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Intercity patient mobility can improve healthcare accessibility and equality in metropolitan areas: A case study of Shenzhen metropolitan area, China

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ABSTRACT

Healthcare accessibility and equality have attracted extensive attention, but few in metropolitan areas, which are characterized by intense intercity connections. Despite of the policy focus on intercity patient mobility in metropolitan areas, the quantitative impact of intercity patient mobility on healthcare accessibility and equality remains understudied. This study develops a comprehensive framework to quantify such impacts by comparing two scenarios (i.e., intercity and intracity) of accessibility to existing and optimized healthcare services. A two-step optimization method, integrating efficiency and equality, is applied to optimize healthcare resources. These analyses are conducted within the context of the Shenzhen metropolitan area. The results reveal that intercity patient mobility can improve efficiency and equality of healthcare accessibility to existing services by 8% and 6%, respectively. Furthermore, optimization that considers intercity patient mobility can improve healthcare accessibility efficiency and equality by 37% and 19% compared to the status quo. The framework and methods developed in this study are valuable for measuring and optimizing healthcare accessibility in metropolitan areas, which is transferrable to other areas with significant regional disparity. This study also provides quantitative evidence of the positive effects of intercity patient mobility on healthcare efficiency and equality in metropolitan areas, which is fundamental for policymaking and planning.

1. Introduction

Residents' health is among the most important goals for socio-economic development of cities and regions. The United Nation's Sustainable Development Goals (SDGs) highlight the importance of health and well-being in "Goal 3: Ensure healthy lives and promote well-being for all at all ages". The access to and utilization of healthcare services are widely considered critical determinants of good health. Spatial accessibility is a concept widely leveraged to assess the distribution of facilities (e.g., healthcare facilities), which is defined as the potential opportunities for residents living in various places to access healthcare facilities (Wang, 2012). Healthcare spatial accessibility can influence residents' healthcare-seeking decisions, their utilization of healthcare services, and their health outcomes (Chang et al., 2023; Shen & Tao, 2022). However, a mass of studies have revealed significant spatial disparity and inequality in healthcare accessibility at various spatial scales (e.g., communities, cities, countries, or global) and across different regions (e.g., developed or underdeveloped countries, urban or rural) (Boisjoly et al., 2020; Jin et al., 2015; Kim et al., 2020; Mao & Nekorchuk, 2013; Weiss et al., 2020; Zafri et al., 2021; Zhao et al., 2020). This inequality in healthcare accessibility poses a fundamental challenge to achieving the objective of "health for all" in SDG 3.

A metropolitan area is a kind of functional urban area, encompassing densely populated urban centers and their surrounding areas, characterized by intensive socio-economic connections and population mobility (Moreno-Monroy et al., 2021). Though the definition and delineation of a metropolitan area vary by country, a typical metropolitan area usually consists of multiple municipalities (Dadashpoor & Malekzadeh, 2022). Regional disparity also exists in socio-economic development across the cities within a metropolitan area (Essletzbichler, 2015; Lee, 2011; Musterd et al., 2020). In China, administrative divisions (e.g., prefecture cities) are fundamental spatial units for governing socio-economic development and policymaking, while a metropolitan area is practically defined as the urban region centered around a mega city (with a population of 5 million or more) within a 1-h commuting distance to urban centers (National Development and Reform Commission, 2019). Healthcare resources and the administration of medical insurance are mainly managed within each municipality (Yan

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et al., 2022). Against this background, the equalization of healthcare and other public services is one of the key objectives in the planning and governance of metropolitan areas (National Development and Reform Commission, 2019).

Uneven distribution of healthcare services can prompt patients to travel beyond municipal boundaries to obtain high-quality healthcare services (Zhang et al., 2023). Such inter-regional movement of patients is termed as patient mobility (Balia et al., 2018; Zhang et al., 2023). Researchers have examined the patterns of healthcare resources and patient mobility within a city. It is commonly observed that healthcare facilities tend to concentrate in the city center or sub-centers with higher population density, while the intracity dynamics of patient mobility exhibits a centripetal tendency (Wang et al., 2020; Xing & Ng, 2022). In recent years, with the reform of the medical system and the improvement in transportation efficiency, intercity patient mobility has developed rapidly in China. It is estimated that nonlocal medical treatments accounted for about 7.9% of total treatments from 2014 to 2017 (NHC, 2019). The increasing intercity patient mobility has reshaped how residents utilize healthcare services, affecting the spatial matching between healthcare demand and supply, and influencing the efficiency and equality of healthcare services (Yan et al., 2022). However, intercity patient mobility still faces great institutional, socio-economic or spatial barriers (Zhang et al., 2022).

Notably, it still lacks quantitative evidences on how intercity patient mobility influences healthcare accessibility and equality. In metropolitan areas, the existence of intense intercity connections highlights the necessity to investigate the potential impacts of intercity patient mobility. Understanding these impacts is fundamental for informing policymaking and effectively allocating healthcare resources. To our best knowledge, previous studies have only paid limited attention to the impacts of intercity patient mobility on the utilization of existing healthcare services, leaving the potential impacts on the optimization and planning of healthcare facilities largely unexplored.

Aiming to fill the above research gaps, **this study attempts to quantitatively answer the following two questions** with a case study of the Shenzhen metropolitan area, China: **(1) What are the potential impacts of intercity patient mobility on accessibility to existing healthcare services in a metropolitan area? (2) How will the optimized configuration of healthcare services differ in terms of efficiency and equality when considering intercity patient mobility?** Spatial accessibility to healthcare services is measured by two complementary methods, namely, the travel time to the nearest facility method and the enhanced two-step floating catchment area (2SFCA) method. Optimization analyses are conducted using a two-step optimization method to balance efficiency and equality objectives.

2. Relevant studies

2.1. Intercity patient mobility: patterns, determinants and effects

Patient mobility is defined as the medical-seeking behavior of patients beyond their places of residence to obtain healthcare services (Balia et al., 2018; Zhang et al., 2023). Patient mobility occurs at various spatial scales, e.g., intracity (Gu et al., 2023), intercity (Li et al., 2021), interprovince (Koylu et al., 2018; Yan et al., 2022), and even cross-border (Glinos et al., 2010; Migge & Gilmartin, 2011). According to the National Health Commission of the People's Republic of China (2021), the five regions with the largest inflow of patients in 2019 were Shanghai, Beijing, Jiangsu, Zhejiang, and Guangdong.

There have been numerous studies discussing the determinants of patient mobility. Balia et al. (2018) found that driving factors of patient mobility include regional income, hospital capacity, organizational structure, performance and technology. Glinos et al. (2010) identified four types of patient motivations, namely availability, affordability, familiarity, and perceived service quality. A consensus among previous studies suggests that disparities in the quantity and quality of healthcare system are major determinants of patient mobility. Patients tend to flow from areas with fewer and lower-quality healthcare services to areas where high-quality healthcare services concentrate (Zhang et al., 2023), moderated by a significant distance decay effect (Jia et al., 2019). Developed and central cities often play a leading role in providing healthcare services and treatments, thereby attracting external patient mobility (Glinos et al., 2010; Li et al., 2021).

In China, patient mobility is influenced by both push and pull factors (Yan et al., 2022). Under China's strict hierarchical administrative management system, high-quality healthcare services concentrate in large cities (Zhao et al., 2020), attracting patients from small cities and rural areas to seek healthcare services across cities. Despite decades of healthcare reform in China, nonlocal medical insurance reimbursement continues to face barriers such as slow settlement, complex processes and low reimbursement amounts, posing obstacles to patient mobility (Zhang et al., 2022).

Patient mobility reshapes the utilization and outcomes of healthcare services in terms of efficiency and equality. First, patient mobility can improve the utilization of medical resources (De Nicola et al., 2014), promote hospitals to upgrade and innovate through competition (Balia et al., 2018), potentially enhancing the efficiency of the healthcare system. However, some discussions have noted that patient mobility might impose additional burdens to local medical insurance systems, especially under imperfect medical insurance policies (Legido-Quigley et al., 2007).

There remains an ongoing debate regarding whether patient mobility can promote healthcare equality in existing studies (Aggarwal et al., 2017). On one hand, Zhang et al. (2023) observed that patient mobility improves healthcare equality and that patient mobility policies have a synergistic effect with intercity transportation. On the other hand, some studies revealed negative impacts of patient mobility on equality. In areas with a positive net inflow of patients, patient mobility not only directly intensifies competition for resources (Snyder et al., 2013), but also indirectly causes negative impacts such as healthcare price premium (Turner, 2007). In areas experiencing patient outflow, disparity in different transportation conditions (Zhang et al., 2023) and socio-economic attributes (Beukers et al., 2014; Exworthy & Peckham, 2006; Migge & Gilmartin, 2011) can lead to inequality in mobility and, consequently, healthcare equality. Moreover, Brekke et al. (2016) found that patient mobility negatively influences healthcare quality in low-income areas, exacerbating regional disparity in healthcare quality.

2.2. Measurement and optimization of healthcare accessibility and its equality

Accessibility of healthcare facilities can be interpreted across various dimensions (Penchansky & Thomas, 1981; Zafri et al., 2021), including proximity (related to physical location), availability (considering supply-demand relationship), affordability, accommodation and acceptability. These dimensions of accessibility have been measured through various methods. For example, Zafri et al. (2021) calculated the coverage of population based on buffer zones around healthcare facilities. Israel (2016) noted a disparity in the financial affordability of healthcare services among various income groups, encompassing both direct and indirect costs. Hodge et al. (2017) examined the digital interactions between service providers and the elderly facilitated by communication technology, relevant to the accommodation dimension.

Notably, among numerous accessibility indicators, spatial accessibility is widely used to explore the spatial pattern of healthcare accessibility, primarily due to its quantifiable nature (McGrail & Humphreys, 2009). Generally, proximity and availability are the two key dimensions of spatial accessibility (Luo et al., 2017; McGrail & Humphreys, 2009; Wang, 2012). Previous studies found that spatial proximity is a primary concern for patients using healthcare facilities (Luo et al., 2017). Proximity is typically measured by the travel distance or time to the nearest facility (Wang, 2012; Yang et al., 2006). However, this method overlooks factors like facility capacity, competition for demand, and the possibilities of visiting multiple facilities. The two-step floating catchment area (2SFCA) method, first proposed by Radke and Mu (2000) and further improved by Luo and Wang (2003), comprehensively considers the interactions between supply and demand on accessibility. Due to its strong practicality and operability, the 2SFCA has been widely applied. Furthermore, researchers extended 2SFCA by considering various factors, including distance decay functions (Wang, 2012), catchment areas (Tao et al., 2020), and travel modes (Mao & Nekorchuk, 2013). Additionally, Wan et al. (2012) pointed out that, the competitive effect between supply facilities should be considered, and proposed a three-step calculation method named 3SFCA.

Equality and equity are two closely related but distinct concepts. Equality focuses on equal opportunities for all people, while equity emphasizes additional support for disadvantaged groups to achieve the same outcomes. According to existing studies, equality is easier to quantify (Culyer & Wagstaff, 1993). Disparities in healthcare accessibility across locations or among various socio-economic groups are widely recognized as indicator of (in)equality in healthcare services (Alam et al., 2023; Gu et al., 2023; Jin et al., 2015; Lu et al., 2019). Recent years have witnessed an increasing attention on inequality of healthcare accessibility at various spatial scales (Jin et al., 2015; Luo & Wang, 2003; Mao & Nekorchuk, 2013; Weiss et al., 2020). At the regional scale, researchers have revealed significantly uneven distribution of medical resources across cities (Alam et al., 2023; Boisjoly et al., 2020; Li & Wang, 2022).

To improve the efficiency and equality of spatial accessibility to healthcare services, a series of spatial optimization models have been developed for optimizing site selection and resource allocation (Li et al., 2017). The location-allocation models are widely used in this regard. These models can be divided into efficiency- and equality-oriented models according to optimization objectives. Classic location-allocation models mainly attempt to enhance efficiency, focusing on improving accessibility or reducing costs, which is reflected in shortening travel distance (the p-median problem) (Drezner & Drezner, 2007), increasing population coverage (the maximum covering location problem, MCLP) (Church et al., 1996) or minimizing facilities number (the location set covering problem, LSCP) (White & Case, 1974). However, there are currently few equality-oriented location-allocation models. Wang and Tang (2013) innovatively proposed the maximal accessibility equality (MAE) model, which solved the equality issue by minimizing the disparity in accessibility. Growing studies have further improved the MAE model by comparing location optimization versus capacity optimization (Li et al., 2017), proposing a hierarchical version of MAE model for allocating hierarchical facilities (Tao et al., 2021), allocating newly-added healthcare resources (Pan et al., 2023), or developing a modified transit-based MAE model considering public transport (Tao & Zhao, 2023).

The trade-off between efficiency and equality has long been a central debate in the location-allocation of healthcare facilities. Luo et al. (2017) proposed the two-step optimization for spatial accessibility improvement (2SO4SAI) model based on sequential decision-making. This model balances efficiency and equality by first selecting facility locations based on efficiency objective and then optimizing facility capacities based on equality objective. The effectiveness of 2SO4SAI model has been demonstrated in multiple cases (Pan et al., 2023; Tian et al., 2019). Following the framework of 2SO4SAI, Wang and Dai (2020) discussed the possibility of combining proximity and availability indicators with efficiency and equality objectives. Looking ahead, research into sequential planning integrating efficiency and equality will be crucial for the rational planning of healthcare services.

2.3. Development of metropolitan areas in China

A metropolitan area is a large urban region consisting of densely populated core cities and their surrounding areas with relatively low population density but strong connections (usually commuting connections) with core cities (Moreno-Monroy et al., 2021). In China, the lack of official commuting statistics renders it challenging to delineate metropolitan areas through commuting ratio (Zhang & Sun, 2023). The National Development and Reform Commission (2019) offered a pragmatic definition of metropolitan area, i.e., an urban region centered around a mega city (with a population of 5 million or more) within a 1-h commuting distance to urban centers.

Existing studies on metropolitan areas mainly focused on spatial distribution of population and jobs, commuting connections and regional transportation infrastructure. For example, Zhang et al. (2019) and Lv et al. (2017) each revealed the phenomenon of employment decentralization in Shanghai and Beijing metropolitan area, potentially linked to regional disparity in job opportunities and resident mobility. Meng et al. (2021) found that highways can contribute to urban sprawl and facilitate the emergence of subcenters in Shanghai metropolitan area. Wang and Zhang (2015) demonstrated that high-speed railways can reduce intercity travel time within metropolitan areas, enhancing intercity human mobility and the optimization of resource allocation across regions.

According to the guidance of National Development and Reform Commission (2019), the co-construction and sharing of public services are among the primary goals in the development plans of metropolitan areas. However, contrary to the numerous studies on the distribution of and accessibility to healthcare services at the intracity-scale, there remains a gap in the accessibility and equality of healthcare services within metropolitan areas. A few studies have noticed the spatial disparity of medical resources at this scale. For example, Hu et al. (2019) revealed an uneven spatial distribution of basic healthcare facilities in Nanjing metropolitan area. Li and Wang (2022) demonstrated that healthcare accessibility analysis at the urban agglomeration scale requires consideration of disparities in the quantity and quality of medical facilities across cities and residents' preferences in choosing hospitals.

To sum up, policymakers and scholars have paid attention to the intercity disparity in healthcare services in metropolitan areas. The Chinese government has proposed initiatives to promote the intercity integration and sharing of healthcare services, and to facilitate intercity patient mobility within metropolitan areas. Given the intense human mobility and socio-economic interactions among cities within the same metropolitan area, it is crucial to quantify the impacts of intercity patient mobility on healthcare accessibility and equality at the metropolitan area-scale. However, there is still a lack of quantitative evidence on the above question. Furthermore, few studies have attempted to optimize healthcare facilities in metropolitan areas with consideration of the impacts of intercity patient mobility.

3. Data and methods

3.1. Study area and data sources

Shenzhen metropolitan area was chosen for our case study. Shenzhen metropolitan area is located in Guangdong Province in Southern China, covering an area of about 15,900 km^2. It is composed of three prefecture cities (Shenzhen, Dongguan and Huizhou), which together encompass 49 districts, including 177 sub-districts (Fig. 1). Since the introduction of the Outline of the Reform and Development Plan for the Pearl River Delta Region (2008–2020), Shenzhen metropolitan area has rapidly developed. By 2021, Shenzhen metropolitan area's GDP was 4852 billion yuan, accounting for 39% of the total GDP of Guangdong Province, with Shenzhen, Dongguan and Huizhou contributing 67%, 22% and 11%, respectively. The 2023 Development Plan for the Shenzhen Metropolitan Area (People' s Government of Guangdong Province, 2023) emphasized the need to promote the co-construction and sharing of public service resources among the cities within the Shenzhen metropolitan area. Previous studies (Yan & He, 2023) have examined the cross-border patient mobility and migration between Shenzhen and

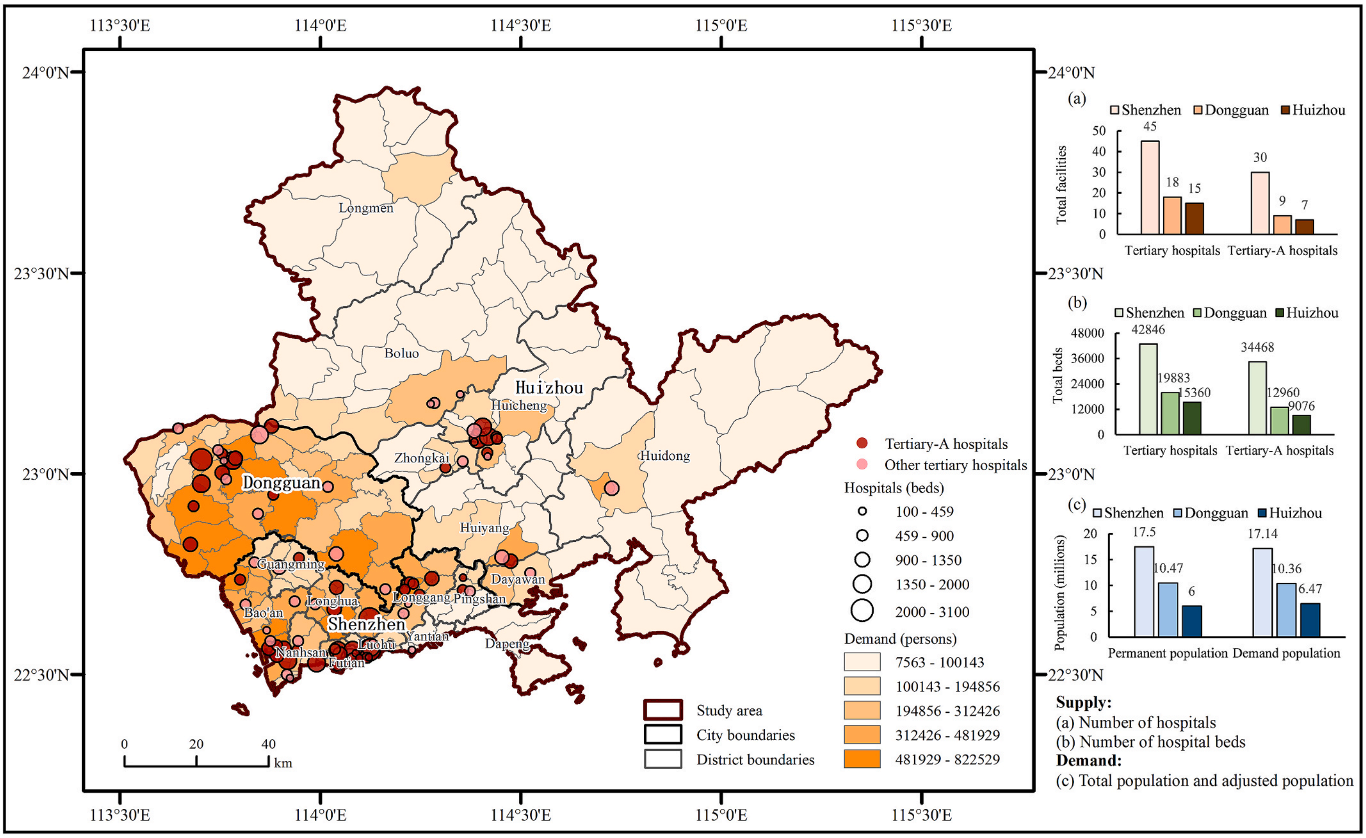

Fig. 1. Distribution of adjusted population and tertiary hospitals.

Hong Kong, regions with different political institutions. They demonstrated that mainland cities and Hong Kong are different in medical insurance systems and residents' perception of healthcare quality. Accordingly, this study focuses on the intercity patient mobility between Shenzhen, Dongguan, and Huizhou.

The data used in this study consisted of three types:

(1) Demand side: sub-district level population data;
(2) Supply side: point-level healthcare facilities with attribute information such as names, hierarchy, number of beds and addresses;
(3) Travel cost: the travel time between each sub-district administrative center to each healthcare facility.

The population data at the sub-district level are collected from the 7th National Population Census of China, including the numbers of permanent residents and the proportions of population across different age groups. By 2020, Shenzhen metropolitan area had a permanent population of about 34.28 million people. Due to the heterogeneity in healthcare demands among various age groups, using total population to represent demand is inaccurate. This study estimates adjusted healthcare demand by considering the age composition of population at each sub-district. Healthcare demand intensity is estimated by the two-week average prevalence rate of each age group. According to the 5th National Healthcare Service Survey Report (NHC, 2013), the two-week prevalence rates of residents ageing 0–14, 15–59, and 60 and above are 0.07, 0.13 and 0.51, respectively. Then the adjusted population is calculated based on the differences in population age composition between each sub-district and the whole metropolitan area. The demand nodes are set as the administrative centers of sub-districts. The demand size of each node is represented by the adjusted population. The calculation process is shown in Equations (1) and (2).

$$H_i = \frac{\sum_n D_{ni} h_n}{\sum_n D_{ni}} \tag{1}$$

where H_i is the average prevalence rate of demand node i, D_{ni} is the population of age group n, h_n is the two-week prevalence rate of age group n. The adjusted population of demand node i can be estimated as:

$$P_i = \frac{H_i}{H_0} \sum_n D_{ni} \tag{2}$$

where P_i is the adjusted population of demand node i, H_0 is average prevalence rate of the metropolitan area. The adjusted population is shown in Fig. 1.

The data of hospitals in 2023 are from the official website of health bureaus in each district and the official website of hospitals. Existing studies (Ding et al., 2023; Zhang et al., 2023) have found that high-quality healthcare resources play a key role in intercity patient mobility. In China, tertiary hospitals are the healthcare facilities with the highest service quality, especially the tertiary-A hospitals. Given this, this study focuses exclusively on tertiary hospitals and tertiary-A hospitals. By 2023, there were 78 tertiary hospitals and 46 tertiary-A hospitals in Shenzhen metropolitan area. There is significant spatial heterogeneity in the distribution of hospitals within the Shenzhen metropolitan area (Fig. 1). Shenzhen has the largest number of hospitals. Large-size tertiary hospitals are mainly concentrated in the southern and northern parts of Shenzhen, the northwest of Dongguan, and the central area of Huizhou.

The travel cost was measured by the travel time between each demand node and hospital. In China, the navigation Application Programming Interface (API) of Baidu Map allows researchers to obtain reliable and accurate estimations of travel time based on diverse travel modes, transport networks and traffic conditions (Tao & Zhao, 2023).

Considering that driving is a primary transport mode for patients to travel across cities, and that intercity public transport is still less developed, as well as that intercity public transport is not available in Baidu Map API, this study used driving navigation API to obtain travel time.

3.2. Research framework

This study is grounded on four key assumptions of patients' behavior (Fig. 2). Behavior assumption 1 and 2 focus on intercity patient mobility, while behavior assumption 3 and 4 focuses on the patients' choice of healthcare facilities.

The study analyzed the impact of intercity patient mobility on healthcare accessibility by comparing two scenarios, i.e., intracity scenario and intercity scenario. In the **intracity scenario**, all mobilities across cities were prohibited. It was supported that patients could only seek medical treatment within the city they reside in. Conversely, in the **intercity scenario**, it was supported that patient could freely commute across cities to seek medical treatment at all hospitals within the metropolitan area. We first measured healthcare accessibility in terms of proximity and supply-demand ratios (Penchansky & Thomas, 1981) in the two proposed scenarios. Second, the two-step optimization for spatial accessibility improvement (2SO4SAI) model was applied to optimize the distribution of healthcare facilities towards both efficiency and equality (Luo et al., 2017) in two scenarios. The proximity measures and p-median model (Drezner & Drezner, 2007) are based on the assumption that patients only choose the nearest healthcare facility for service. The supply-demand ratios measures (Wang, 2012) and MAE model (Wang & Tang, 2013) are based on the assumption that patients select facilities within a defined catchment area, with a selection probability that decreases in accordance with the distance decay effect.

Comparative analysis of the outcomes elucidated the influence of intercity patient mobility on the existing and optimized state of healthcare accessibility and equality, respectively.

3.3. Methods

3.3.1. Accessibility measures

This study first measured the proximity of healthcare services by the distance to the nearest facility method, i.e., the travel time from each demand node to the nearest hospital. Then, the Enhanced 2SFCA method is applied to measure the supply-demand ratio of healthcare services, which can be written as (Wang, 2012):

$$A_i = \sum_{j \in \{d_{ij} \le D_0\}} \frac{S_j f(d_{ij}, D_0)}{\sum_{k \in \{d_{kj} \le D_0\}} P_k f(d_{kj}, D_0)} \tag{3}$$

where A_i is the accessibility of demand node i, S_j is the capacity (number of beds) of facility j, P_k is the adjusted demand population of demand node k, d_{ij} is the travel time between demand node i and facility j, D_0 is the size of catchment area, and f is a distance decay function. In this study, the Gaussian function was adopted to model the distance decay

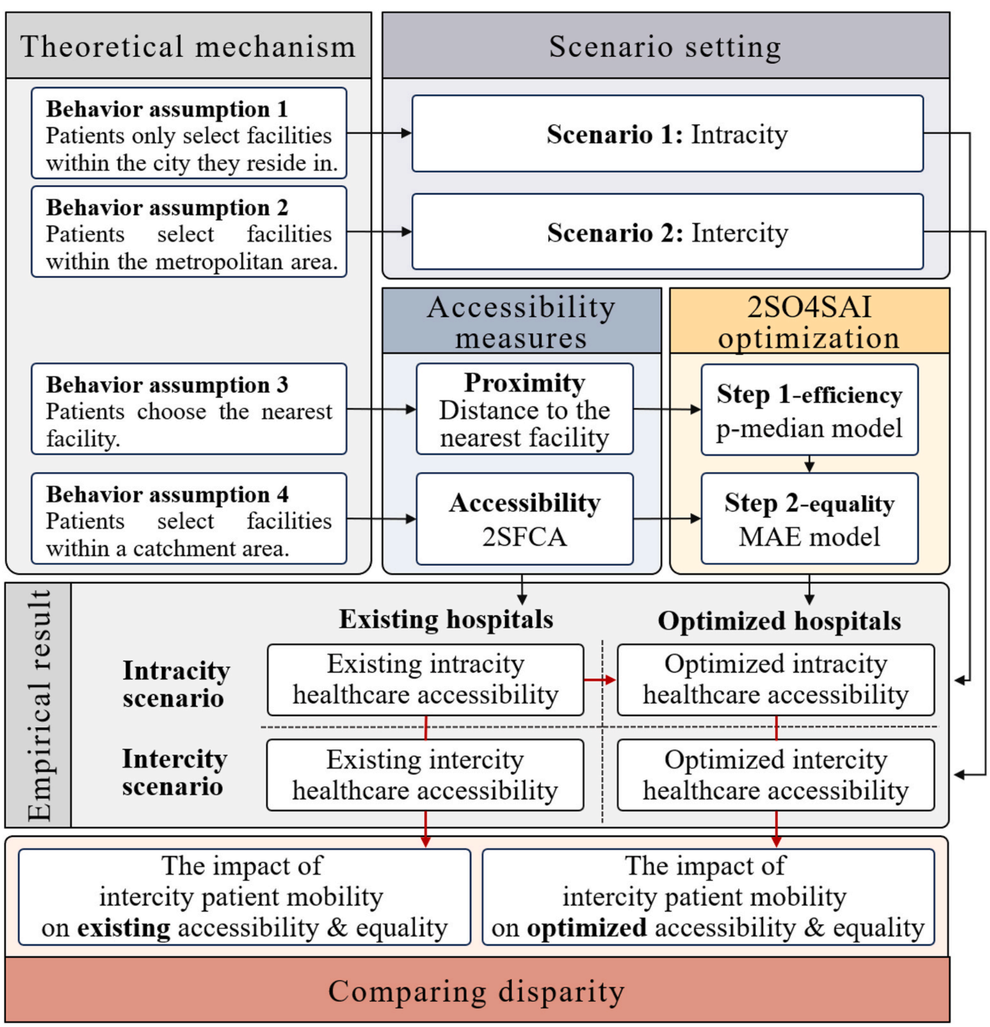

Fig. 2. The research framework in this study.

effects, which can be formulated as:

$$f(d_{ij}, D_0) = \begin{cases} \dfrac{e^{-1/2\times(d_{ij}/D_0)^2} - e^{-1/2}}{1 - e^{-1/2}}, d_{ij} \le D_0 \\ 0, d_{ij} > D_0 \end{cases} \tag{4}$$

where D_0 is the only one parameter in Gaussian function, usually set as the threshold travel distance. In this study, D_0 was set as the maximum travel time from each demand node to the nearest hospital, so that each demand node could access at least one hospital within the catchment area (Tao et al., 2020).

3.3.2. The two-step optimization for spatial accessibility improvement method

Following the 2SO4SAI method (Luo et al., 2017; Tian et al., 2019), this study conducted spatial optimization by two steps to balance efficiency and equality goals:

Step 1: Site selection, i.e., selecting the sites of the new hospitals by the p-median model aiming to achieve the efficiency goal;
Step 2: New-supply allocation, i.e., allocating the newly-added healthcare resources by the maximal accessibility equality (MAE) model.

The p-median model selects a given number of facilities from a set of candidate facility sites, in order to minimize the total distance between all demand nodes and the nearest facility (Luo et al., 2017). The p-median model formulation can be written as:

$$\text{Minimize}: Z = \sum_i \sum_j h_i d_{ij} Y_{ij} \tag{5}$$

$$\text{Subject to}: \sum_j X_i = P, \forall j \tag{6}$$

$$\sum_j Y_{ij} = 1, \forall i \tag{7}$$

$$Y_{ij} - X_i \le 0, \forall i, j \tag{8}$$

$$X_j \in (0, 1), \forall j \tag{9}$$

$$Y_{ij} \in (0, 1), \forall i, j \tag{10}$$

where h_i is the adjusted demand population of demand node i, d_{ij} is the travel time from demand node i to facility j, P is the number of facilities to be located. Y_{ij} is an intermediate variable, which is 1 if facility j is selected by demand node i, or 0 otherwise. X_j is the decision variable to be solved, which is 1 if candidate site j is selected to configure facilities, or 0 otherwise.

The MAE model aims to maximize the equality by minimizing the disparity of accessibility. This study used the weighted mean absolute deviation indicator to measure accessibility disparity across all demand nodes (Tao & Zhao, 2023). As argued by existing studies (Tao & Zhao, 2023), reallocating existing resources among all facilities is infeasible for healthcare planning practice, whereas allocating newly-added resources among facilities (both existing and newly-planned facilities) can better inform decision making. The MAE model for allocating newly-added resources can be written as (Tao & Zhao, 2023):

$$\text{Minimize}: WMAD = \frac{\sum_i^n P_i |A_i - \overline{A}|}{\sum_i^n P_i} \tag{11}$$

$$\text{Subject to}: \sum_j^m IS_i = IS_{total} \tag{12}$$

$$IS_{min} \le IS_j \le IS_{max}, \forall j \tag{13}$$

$$S_j = IS_j + AS_j, \forall j \tag{14}$$

where A_i is the accessibility of demand node i, which is calculated by Equation (3). $\overline{A}$ is the population-weighted average accessibility of all demand nodes, which equals the ratio of total supply to total demand for 2SFCA-based accessibility. P_i is the adjusted demand population of demand node i, IS_j is the newly-added supply at facility j, IS_{total} is the total supply that is intended to add, IS_{min} and IS_{max} are the lower and upper bounds of the newly-added supply at each facility, respectively, AS_j is the actual supply at facility j, and S_j is the total supply at facility j. The MAE model was solved by using the particle swarm optimization (PSO) algorithm, which has been verified in existing studies (e.g., Tao et al., 2021).

Several parameters are needed in the application of 2SO4SAI. First, the number and locations of candidate sites needed to be specified. This study selected existing non tertiary-A hospitals in the study area as candidate sites for optimization. There were 66 primary, secondary, and tertiary hospitals considered as candidate sites in total. Second, the number of newly-added hospitals (P in Equation (5)) was determined based on the Guiding Principles for the Planning of Medical Institution Setting (2021–2025) (NHC, 2022a) and the 14th Five Year Plan for the Health Industry of three cities. 9 tertiary-A hospitals were added to Shenzhen metropolitan area in total. Specifically, for intracity optimization, the numbers of newly-added hospitals in Shenzhen, Dongguan and Huizhou were 1, 5 and 3, respectively. Third, the total number of newly-added beds (IS_{total} in euqation (6)) was determined by referring to the Guiding Principles for the Planning of Medical Institution Setting (2021–2025) (NHC, 2022a), which gives the standards on healthcare service provision according to populatiton. There were 1390, 3952, and 193 beds to be added to tertiary-A hospitals in Shenzhen, Dongguan and Huizhou, respectively. Fourth, in Equation (6), IS_{min} and IS_{max} were set as 0 and 1000 beds, respectively. It not only ensured that S_j was not lower than AS_j but also avoided excessive concentration of resources on a small proportion of facilities. As our analyses will demonstrate, intercity patient mobility has a more significant impact on the accessibility to tertiary-A hospitals than tertiary hospitals. Therefore, only tertiary-A hospitals were considered in the optimization analyses.

3.3.3. Equality evaluation

The Lorenz curve and the Gini coefficient (GC) have been widely used to measure the equality of healthcare accessibility. Considering the difference in population among demand nodes, this study drew the

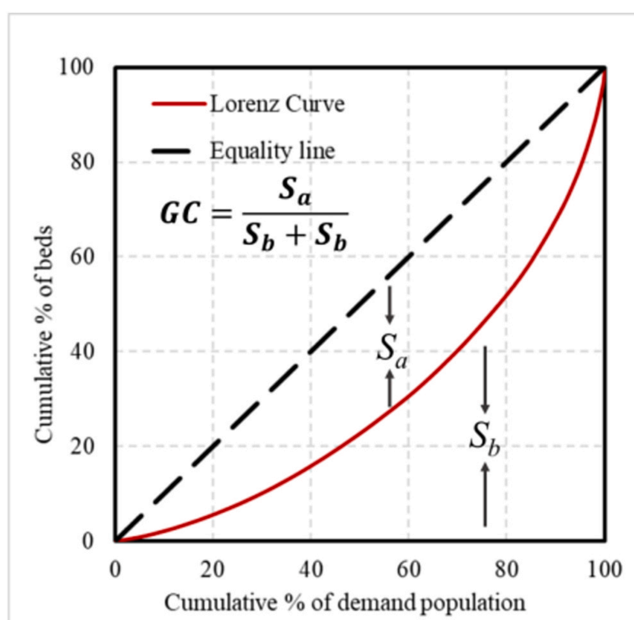

Fig. 3. Illustration of Lorenz curve and Gini coefficient.

Lorenz curve with the cumulative percentage of population instead of the number of demand nodes as the horizontal axis (Fig. 3). The equality line represents the ideal state that accessibility is absolutely equal across all demand nodes. The degree of curvature of the Lorenz curve represents the degree of accessibility equality. The closer the Lorenz curve is to the equality line, the smaller the inequality in accessibility. A greater value of the Gini coefficient indicates a lower accessibility equality.

4. Results

With the data and methods described above, two scenarios (i.e., intercity and intracity) of accessibility to existing and optimized newly-added healthcare services are calculated and compared. Section 4.1 and section 4.2 answer the first question, namely the potential impacts of intercity patient mobility on accessibility to existing healthcare services in Shenzhen metropolitan area. Section 4.3 analyzes the differences between the optimized allocations of healthcare services with or without intercity patient mobility, further answering the second question.

4.1. Healthcare accessibility in the intracity scenario

In the intracity scenario, patients are confined to visit local hospitals. As shown in Fig. 4, the travel time to the nearest hospital is relatively long. The travel time to the nearest tertiary hospital from all sub-districts in Shenzhen is under 35 min (Fig. 4a). In contrast, 37% of the sub-districts in Huizhou require commuting over 40 min to reach the nearest tertiary hospital, with the maximum travel time extending to 66 min.

In Shenzhen metropolitan area, tertiary-A hospitals are unevenly distributed in three cities (Fig. 4b). In Shenzhen, 67% of tertiary hospitals are tertiary-A hospitals, compared to 50% in Dongguan and 47% in Huizhou. The travel time to the nearest tertiary-A hospital is more unequal than that to the tertiary hospital. This difference is more obvious in areas near city boundaries. In Shenzhen, the travel times to two types of hospitals are similar. However, the distribution of tertiary-A hospitals in Dongguan and Huizhou is more uneven compared to tertiary hospitals. The travel time to the nearest tertiary-A hospital is longer than that to the tertiary hospitals in the eastern Dongguan and most areas of Huizhou.

The distance to the nearest facility method assumes that patients exclusively utilize the nearest hospital, whereas accessibility calculated by 2SFCA better reflects the patient's access to medical resources provided at potential hospitals. The average accessibility to tertiary hospitals in Shenzhen, Dongguan, and Huizhou is 2.5, 1.9, and 2.0 beds/thousand people, respectively. The average accessibility to tertiary-A hospitals in three cities is 2.0, 1.3, and 1.2, respectively. The accessibility based on 2SFCA varies significantly between cities, and Shenzhen has the highest overall healthcare accessibility.

As Fig. 5 shows, regardless of the level of hospital, the healthcare accessibility decreases from the city center to the peripheral areas in all cities. There is a noticeable disparity at the junction where the boundaries of the prefecture cities intersect, significantly affecting intercity healthcare accessibility inequality. The central area of Shenzhen has the highest accessibility to tertiary-A hospitals (Fig. 5b). An interesting observation is that the highest accessibility to tertiary hospitals appears in the central area of Huizhou, rather than Shenzhen (Fig. 5a). Compared to Shenzhen, Huizhou has a smaller demand population, which results in a larger supply-demand ratio. Similarly, even though there are more hospitals in Dongguan than in Huizhou, their distribution is relatively scattered. Moreover, the demand population in Dongguan is larger. Thus, Dongguan has the lowest healthcare accessibility. This finding highlights the importance of considering patient's choices of various hospitals when estimating healthcare accessibility.

4.2. Differences in healthcare accessibility and equality between two scenarios

In the intercity scenario, patients were assumed to select facilities within the metropolitan area. Patients from the eastern and southern part of Dongguan can travel to Shenzhen to seek healthcare services, and patients from the northwest of Huizhou can seek services in Dongguan. Fig. 6 visualizes the differences in travel time to the nearest healthcare facility between the intercity and intracity scenarios. The travel time to the nearest tertiary hospital can be shortened in 5 sub-districts by allowing for intercity patient mobility. The maximum reduction in travel time is 31 min. More obviously, 14 sub-districts (8% of all sub-districts) can experience reduction in travel time to tertiary-A hospitals in the intercity scenario, and the maximum reduction is up to 52 min (Fig. 6b). Significant improvements in proximity to tertiary-A hospitals are observed primarily in the northwest of Huizhou and the southeast of Dongguan. The above findings suggest that intercity patient mobility can enhance the efficiency of healthcare accessibility.

Compared with the results in the intracity scenario, healthcare accessibility shows a different pattern in the intercity scenario. As shown in Fig. 7, high accessibility appears in the border areas of three cities. In these areas, the demand population is relatively low and the distances to tertiary and tertiary-A hospitals are moderate. The fringe areas in the northern, eastern, and southern Huizhou have the lowest accessibility.

Fig. 8 visualizes the differences between the 2SFCA-based accessibility in the intercity and intracity scenarios. Improvements of accessibility are mainly observed in the junction areas of three cities and the

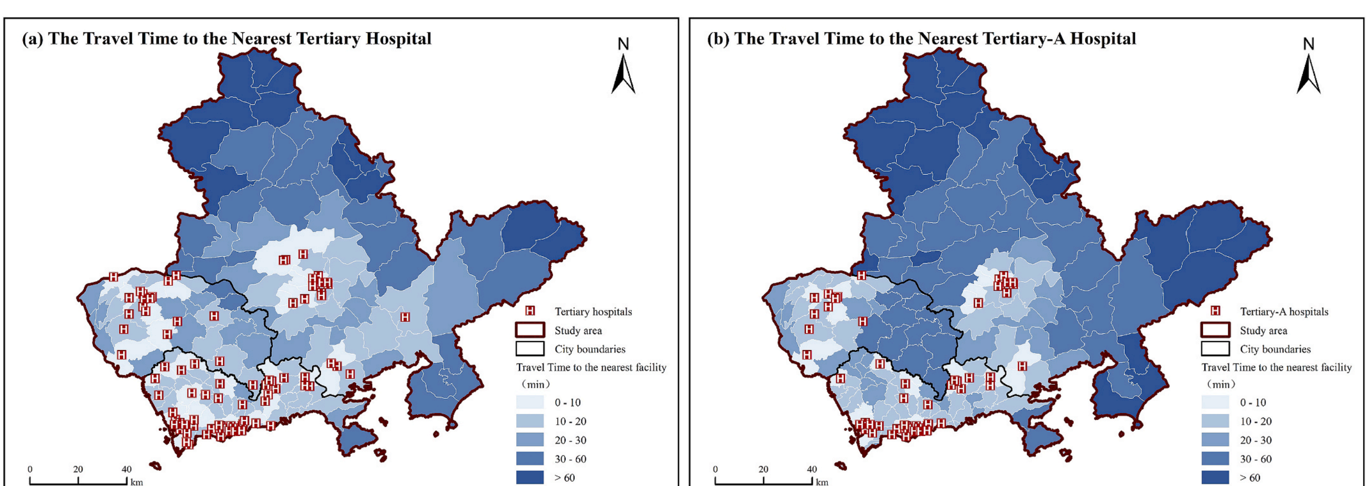

Fig. 4. Travel time to the nearest tertiary and tertiary-A hospitals in the intracity scenario.

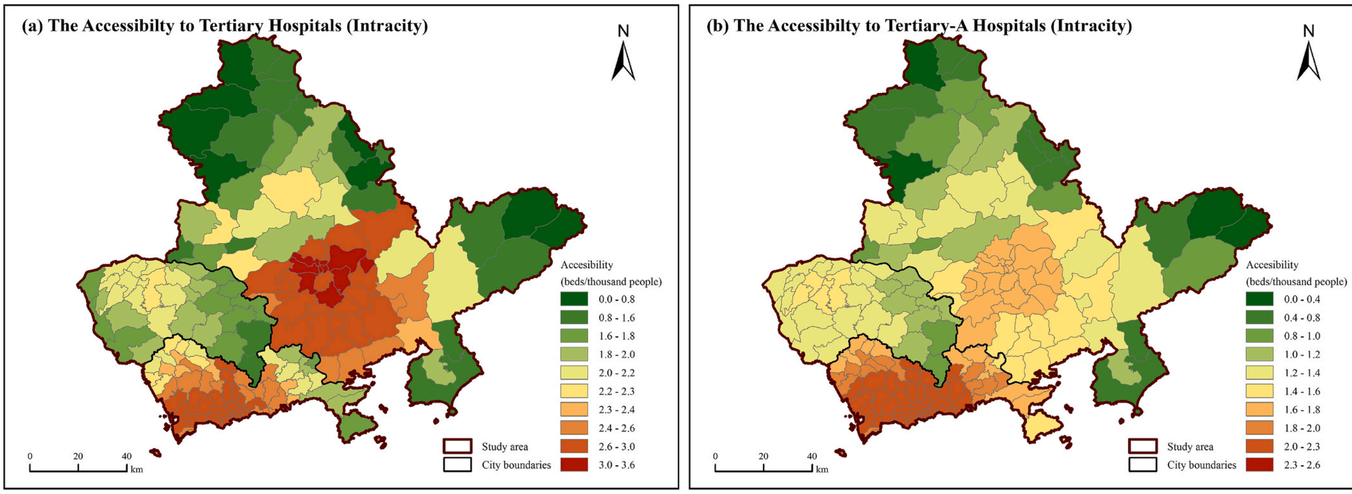

Fig. 5. 2SFCA-based healthcare accessibility to tertiary and tertiary-A hospitals in the intracity scenario.

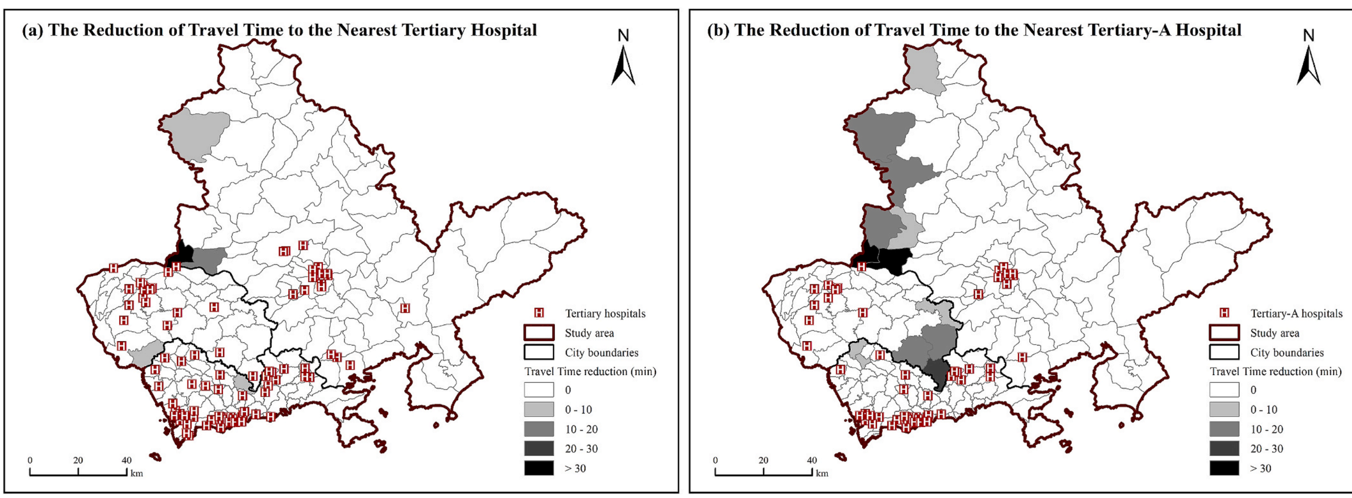

Fig. 6. The differences in the travel time to the nearest tertiary and tertiary-A hospitals between the intercity and intracity scenarios.

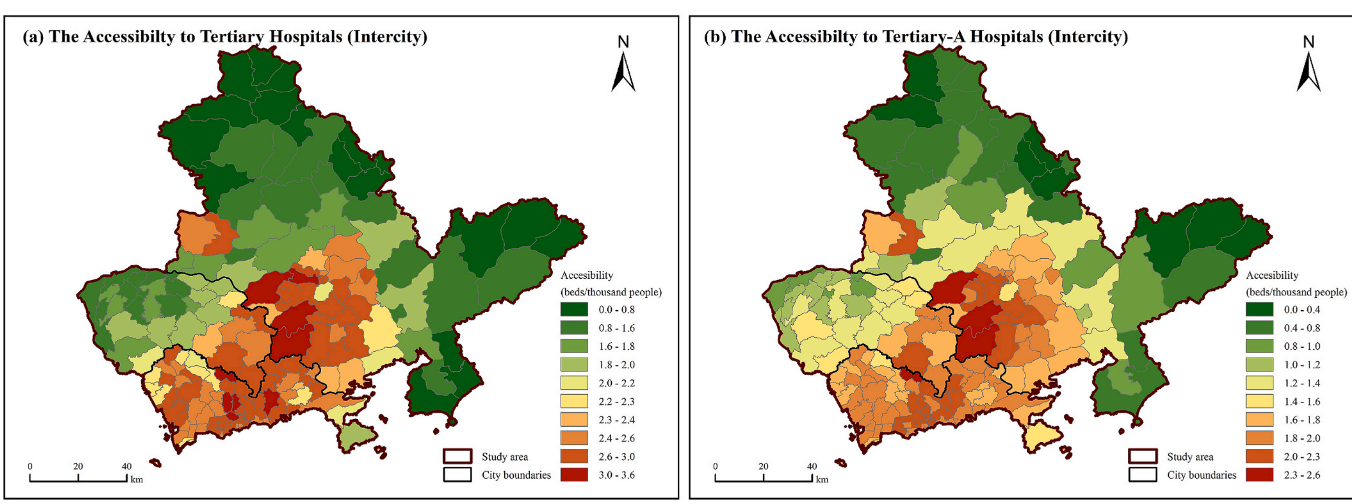

Fig. 7. 2SFCA-based healthcare accessibility to tertiary and tertiary-A hospitals in the intercity scenario.

western part of Huizhou adjacent to Dongguan. Sub-districts showing improved accessibility to tertiary and tertiary-A hospitals account for 44% and 40%, respectively. The average changes in accessibility to tertiary hospitals in Shenzhen, Dongguan and Huizhou are 6%, -15% and -3%, respectively. The average changes in accessibility to tertiary-A hospitals in Shenzhen, Dongguan and Huizhou are -4%, 5%, and 4%,

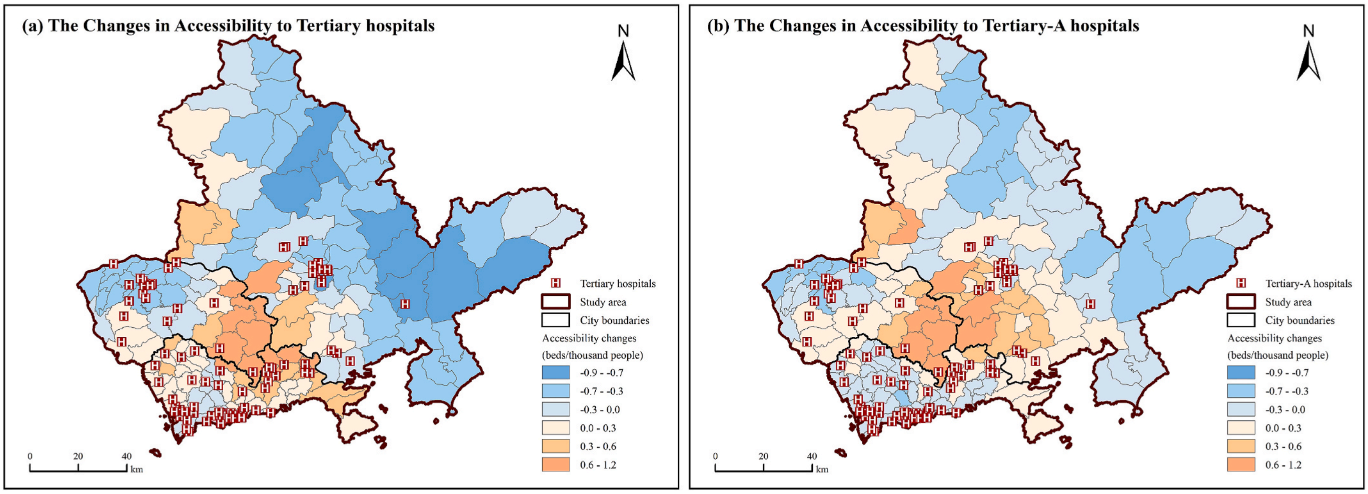

Fig. 8. The impact of intercity patient mobility on the 2SFCA-based healthcare accessibility to tertiary and tertiary-A hospitals.

respectively. The improvement in accessibility to tertiary hospitals is concentrated in the junction areas of three cities (Fig. 8a), while the improvement in accessibility to tertiary-A hospitals is mainly found in the western part of Huizhou and the eastern part of Dongguan (Fig. 8b). The above results demonstrate Shenzhen's advantages in high-quality healthcare resources. Intercity patient mobility will facilitate the cooperation and sharing of high-quality healthcare services within Shenzhen metropolitan area.

Based on the accessibility measured by 2SFCA, we plotted the Lorenz curve and calculated the Gini coefficient (Fig. 9). The Gini coefficients across all scenarios are below 0.15, indicating a relatively high healthcare equality in Shenzhen metropolitan area. In the intracity scenario, the Gini coefficient for tertiary hospitals (0.107) is lower than that for tertiary-A hospitals (0.140), indicating a lower equality of high-quality resources in the current city-based configuration of healthcare services.

The Gini coefficient for tertiary-A hospitals is 6.4% lower in the intercity scenario (0.131) than that in the intracity scenario (0.140). These results suggest that intercity patient mobility can improve the equality of high-quality healthcare services (i.e., tertiary-A hospitals). By contrast, when intercity patient mobility is encouraged, the equality

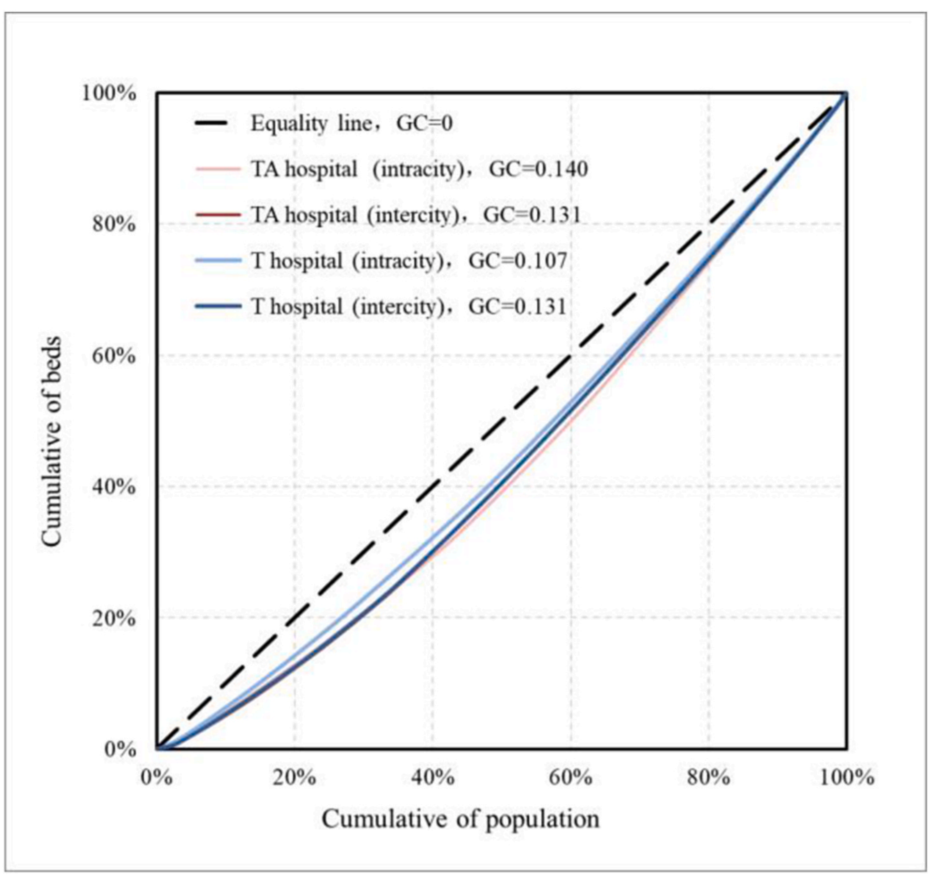

Fig. 9. The impact of intercity patient mobility on healthcare accessibility equality ('TA hospital' refers to tertiary-A hospital, 'T hospital' refers to tertiary hospital, the same below).

of accessibility to tertiary hospitals decreases, with the Gini coefficient increases from 0.107 in the intracity scenario to 0.131 in the intercity scenario. According to the behavior assumption 2 (Fig. 2), the denser population in eastern Dongguan and northeastern Shenzhen are likely to compete for healthcare resources beyond city boundaries. This may lead to a reduction in accessibility in many sub-districts in northern and eastern Huizhou, thereby exacerbating inequality.

4.3. Differences in two-step optimization results between two scenarios

The above results reveal that intercity patient mobility has a positive effect on healthcare accessibility efficiency and equality under the existing distribution of resources. This section further aims to investigate how intercity patient mobility would influence optimized healthcare accessibility. The 2SO4SAI method is applied to optimize both locations and capacities of tertiary-A hospitals in both the intracity and intercity scenarios.

The first step aims to select the best locations for new hospitals through the p-median model. As shown in Figs. 10a, 1 new tertiary-A hospital in Shenzhen is sited in the northwest part. 5 hospitals in Dongguan are all sited in the eastern part. 3 hospitals in Huizhou are distributed across various regions. In the intercity scenario, the number of hospitals in each city is endogenously determined by the optimization model. As a result, 2, 3, and 4 hospitals are added in Shenzhen, Dongguan and Huizhou, respectively (Fig. 10b). The distribution of these new hospitals is more dispersed at the metropolitan area scale.

The first optimization step prioritizes efficiency by comparing the optimized travel times in each scenario with the actual status to assess improvements in accessibility. The intracity optimization decreases travel time in 61 sub-districts by 0.18–49.97 min. The intercity optimization decreases travel time in 65 sub-districts (37% of all sub-districts), with a maximum reduction of 70.63 min. As shown in Fig. 10 and Table 1, the two optimization scenarios both significantly reduce travel time in northern Huizhou and eastern Dongguan. The intercity optimization can better improve the efficiency of accessibility in terms of average travel time to the nearest hospitals compared to the intracity optimization.

The second step of optimization aims to allocate the newly-added beds among existing hospitals and the new hospitals sited in the first step. As shown in Fig. 11, more newly-added beds are allocated to areas with relatively low accessibility and high demand population, such as the western and eastern parts of Dongguan. Intracity optimization mainly improves the accessibility in the central urban areas, especially Dongguan, while intercity optimization mainly improves the accessibility in the junction areas of three cities. The accessibility is improved in 147 and 163 sub-districts in the intracity and intercity scenarios, respectively.

After optimization, accessibility is higher in the central areas of three cities in the intracity scenario, where city boundaries pose strong restriction on patient mobility (Fig. 12a). In the intercity scenario, however, high accessibility is observed in Shenzhen and the junction areas between Dongguan and Huizhou (Fig. 12b).

As shown in Table 2, intercity optimization has a more profound impact on average accessibility in Shenzhen and Huizhou, but a slighter impact in Dongguan. Both intracity optimization and intercity optimization improve accessibility by 0.3 beds/thousand people in Shenzhen metropolitan area. Intercity optimization allows for the sharing of healthcare resources between cities. Patients select hospitals according to the urban commuting distance and hospital's capacity, which can balance supply and demand at a larger scale and alleviate the coexistence of resources surplus and shortage.

The Lorenz curve and the Gini coefficient for equality optimization results are shown in Fig. 13. Both intercity optimization and intracity optimization mainly improve the accessibility of the middle 30%–70% of the population. The Gini coefficients indicate that both optimization scenarios can improve the equality of healthcare accessibility compared to the status quo. Intracity optimization has a larger effect than intercity optimization (Gini coefficients are 0.091 and 0.113, respectively).

5. Discussion

Healthcare accessibility and equality is at the center of discussion on "health for all" objective in SDG 3. Traditionally, healthcare services are planned, provided and utilized within the city boundaries in China. However, due to disparities in healthcare services distribution (especially high-quality services) across cities, patients might seek healthcare services outside the city they reside in. Such intercity patient mobility is increasingly recognized in the planning of metropolitan areas, where intercity human mobility and socio-economic connections prevail. However, it still remains unclear how intercity patient mobility would influence healthcare accessibility and equality in metropolitan areas. This study proposes a comprehensive framework for quantifying the accessibility and equality impacts of intercity patient mobility, which sets up and compares two scenarios (intercity and intracity) of accessibility to both existing healthcare services and optimized newly-added healthcare services.

While some pilot studies have laid the groundwork in this area, this study is poised to offer additional contributions. For example, Yan et al. (2022) used individual-level healthcare-seeking data to examine the impacts of intercity patient mobility on healthcare equality and

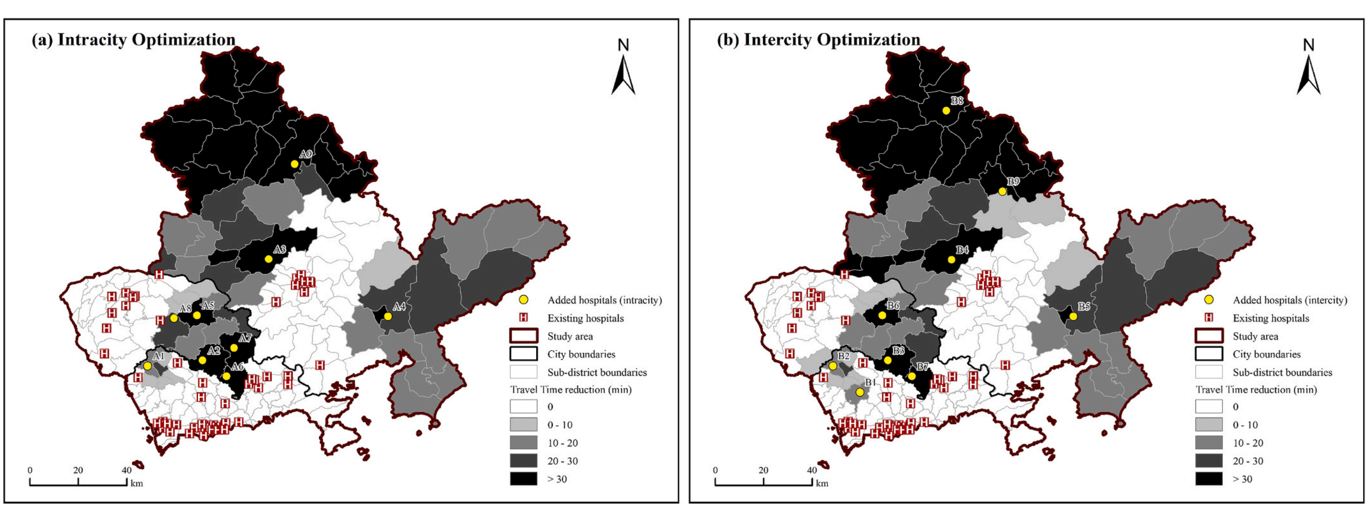

Fig. 10. The reduction of travel time to the nearest tertiary-A hospitals after optimization in the intracity and intercity scenarios.

Table 1
Average and maximum travel time to the nearest tertiary-A hospitals in different scenarios.

City/region	Weighted average travel time (minutes)			Maximum travel time (minutes)		
	Actual	Intra_Opt	Inter_Opt	Actual	Intra_ Opt	Inter_Opt
Shenzhen	14.17	13.09	12.43	35.65	35.65	35.65
Dongguan	23.93	14.67	15.70	54.68	32.12	32.12
Huizhou	31.56	19.99	17.26	108.17	88.77	88.77
Shenzhen metropolitan area	20.46	14.89	14.35	108.17	88.77	88.77

Note: "*Actual*" refers to the actual travel time in intracity scenario, "*Intra_Opt*" refers to intracity optimization, and "*Inter_Opt*" refers to intercity optimization. The same below.

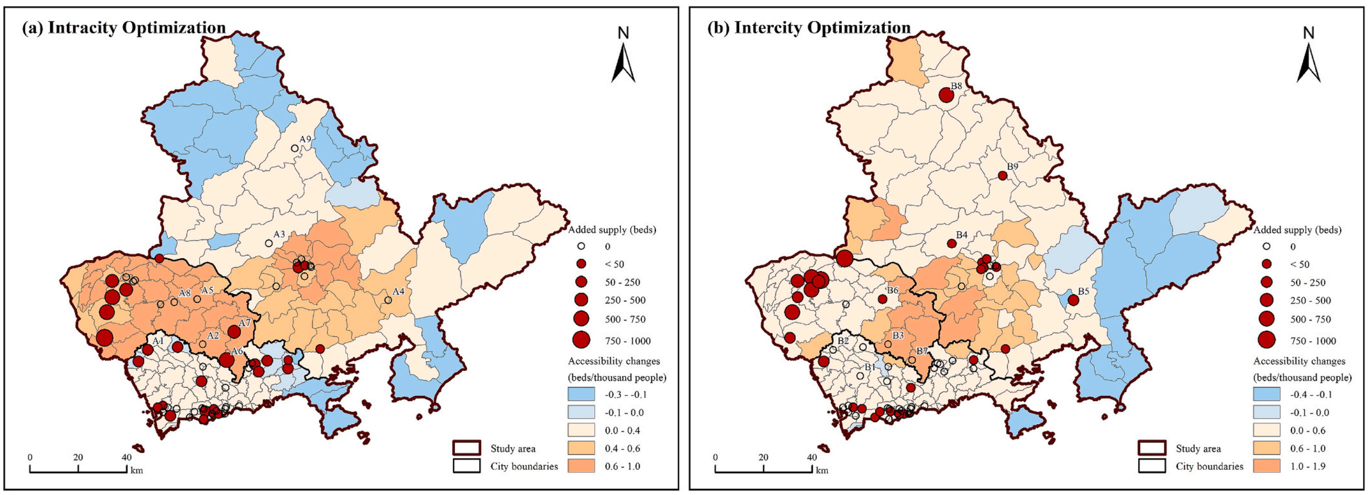

Fig. 11. The changes of 2SFCA-based accessibility to tertiary-A hospitals in two optimization scenarios compared to the actual scenario.

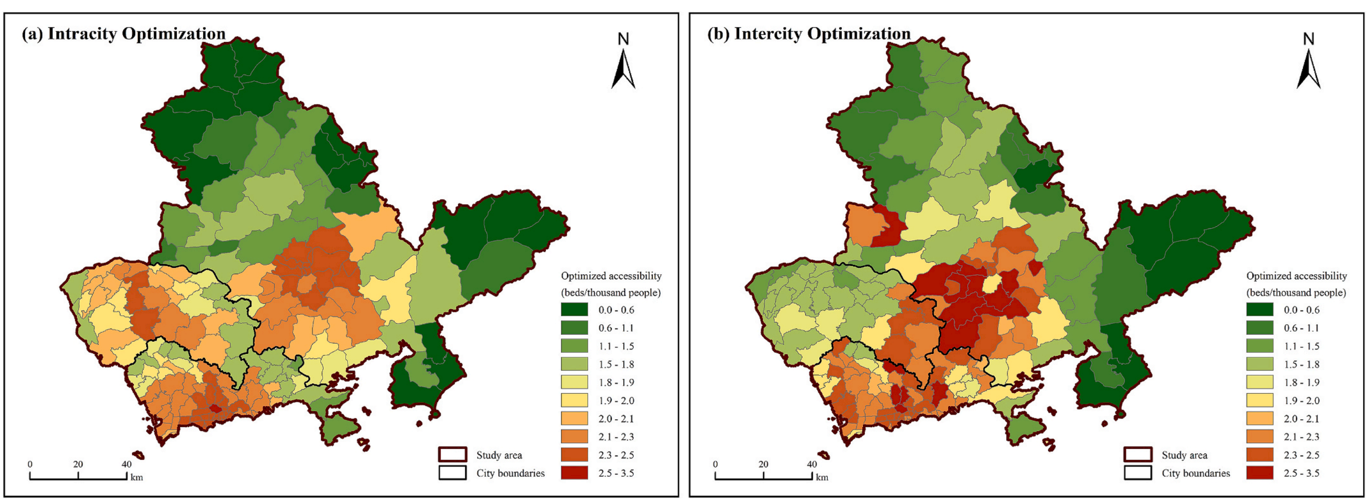

Fig. 12. Optimized 2SFCA-based accessibility to tertiary-A hospitals in two optimization scenarios.

Table 2
Average accessibility in different scenarios.

City/region	Weighted average accessibility (beds/thousand people)		
	Actual	Intra_Opt	Inter_Opt
Shenzhen	2.0	2.1	2.3
Dongguan	1.3	2.0	1.8
Huizhou	1.4	1.8	1.9
Shenzhen metropolitan area	1.7	2.0	2.0

efficiency. Though their analysis is advanced in revealing the actual utilization of healthcare services at the individual level, it is incapable to provide a full picture of the spatial configuration of healthcare resources. What's more, the study only considered residents in a single city (Hefei). Zhang et al. (2023) evaluated the improvement effects of intercity multi-modal transport on the equality of high-quality healthcare resources in China, but did not specially focused on metropolitan areas. Brekke et al. (2016) investigated the impacts of patient mobility on the equality of healthcare quality among different income groups using a theoretical model, but lacked empirical analysis. In this study, healthcare accessibility in terms of proximity and supply-demand ratios in the intracity and intercity scenarios were compared, in order to

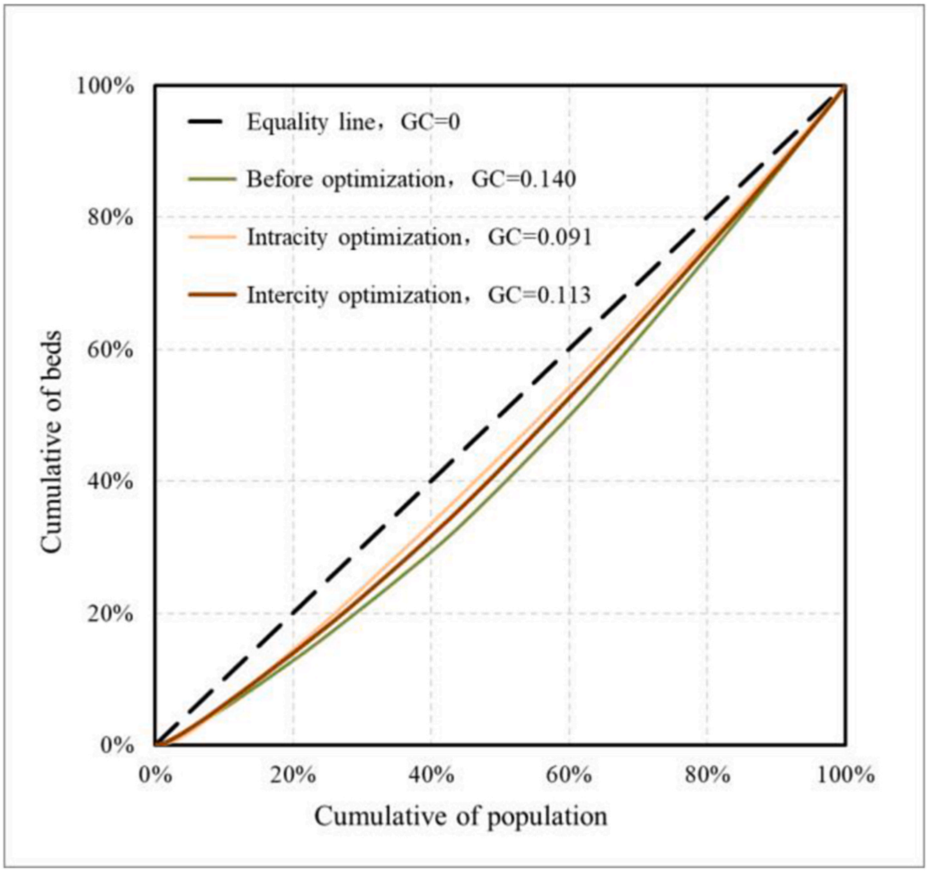

Fig. 13. The impact of optimization on healthcare equality.

comprehensively evaluate accessibility impacts of intercity patient mobility. The results revealed that intercity patient mobility can improve both efficiency and equality of healthcare accessibility in metropolitan areas.

Furthermore, existing studies have paid few attentions to the impacts of intercity patient mobility in optimization analysis of healthcare services. This study is innovative in comparing the optimization methods in two scenarios to fill the above research gap. Our results demonstrated the two-step optimization considering intercity patient mobility can better improve both efficiency and equality of healthcare accessibility in metropolitan areas compared to the status quo. The proposed optimization method is more applicable to the future planning of healthcare facilities in metropolitan areas.

Notably, however, the improvement in accessibility equality in the intercity optimization scenario was less pronounced compared to the intracity scenario. The two-step optimization approach was adopted in this study, among which the first step aims to maximize efficiency of accessibility (i.e., minimizing average travel time to the nearest hospital), and then the second step aims to maximize equality (i.e., minimizing the spatial disparity in accessibility). As a result, in the first step, accessibility efficiency was improved to a larger extent in the intercity scenario, since the restriction effect of city boundaries was relaxed and patients could select the nearest hospital even located in other cities. The sites of newly-added hospitals were determined in the first step, based on which the capacity optimization was conducted in the second step. Nevertheless, the equality of accessibility was obviously improved in the intercity optimization scenario compared to the status quo. These findings demonstrated that the two-step optimization for spatial accessibility improvement (2SO4SAI) approach can well balance efficiency and equality goals.

The contributions of this study can be summarized in two aspects. First, **it provides a set of methods for comparing and optimizing the healthcare accessibility and equality in intracity and intercity scenarios**, which is essential for the regional planning of healthcare resources. These methods offer applicability to other areas with obvious regional disparity. Second, **this study provides quantitative evidences on the positive effects of intercity patient mobility on healthcare efficiency and equality within metropolitan areas.**

Our findings can provide policy suggestions regarding the planning of healthcare resources in metropolitan areas. First, results suggest an uneven distribution of high-quality hospitals in three cities. In intracity scenario, optimization should focus not only on city centers, but also on subcenters and fringe areas with relatively high population density. Second, this study suggests that intercity patient mobility can improve both efficiency and equality of healthcare accessibility in metropolitan areas. This provides evidences for policies facilitating intercity patient mobility, including registration system of hospitals, medical insurance system and intercity transportation connectivity. For instance, the National Healthcare Security Administration (2020) has introduced online inquiries for the direct settlement of cross-regional healthcare expenses. Third, the intercity optimization scenario allowing for intercity patient mobility outperforms the intracity scenario in terms of balancing efficiency and equality. Therefore, in the planning of healthcare resources in metropolitan areas, the systematic view is of urgent need to collaboratively allocate healthcare resources across various cities. This supports the formulation of policies aimed at establishing medical centers at both national and regional levels (NHC, 2019). Fourth, emphasis should be put on high-quality healthcare services in the co-construction and sharing of healthcare services across cities as well as the governance of intercity patient mobility. Recent years have seen a rapid increase in the number of tertiary-A hospitals in China, from 989 in 2012 to 1716 in 2022, with its share in the total number of hospitals rising from 4.27% to

4.64% during the same period (NHC, 2012; NHC, 2022b). This change necessitates further research and government policies in patients' mobility in seeking high-quality healthcare services.

Finally, we would like to acknowledge that our study still faces some limitations. First, due to unavailable data on healthcare seeking behavior, we were unable to analyze the spatial pattern of actual intercity patient mobility. Second, in the measurement of healthcare accessibility, it was assumed that patients are possible to select all hospitals within the catchment areas. In reality, however, the flow of patients might be directional. For example, patients living in peripheral areas might select hospitals in the core city, but it might be unrealistic conversely. In future studies, improved measures of healthcare accessibility can be developed to incorporate such directionality of patient mobility. Third, only driving mode was considered in this study, with other possible transport modes overlooked, which can be improved in future studies. Fourth, there is obvious regional disparity in healthcare resources in Shenzhen metropolitan area, which makes it a representative study area for intercity patient mobility. However, the generalization of the conclusions could be limited because Shenzhen metropolitan area is relatively developed with more healthcare resources compared to inland regions in China. More case studies, especially in less developed regions, are needed to validate and strengthen our findings. Finally, time trend analysis of healthcare accessibility changes is of significance, but obtaining additional time series data (especially historical travel time data) remains challenging. Future studies can make efforts in this aspect to deepen our understanding.

6. Conclusions

This study develops a comprehensive framework for quantifying the impacts of intercity patient mobility on healthcare accessibility and equality in metropolitan areas. Two scenarios (i.e., intercity and intracity) of accessibility to existing and optimized newly-added healthcare services are calculated and compared. Healthcare accessibility is interpreted and measured in terms of proximity and supply-demand ratios, with the former focused on efficiency and the latter on equality. The results revealed that intercity patient mobility can improve both efficiency and equality of healthcare accessibility to existing services in Shenzhen metropolitan area. This study also applies the two-step optimization approach integrating efficiency and equality to optimize the allocation of healthcare resources. The results demonstrate that optimization considering intercity patient mobility can improve both efficiency and equality of healthcare accessibility in metropolitan areas compared to the status quo. The framework and methods developed here are applicable for measuring and optimizing the efficiency and equality of healthcare accessibility in metropolitan areas, particularly those with pronounced regional disparity. This study also provides quantitative evidences on the positive effects of intercity patient mobility on healthcare efficiency and equality in metropolitan areas, offering valuable insights for policymaking.

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CRediT authorship contribution statement

Qianyu Zhong: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Jiangyue Wu:** Writing – review & editing, Validation, Investigation, Conceptualization. **Zhuolin Tao:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

None.

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