, to minimize the impact of a single search radius on the study results, we assume that RMFs serve the entire city. Referring to Shanghai's "1560 Medical Service Circle" (that is, the idea that Shanghai citizens can reach a medical service station within 15 min on foot and a tertiary hospital within 60 min by public transportation) and existing studies on the accessibility of medical services [61], this paper attempts to set the search radius to 45 min and compare the accessibility results of 30 min and 60 min to analyze the robustness of the results.

3.3.2. Lorenz Curves and *Gini* Coefficient

The Lorenz curves and the *Gini* coefficient provide an intuitive and quantitative toolset widely applied to evaluate the equity of accessibility [62]. By plotting the cumulative

percentage of population on the x-axis against the cumulative percentage of accessibility on the y-axis, the Lorenz curves illustrate the degree of inequality in resource allocation. The more curved the curve, the more unfair the allocation of RMFs; conversely, the closer the curve is to the diagonal line, the more equal the resource allocation. The *Gini* coefficient serves as a quantifiable measure of this inequality, defined as the ratio of the area between the Lorenz curve and the line of absolute equality to the total area under the line of absolute equality. Its calculation formula is as follows:

$$Gini = 1 - \sum_{i=1}^{n} (X_{i+1} - X_i)(Y_{i+1} + Y_i) \quad (4)$$

where *Gini* represents the *Gini* coefficient, X_i denotes the cumulative percentage of population, and Y_i denotes the cumulative percentage of accessibility.

The value of the *Gini* coefficient ranges from 0 to 1, where 0 represents complete equality and 1 indicates complete inequality. According to Price's research [63], the equity of medical services can be categorized into five levels based on the *Gini* coefficient: below 0.2 indicates high equity, between 0.2 and 0.3 indicates relatively high equity, between 0.3 and 0.4 indicates moderate equity, 0.4 acts as a warning threshold, between 0.4 and 0.6 indicates significant disparities, and above 0.6 signifies extremely large disparities, implying in this study that the spatial allocation of RMFs is highly inequitable.

3.4. Data Collection and Processing

The steps of data collection and processing in this study encompass the collection, calibration, and integration of supply and demand data, as well as travel time information. The overall steps of data collection and processing are shown in Figure 3.

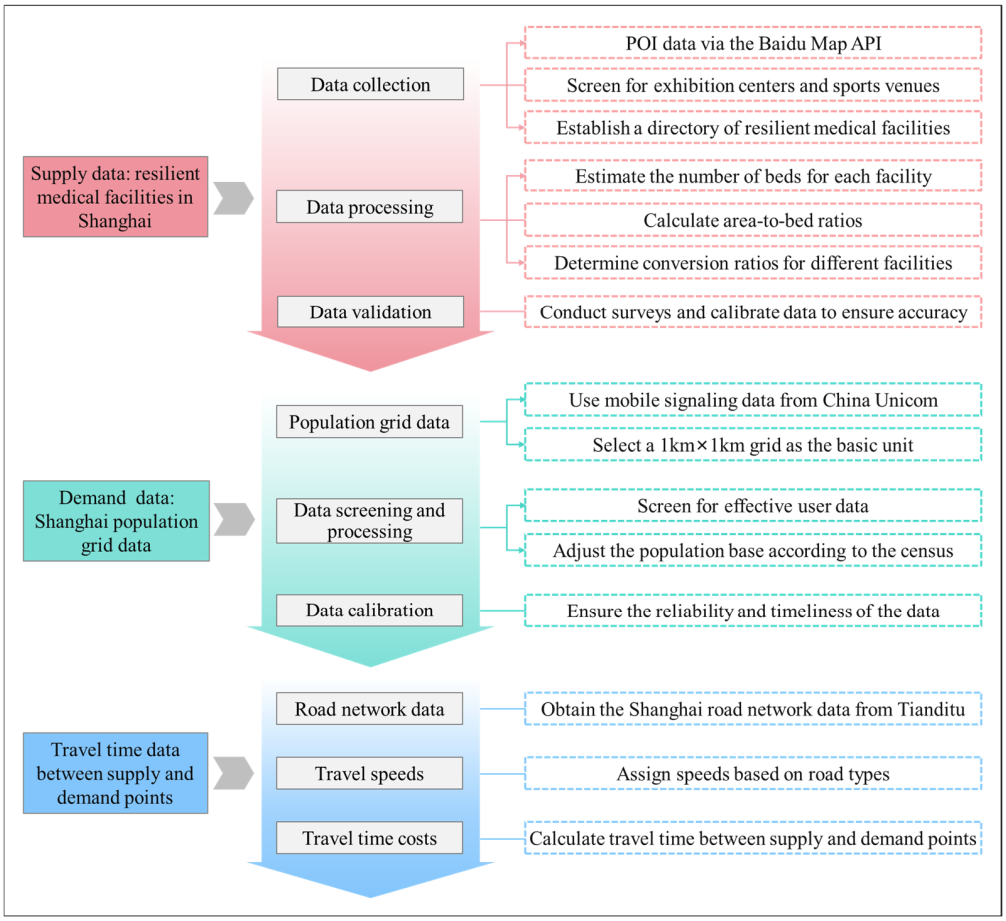


Figure 3. Overall steps of data collection and processing.

3.4.1. Supply Data: Resilient Medical Facilities in Shanghai

To estimate as accurately as possible the number of emergency medical beds that these facilities can provide during emergencies, this study adopted a two-phase data collection and processing methodology.

In the first phase, we focused on acquiring Points of Interest (POI) data and establishing a comprehensive directory of RMFs. Using Python 3.10 to call the Baidu Map API (https://lbsyun.baidu.com/, accessed on 18 April 2022), we scraped data for sports venues and large exhibition centers within Shanghai. By setting parameters such as keyword searches and boundary conditions, we ensured that the collected data were both comprehensive and accurate. Subsequently, based on information from the official websites of Shanghai's district governments and announcements from the Sports Bureau, we further screened out public sports venues at both municipal and district levels. This process culminated in the establishment of a detailed directory of RMFs along with their geographical locations.

The second phase involved estimating the number of emergency medical beds. Initially, we gathered information from news reports, Baidu Baike (the Chinese version of Wikipedia), and the "Design Guidelines for Temporary Medical Centers Converted from Sports Venues During Public Health Emergencies". We compiled data on the area and corresponding bed counts when venues such as the Wuhan International Expo Center, Wuhan International Convention Center, Hongshan Gymnasium, Dahuashan Sports Center, Wuhan Sports Center, and Wugang Gymnasium were converted into makeshift hospitals. Exhibition centers utilized exhibition hall areas, while gymnasiums were calculated based on building area or indoor arena area.

Next, we computed the area-to-bed ratios for each facility, obtaining preliminary conversion rates. Following this, we categorized the areas according to different measurement criteria and calculated average values. Ultimately, we determined empirical conversion ratios for the two types of facilities: 9.5 m^2 per bed for exhibition centers, and 21.6 m^2 per bed for sports venues based on building area or 9.7 m^2 per bed based on indoor center area.

Finally, using the aforementioned conversion ratios, we estimated the number of beds that each facility could provide by leveraging publicly available resources such as Baidu Baike and Venue Treasure for the exhibition hall areas of convention centers and the building areas of sports venues. For sports venues where building area data were not directly obtainable, we conducted field surveys and measured the indoor arena areas to ensure data accuracy.

3.4.2. Demand Data: Shanghai Population Grid Data

The incidence of sudden public health events is closely related to population distribution [64], and data at a finer grid scale can more accurately reflect the spatial pattern of population distribution compared to data at the street/township level (the smallest administrative unit in China) or even the community level. For this study, we utilized mobile phone signaling data from China Unicom for Shanghai in January 2021. Given that each cell tower has a capacity limit, densely populated areas may experience frequent identification of the same user by adjacent towers, leading to a primary cell tower spacing of less than 1 km within Shanghai's mobile phone signaling data. Therefore, this paper selects a 1 km $\times$ 1 km grid as the basic research unit to obtain population grid data for Shanghai.

For analysis, we selected grid cells with an effective number of users greater than zero, resulting in a total of 7019 basic research units. Moreover, this dataset comprehensively considers trends in birth rates and mortality rates from 2010 to 2020 and adjusts the population base according to the seventh national census data for Shanghai. Moreover, we also incorporated adjustments for population mobility and temporary residents based on

additional survey data from local communities. By doing so, we ensured that the data have high reliability and timeliness, providing robust support for demand data in our study.

3.4.3. Travel Time Data Between Supply and Demand Points

The road network information was sourced from the 2016 Shanghai road network data downloaded from Tianditu, the National Geographic Information Public Service Platform. Considering that during a pandemic outbreak, actual travel is less affected by traffic congestion or traffic signals, we referred to the design speeds outlined in the "Urban Road Engineering Technical Specifications (GB51286-2018)" [65] for different types of roads. Accordingly, travel speeds were assigned as follows: expressways at 100 km/h, urban express roads at 80 km/h, arterial roads at 50 km/h, secondary arterial roads at 40 km/h, collector roads at 25 km/h, and roads below the collector level at 15 km/h. Pedestrian paths were uniformly set at 5 km/h. These speed assignments were used to calculate the travel time costs between supply and demand points.

4. Research Results

4.1. Spatial Distribution of Resilient Medical Facilities

This study identified a total of 36 RMFs within the Shanghai metropolitan area, including 9 exhibition centers and 27 sports venues, capable of providing over 110,000 emergency medical beds. Based on the permanent resident population, this translates to a supply capacity of 4.5 emergency medical beds per thousand people. The scale of supply is significantly influenced by the type of facility. As shown in Table 1, exhibition centers have a large supply capacity, offering a total of 89,015 beds, accounting for 79% of the total supply. This high capacity benefits from the spacious exhibition areas within convention centers and their efficient conversion rates. Notably, two major international exhibition centers—the National Exhibition and Convention Center and the Shanghai New International Expo Center—possess exhibition areas of 470,000 m^2 and 200,000 m^2, respectively, which can provide over 70,000 beds combined. Additionally, six other large exhibition centers can each offer more than 2000 beds. In contrast, despite outnumbering exhibition centers, sports venues can only provide a total of 23,571 beds, significantly fewer than those provided by exhibition centers. Moreover, there are differences in supply capacity between different levels of sports venues. Large sports venues, such as the Oriental Sports Center, Minhang Gymnasium, Baoshan Sports Center, Jiading Gymnasium, Chuansha Gymnasium, and Shanghai International Gymnastics Center, can provide over 1500 beds each. On the other hand, smaller venues like the Jing'an Gymnasium and Yangpu District Gymnasium can only offer around 100 to 200 beds.

Table 1. Number of emergency medical beds in each RMF (Top 10).

Name of Facility	Type	Number of Beds
National Exhibition and Convention Center	Exhibition center	49,683
Shanghai New International Expo Center	Exhibition center	21,142
World Trade Mall	Exhibition center	4228
Oriental Sports Center	Sports venue	3606
Guangda Convention Center	Exhibition center	3171
Automotive Exhibition Center	Exhibition center	3171
World Expo Exhibition Hall	Exhibition center	2800
Shanghai Exhibition Center	Exhibition center	2326
Minhang Gymnasium	Sports venue	1853
Baoshan Sports Center	Sports venue	1803

From a spatial distribution perspective, the RMFs in Shanghai exhibit an overall pattern characterized by "core concentration–peripheral dispersion" (Figure 4). "Core

concentration" is evident in the high density of these facilities in the central urban area and its eastern parts, including districts such as Xuhui, Changning, Huangpu, Putuo, Jing'an, Yangpu, Hongkou, northern Minhang, and northwestern Pudong. This region not only hosts a significant number of RMFs but also includes several high-capacity facilities, such as the World Trade Mall, Guangda Convention Center, World Expo Exhibition Hall, and Minhang Gymnasium. Furthermore, this core region partially overlaps with high-population-density areas, where high supply capabilities will face equally high demand. "Peripheral dispersion" refers to the scattered locations of other RMFs across various districts, which are relatively evenly distributed. These facilities exhibit varying capacities; for example, the Baoshan Sports Center can provide nearly 1800 beds, while the Jinshan Gymnasium offers only 567 beds.

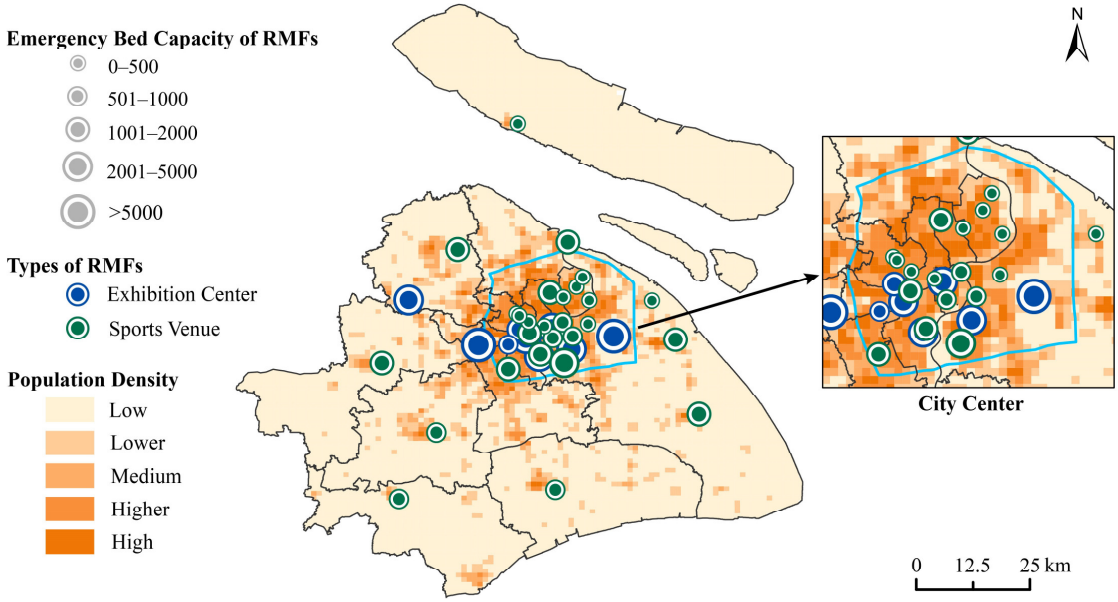


Figure 4. Supply scale and spatial distribution of RMFs in Shanghai.

The spatial distribution characteristics of different types of RMF vary based on their inherent attributes. Exhibition centers are typically located in central urban areas or near transportation hubs. This layout aligns with the short-term and high-frequency requirements for human and logistics flow associated with exhibitions. Exhibitions are usually temporary events that require a rapid attraction of large numbers of visitors and efficient logistical support. Therefore, selecting central urban areas with convenient transportation, dense populations, and well-developed service facilities maximizes the satisfaction of these needs [66]. In comparison, sports venues are more evenly distributed across Shanghai's districts. This reflects the goal of equitable service provision pursued by local government investment in public service facilities. Sports venues serve multiple functions, including sports events, community fitness, and cultural activities, making them important public welfare facilities [67]. Hence, the government tends to strategically locate sports venues in different administrative regions to ensure residents can equitably benefit from these facilities.

4.2. Spatial Accessibility of Resilient Medical Facilities

Within a 45 min travel time (search radius), Shanghai's existing resilient medical facilities can cover 91% of the metropolitan area. The accessibility results, based on a 45 min travel time, are presented using the natural breaks classification method, revealing significant spatial disparities and exhibiting a typical "core–periphery" structure (Figure 5).

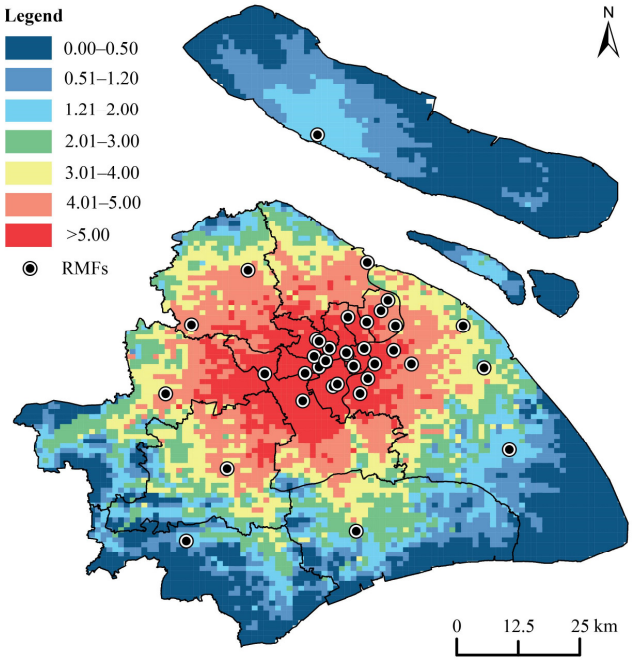


Figure 5. Spatial disparities in accessibility of RMFs in Shanghai.

The high-accessibility core areas can provide between 5 to 6 emergency medical beds per thousand people. These areas are primarily concentrated in districts such as Xuhui, Changning, Putuo, Huangpu, Hongkou, Jing'an, the southwestern corner of Yangpu, the central–northern part of Minhang, eastern Qingpu, and the northeastern corner of Songjiang. This region encompasses most of the central urban area and extends southwestward into the outskirts of the city center. Within this area, there are a total of 24 resilient medical facilities, including large-scale ones like the National Exhibition and Convention Center and the Minhang Gymnasium located at the southwestern edge of the outskirts of the city center, which provide a substantial number of emergency medical beds.

In contrast, low-accessibility peripheral areas can only offer fewer than 0.50 emergency medical beds per thousand people, showing a stark difference from the core areas. These regions mainly include the southwestern, southern, and northeastern peripheries of Shanghai's metropolitan area, involving parts of Jinshan District, Fengxian District, some areas of Qingpu District, the Lingang area of Pudong New Area, and the southern part of Chongming Island and Hengsha Island. Not only do these areas lack resilient medical facilities, but they are also far from the core areas where facilities are densely distributed, resulting in the least accessible emergency medical resources.

The accessibility values of other areas decrease in concentric layers from the high-value core to the low-value periphery, with the number of beds available per thousand people decreasing by approximately one bed for each tier—from sub-high core areas (accessibility value 4.01–5.00) to sub-low peripheral areas (accessibility value 0.51–1.20). This layered structure clearly illustrates the spatial distribution inequality of Shanghai's RMFs.

To further validate the robustness of the aforementioned findings, this study also included an analysis of accessibility within 30 min and 60 min travel times (Figure 6). As shown, with the increase in travel time, the coverage of demand points for RMFs significantly improves. Specifically, within a 30 min travel time, RMFs can cover 70% of the demand points; this proportion increases to 97% within a 60 min travel time. This indicates that as the search radius expands, more demand points can reach RMFs, thus being included in the accessibility calculation.

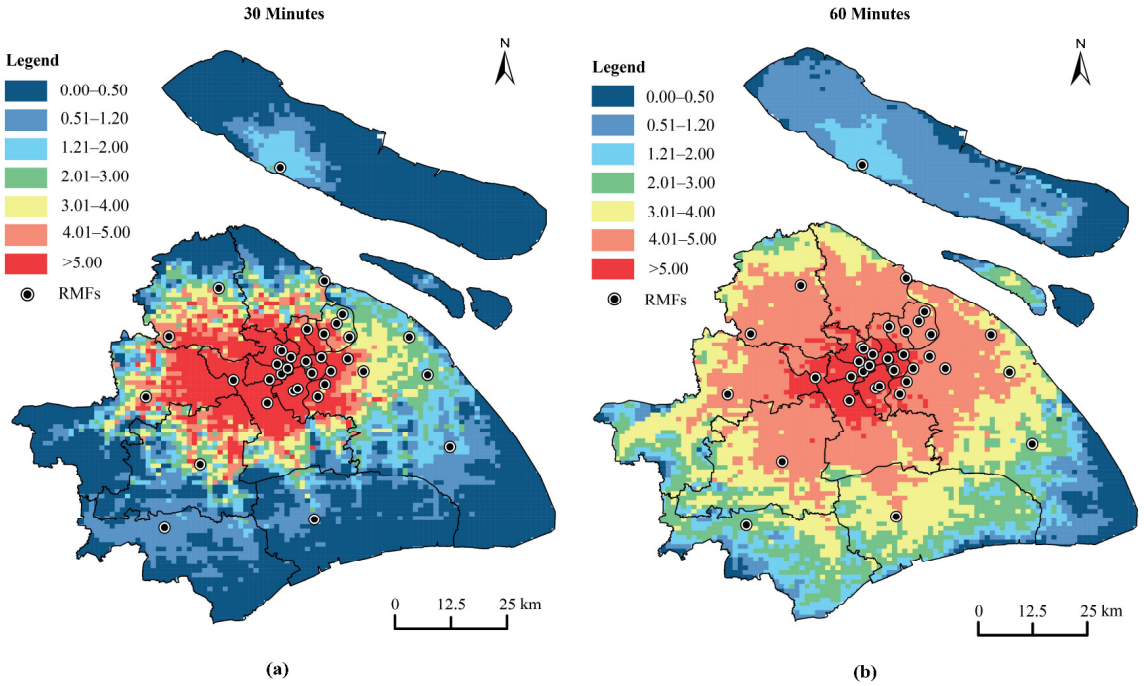


Figure 6. Accessibility of RMFs under 30 min and 60 min travel times in Shanghai.

Despite variations in coverage rates under different travel times, the overall spatial structural characteristics remain consistent, still presenting a clear "core–periphery" distribution pattern. Regardless of whether the search radius is set at 30 min or 60 min, the highest accessibility areas within Shanghai's metropolitan area remain concentrated in most of the central urban districts, while the lowest accessibility areas continue to be the western and southern peripheries of the metropolitan area and the Chongming Island district. Moreover, the change from the high-value core to the low-value periphery continues to follow the rule of concentric layer reduction, with the number of beds available per thousand people gradually decreasing as distance increases. These results confirm the robustness of the previous findings, indicating that regardless of changes in travel time, the spatial distribution inequality of Shanghai's RMFs persists. This underscores the importance of optimizing resource allocation to ensure that a broader population can access timely medical services during emergencies.

4.3. Spatial Equity of Resilient Medical Facilities

As travel time decreases, the maximum accessibility values increase, highlighting regions with extreme accessibility values more prominently. When the travel time is set to 30 min, the areas with extremely high and extremely low accessibility values are more pronounced, while regions with intermediate accessibility values occupy a smaller area. With increasing travel time, the average accessibility levels for resilient medical facilities across Shanghai gradually improve, and spatial disparities diminish. This trend is reflected in the increasing average number of beds per thousand people and decreasing standard deviation in Shanghai (Table 2).

Table 2. Accessibility statistics under different travel time scenarios.

Travel Time	Range	Standard Deviation	Mean
30 Minutes	9.03	2.19	2.14
45 Minutes	6.13	1.84	2.36
60 Minutes	5.32	1.58	2.86

To provide a comprehensive analysis of the spatial equity of RMFs in Shanghai, this study employs Lorenz curves and the *Gini* coefficient for quantification (Figure 7). The results indicate that under different travel time scenarios, the *Gini* coefficient for the accessibility of RMFs is as follows: 0.721 for a 30 min travel time, 0.663 for a 45 min travel time, and 0.608 for a 60 min travel time. According to the standard criteria for interpreting the *Gini* coefficient, a value exceeding 0.6 signifies significant disparity and severe spatial inequality. In all three scenarios, the *Gini* coefficient significantly surpasses the warning line of 0.4, indicating severe inequities in the spatial distribution of RMFs in Shanghai. Specifically, the supply disparity between central urban areas and peripheral suburban regions is particularly pronounced, contributing to the high *Gini* coefficient. This imbalance not only affects the fairness of residents' access to emergency medical services but also potentially exacerbates resource allocation pressures and efficiency issues during emergencies. The stark contrast in accessibility highlights the need for strategic interventions to enhance equitable access to RMFs across different parts of Shanghai.

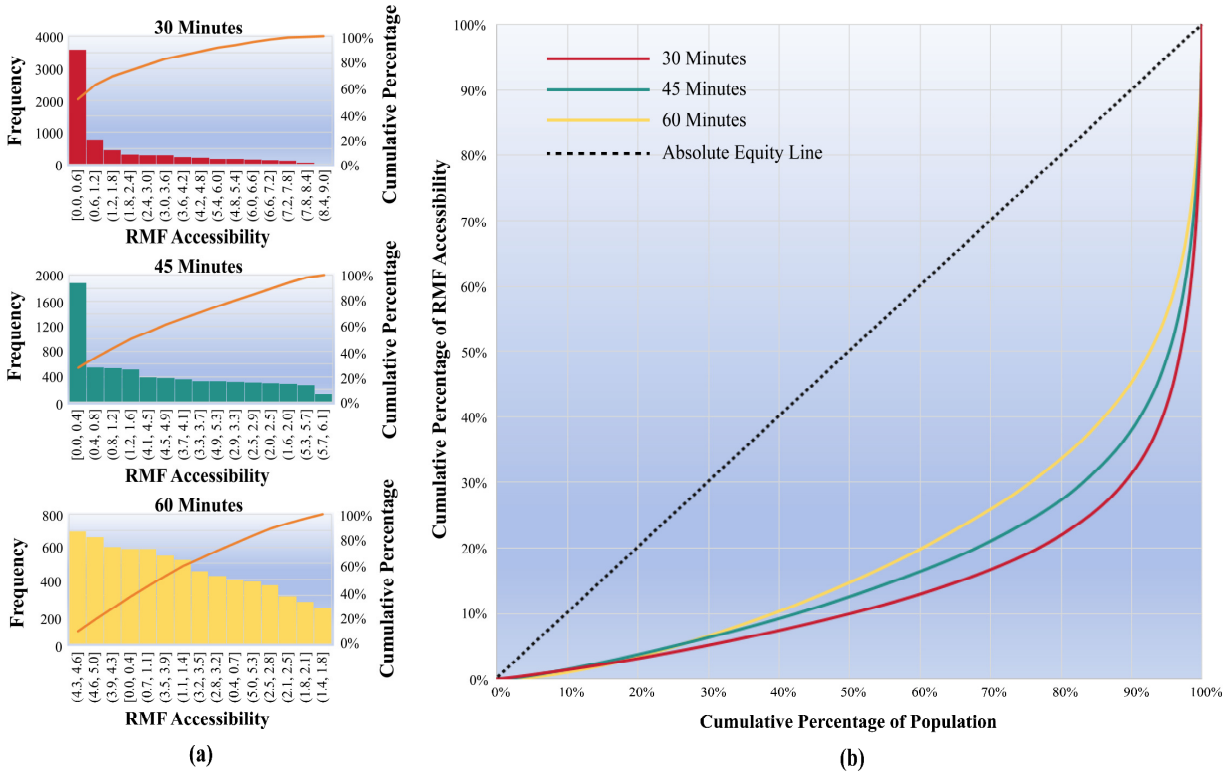


Figure 7. Histograms and Lorenz curves for accessibility of RMFs in Shanghai. In histograms, the columns representing the frequency of the data in each group, and the curve representing the cumulative percentage. In the Lorenz curve graph, the solid curve representing the Lorenz curves under different travel time scenarios.

5. Conclusions

5.1. Key Findings

This study estimated the supply scale and spatial layout of RMFs in Shanghai, evaluated their accessibility within a 45 min travel time using the KD2SFCA method, and compared accessibility at 30 min and 60 min travel times to validate result robustness. Finally, it assessed spatial equity using Lorenz curves and the *Gini* coefficient. Key findings include the following:

Shanghai has 36 RMFs that can be converted into temporary emergency hospitals, providing over 110,000 emergency medical beds. This equates to 4.5 beds per thousand residents, sufficient for an infection rate of approximately 4.5‰. Supply capacity varies

significantly by facility type, with exhibition centers and large sports venues offering far greater capacity than standard gyms.

RMF accessibility exhibits distinct spatial disparities, characterized by a "core–periphery" structure, with values decreasing from high-value core areas to low-value peripheral regions. Core high-value areas, excluding Yangpu District, cover most central urban districts and their southwest outskirts, providing 5–6 beds per thousand people. Low-value peripheral areas, such as Fengxian, Jinshan, the Lingang area of Pudong New Area, and Chongming, offer fewer than 0.9 beds per thousand people. RMFs cover 70%, 91%, and 97% of demand points within 30, 45, and 60 min travel times, respectively. An increased travel time improves average accessibility and reduces spatial disparities but maintains the "core–periphery" structure.

Under all travel time scenarios, the *Gini* coefficient for RMF accessibility significantly exceeds the warning threshold, indicating severe spatial inequality. The pronounced disparity between central urban and peripheral suburban areas not only affects equitable access to emergency medical services but also exacerbates resource allocation pressures during emergencies.

5.2. Policy Recommendations

The COVID-19 pandemic has highlighted the significance of urban resilience in dealing with sudden public health emergencies. Public sports venues and large exhibition centers serve as crucial resilient medical facilities (RMFs). During pandemics, these facilities can be rapidly converted into temporary emergency hospitals at a low cost, effectively alleviating shortages in reserved emergency spaces and significantly meeting the isolation and treatment needs of infected individuals. Post-pandemic, they revert to their original functions without causing significant resource wastage, aligning with the "peacetime–pandemic integration" principle and sustainable development concepts.

Based on this understanding, this study examines the spatial allocation of RMFs in megacities using Shanghai as a case study. According to our findings, we propose the following policy recommendations aimed at enhancing resilience in Shanghai and other megacities.

5.2.1. Building a Resilient Medical Facility System

Constructing an RMF system is a core component of "resilient city" development, especially critical during public health crises. Since the onset of the COVID-19 pandemic, many cities have begun emphasizing and planning multi-tiered emergency healthcare facilities. Converting large public buildings into temporary hospitals has become a key strategy to realize the triage of patients with mild and severe cases and reduce the burden on the medical system. By concentrating mild cases in converted emergency hospitals and transferring severe cases to designated hospitals, medical resource congestion can be effectively mitigated, ensuring that routine medical services remain unaffected. However, it was found that the distribution of large exhibition halls and municipal-level sports venues converted into temporary hospitals in Shanghai is uneven, leading to service deficiencies in certain areas. From the perspective of the "resilient city" theory, which emphasizes maintaining urban functionality during disasters, to address these underserved regions, consideration should be given to supplementing and renovating local school gymnasiums and community activity centers to increase emergency bed supply. This approach aligns with the goal of enhancing urban resilience by ensuring a more comprehensive and accessible emergency medical service system. Simultaneously, there should be a zonal assessment of the emergency capabilities of various RMFs, determining the number of

beds per thousand people post-renovation, to formulate comprehensive emergency plans ensuring rapid response during crises.

5.2.2. Integrating "Peacetime–Pandemic Integration" into Design

In line with the "resilient city" theory, which values adaptability and flexibility in urban infrastructure, the design and layout of large public service facilities must fully consider their potential as emergency medical facilities. When constructing or renovating large public buildings, pre-planning for their conversion into emergency hospitals should include considerations such as design flexibility, optimized ventilation systems, and contingency plans for switching between peacetime and pandemic states. This ensures a seamless transition between daily operations and emergency use. In terms of location, special attention should be paid to areas far from the city center where emergency medical resources are relatively scarce, ensuring these facilities meet regular service demands while providing necessary emergency support during crises. Through scientific and reasonable planning, taking into account both the functionality of the facilities and the convenience of residents' emergency medical treatment, we can enhance the overall risk-resistance capacity of the city, which is a fundamental goal of resilient city construction. This also provides an experience model for other cities worldwide.

5.3. Limitations and Prospects

This study proposes the concept of "resilient medical facilities" (RMFs) based on resilience theory, aiming to provide a comprehensive analytical framework for responding to sudden public health emergencies. Through this framework, not only can the spatial allocation of RMFs in megacities be evaluated, but a scientific and precise evaluation methodology can also be provided, filling gaps in existing research. The framework emphasizes the importance of spatial layout to ensure rapid response and coverage of medical resources during emergencies. It also highlights how large public buildings (such as exhibition centers and sports venues) can be converted into temporary emergency hospitals to achieve effective triage of patients, thereby reducing pressure on existing medical systems. This contribution deepens our understanding of RMFs and offers valuable references for urban planners and policymakers worldwide.

However, the study acknowledges certain limitations and areas for improvement. Firstly, regarding the optimal scale of temporary emergency hospitals, there is currently no clear guiding principle, which directly impacts the assessment of bed supply in RMFs. Future research should aim to explore the optimal scale range to ensure both emergency needs are met and resource waste is minimized. Moreover, beyond physical bed supply, incorporating medical personnel into accessibility indicators is essential. Even with adequate hardware facilities, insufficient numbers of professional healthcare staff would greatly diminish actual emergency response capabilities. Therefore, exploring comprehensive resource allocation, including that of medical professionals, is crucial for accurately assessing and enhancing a city's ability to respond to pandemics, contributing to the establishment of a more comprehensive and effective resilient medical system.

Additionally, we emphasized large exhibition centers and sports venues, drawing on the experience from the COVID-19 period. While these facilities have proven to be effective during the pandemic, future public health emergencies may present different scenarios. There are other potential facilities that could serve as RMFs, such as large-scale hotels and unused office buildings. These facilities may have different spatial distributions, conversion costs, and service capabilities compared to exhibition centers and sports venues. Their inclusion in the study could potentially change the research findings. Future research

should investigate these additional facilities to offer a broader perspective on the spatial allocation of RMFs.

Finally, in the current study, we focused on evaluating the spatial allocation of RMFs. However, it is crucial to note that emergency medical facilities do not function in isolation. They should be used in conjunction with hospital beds. To better understand the comprehensive impact, future research could include an additional experiment. This experiment would compare the results of spatial accessibility and equity evaluations when incorporating hospital beds into the analysis versus not incorporating them. Such a comparison can help identify the differences and potential deviations in the assessment of RMF spatial allocation, providing a more accurate and comprehensive understanding of the overall emergency medical service system.

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