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A multi-scale approach mapping spatial equality of urban public facilities for urban design

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ABSTRACT

Spatial equality analysis is useful for urban designers and policy makers to produce and/or adapt urban services provision, while supporting the pursuit of the public interest in the urban design process. This research focuses on urban public facilities (UPFs), the most relevant physical elements serving the public interest, and proposes a multi-scale methodology from a practical perspective to understand and foster the spatial equality of UPFs. Using Shenzhen to test the approach, this research first investigates the density and aggregation of UPFs at the district level to recognize how developing differentiations and social context act on the spatial patterns in UPFs. Second, the accessibility of different types of UPF are measured at the sub-district level which emphasizes the spatial impedance between demand and supply and the availability of services. Then, we draw location-specific design strategies for better spatial equality at a site scale. The results show "cross-district impact" plays an important role in influencing overall spatial equality. Also, sufficient transportation networks, road configurations, and the diversity of UPFs could significantly improve service capacity and impact the achievement of spatial equality. This paper draws attention to the improvement of spatial equality and can contribute new insights to the interpretation and measurement of the spatial equality in urban design debates.

1. Introduction

Spatial equality analysis is crucial for urban design [1–3]. This is due to the fact that urban design is more than urban morphology and the distribution of building masses and the space between buildings, but also about serving the public interest through creating better spaces [4], for instance to create better communities, clean environments, public spaces, accessible facilities, and good educational and job opportunities [5]. The results of a comprehensive spatial equality analysis can help urban designers and policy makers assess the existing urban services provision from a spatial perspective through scales, identify places with relatively good or bad spatial equality, and provide advice for creating and adapting urban services delivery to pursue equality ambitions [6].

Spatial equality analysis usually focuses on the allocation of urban public facilities (UPFs), as UPFs are the most relevant physical elements to public interests [7]. Extensive attempts have been made to parse and understand how social differentiations, decision making processes, and spatial patterns act on the spatial inequality in UPFs [8]. However, relevant approaches addressing the spatial equality analysis in UPFs as scale-continuum in a broader context including different scales of content connecting social-geographical

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and morphological entities are still lacking. To be particular, 1) the analysis of spatial equality in UPFs is often based on spatial accessibility measures [6,9]. It evaluates whether residents are equally treated or not in terms of in public services allocation, irrespective of where they live [10]. Such accessibility research usually investigates the situation of spatial (in)equality at the sub-district level. In other words, they do not provide the overall picture of UPF's spatial organization from a larger perspective [7].

Considering the allocation and distribution of UPFs is potentially influenced by multiple factors, such as the regional development trend, economic activity, governmental policy at the administrative district level, it is essential for urban designers and policy makers to better link the administrative district's attributes and UPFs' features in order to effectively appraisal and allocate specific UPFs. 2) Urban designers mainly elaborate the corporeal and incorporeal notions into physical structures which manipulate distinctive spatial elements and urban fabric into a richer interaction (e.g., the spatial relatum among facilities, residential communities, and road network) for better living environment. Nevertheless, the existing spatial equality analyses often remain at the interpretation level by indicating the extent of (in)equality, putting forward spatial design strategies at site scale (on the ground) for more equitable opportunities to access and use UPFs is still problematic [11]. This facilitates detailed location-specific design principles for the co-construction of urban architectonic compositions to foster spatial equality in the city.

To sum up, though the previous research provides valuable clues for investigating the spatial equality of UPFs, they indicate the fundamental knowledge and communication gap between urban design practice and academia. Therefore, this paper aims to provide a comprehensive processing to understand the spatial equality of UPFs through scales and subsequently to explore substantive spatial strategies and guidance for the future urban development. In order to fulfil this objective, a multi-scale approach is proposed. This approach first inquires the density and aggregation of UPFs at the district level in order to recognize a general idea of the spatial distribution of UPFs based on the different social orientation and community development. Then, it measures the accessibility of various types of UPFs at the sub-district level which emphasizes the spatial impedance between demand and supply, and the availability of services. Third, this approach draws location-specific design strategies at a site-scale level for improved spatial equality. The case city for this paper is Shenzhen, China since urban expansion and economic growth in Shenzhen has resulted in many urban problems including spatial inequalities [12,13].

The paper is arranged as follow: section 2 reviews key concepts associated with the spatial equality of UPFs and introduces a multi-scale approach for analysis; section 3 introduces methods for case selection, data collection, and data analysis; section 4 presents the main results regarding the five types of UPFs across different scales; section 5 discusses the design guidelines, potential applications, and limitations in conjunction with the arguments made in section 4; Section 6 provides some conclusions.

2. A multi-scale approach analyzing the spatial equality of UPFs

2.1. Urban design and spatial equality analysis

In a broad sense, urban design comes into existence when human settlements have been intentionally designed. However, many scholars state that urban design as an official discipline emerged in the 1950s [14,15] to bridge the gap between planning and architecture while combing art and science [14,16,17]. Therefore, urban design blends architecture, landscape architecture, and city planning and aims to make functional and attractive urban spaces [3,18,19]. Although currently there is no consensus regarding the definition of urban design, various scholars have agreed that urban design is about place making [3,20]. They argue that urban design refers to a process of planning, designing, and placing infrastructures, roads, architecture, public spaces, etc., and, in the end, shape urban forms [21,22]. In the meanwhile, this form shaping of urban design happens at different scales such as streets, neighborhoods, infrastructure projects, and whole cities [23].

A large body of literature emphases that urban design is more than the placement of physical and tangible elements, but is rather a process shaped by public interests [3,24–26]. This means urban design tries to place the "right element" in the "right location" and to create better spaces for people. As stated by Landman [27], "urban design has been evolved from a predominantly aesthetic concern with the distribution of building masses and space between buildings to being concerned with the quality of the public realm". For instance, to design a walkable and pedestrian-oriented neighborhood with accessible public spaces can foster social interactions, which can result in a good sense of community, social capital, and collective efficacy [28].To take the public interest into consideration, spatial equality analysis is thus useful for urban designers and policy makers to produce and adapt urban services-provision, and can support the urban design process in order to pursue the goal of equality [29].

In the realm of urban design, three commonly used terms are "spatial equality," "spatial equity," and "space justice", all of which prioritize precise or redefined spatial allocation in order to serve the public interest [30]. These terms address the fact that an "adequate" supply of physical elements such as infrastructure, roads, architecture, and public spaces does not necessarily equate to a "good" supply that effectively meets the demands of the public. In definitional terms, spatial justice and spatial equity are conceptually interchangeable as they both aim to achieve fair and equal distribution of space and opportunities while considering the socio-economic characteristics of different groups of residents [31,32]. However, equality means that in general everyone is provided with equal opportunities to fulfill their needs [33]. Put differently, spatial equality analysis does not inherently entail the incorporation of the specific service requirements pertaining to a particular societal subgroup. Since this study emphasizes a multi-scale approach to analyzing UPFs, "spatial equality" is our focus, meaning the equal distribution of facilities that corresponds to the demand for those facilities in different spatial locations [34].

At the center of spatial equality analyses lies the study of UPFs (urban public facilities), which are structures built by government or non-governmental organizations that provide public services. The uneven distribution and accessibility of UPFs might possibly lead to the poor access to public resources, marginalized vulnerable communities, and ultimately the overall inequality in the society [35,36].

Since UPFs are the most relevant physical elements to the public, they are a main concern for urban designers [7]. As Taleai, Sliuzas [6] put it, the spatial equality of UPFs can be understood as "the degree to which services are distributed spatially in an equal way over different areas corresponding to the spatial variation of 'need' for those services".

The research scope of UPF studies has expanded more recently, where some academics have focused on essential livelihood facilities, such as educational facilities and healthcare services [6,37–39], while others have focused on public services for higher-level needs including landscape and recreational facilities [40–42]. Throughout previous studies, five main categories of UPF can be generated as: commercial facilities (e.g. shopping center, retail shop), educational facilities (e.g. primary school, middle school), landscape facilities (e.g. community park, comprehensive urban park), cultural and sports facilities (e.g. library, stadium), and healthcare facilities (e.g. clinic, hospital) [43–45].

According to Wu and Liu (2022), research on the spatial (in)equality found in UPFs is highly interdisciplinary and integrates social, political, and morphological concerns, which can be categorized into three approaches: (1) Socio-demographic factors; The corresponding research intends to explore the relationship between demographical characters and UPFs from a spatial perspective [46]; (2) Governmental policies and economic activities; Studies under this category showed a significant interest in investigating the underlying reasons of spatial inequality in the supplement of UPFs through governmental policies and economic activities [47]; (3) The spatial allocation and distribution of UPFs. This category addressed the attributes and organization of UPFs from a spatial perspective, which mainly includes research that models the location-allocation of facilities, analyses the spatial layouts of UPFs, as well as the unequal accessibility of different UPFs caused by uneven urban development [48].

Though extensive studies have explored the relationship between spatial (in)equality and UPFs, they did not provide niche targeting principles and guidelines in a practical way to develop an equal and inclusive urban environment from a spatial design perspective. Specifically, studies to analyze the spatial equality of UPFs have two main drawbacks.

First, a large number of research only focuses on the measurement of UPF accessibility and reveal the situation of spatial (in) equality at the sub-district level. Therefore, they do not state enough insights for understanding the allocation and distribution of UPFs' from a larger scale (i.e. at the administrative level) [7,9,49,50]. As the most widely used tool, accessibility analysis provides a quantitative operational method for the evaluation of spatial equality [6,9,10]. That is, to evaluate whether residents are equally treated or not without paying attention to where they live [51]. Apparicio and Séguin [37], Tahmasbi, Mansourianfar [7] and Li, Lin [52] argue that good accessibility to UPFs benefits people living in urban area in many ways. Accessibility enhances their skills, strengthens their health, increases employment and education opportunities, and thus promotes economic growth and reduces poverty. This can help achieve sustainable and equal urban development [53]. Poor access to UPFs can possibly reduce social stability and increase inequality. Based mainly on geographical information systems (GIS) technology from a design perspective, the measurement of accessibility could effectively provide corresponding suggestions for a better distribution and planning of urban settings [54–56]. However, spatial equality of UPFs includes more than accessibility measurements from the place of residence, but also considers an overview of the public service's organization based on different districts' features. Urban designers and policy makers should have a holistic picture about correlations between the attributes of administrative districts and UPFs before decision-making takes place. It can help provide operational clues to balance the budget in terms of different districts' development directions and supply-demand concerns of the UPFs.

Second, existing studies on spatial equality have not paid attention to the formulation of location-specific design strategies at a site scale [57,58]. They lack of adequate analyses and an interpretation of how physical elements are composed and shape urban equality in a spatial way. A successful urban design is, however, about practical design strategies from a spatial perspective [59]. Urban design

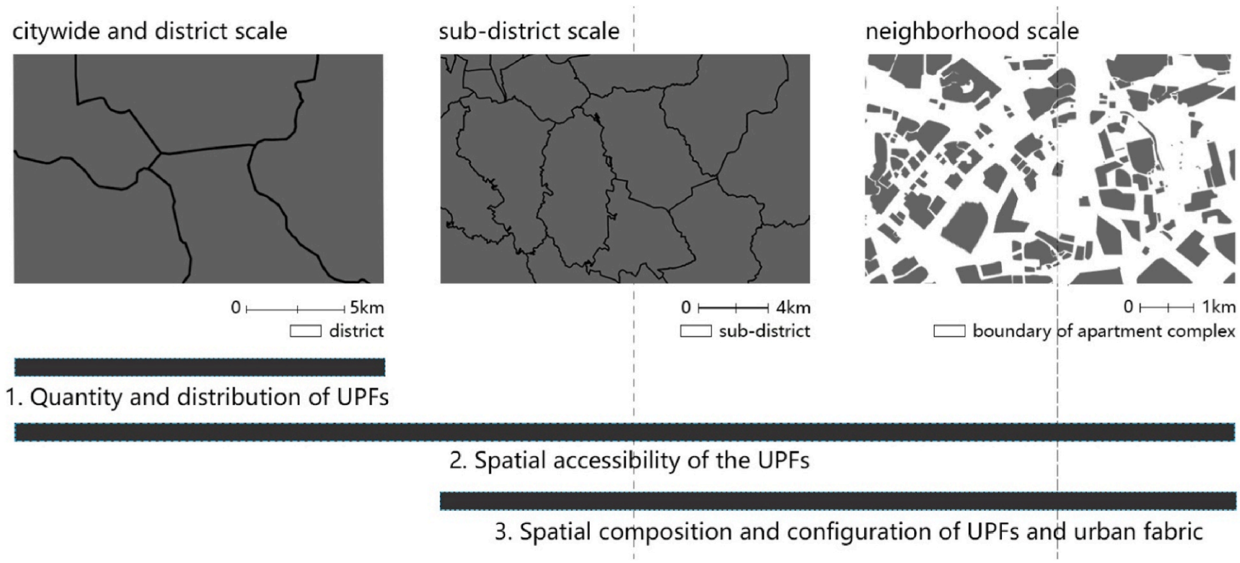

Fig. 1. A multi-scale approach investigating the attributes and organization of UPFs from the perspective of spatial design.

strategies can help to well organize urban elements to bring equality to the city in a spatial way [11].

The aforementioned research gaps could lead to the lack of information and guidelines in urban design processes concerning spatial equality. In order to fill the two gaps, this paper proposes a so-called multi-scale approach for investigating the spatial equality of UPFs from a spatial planning and design perspective. It starts at a district level to first build up a whole picture of the UPFs' layout, then conducts an advanced accessibility analysis in order to evaluate the spatial equality at a sub-district level, in the end, design strategies, including guidelines and principles, are carefully explored for information acquisition in accordance with the future implementation of spatial equality at site scale. This multi-scale approach contributes to understanding the spatial distribution and configuration of UPFs in Shenzhen, in order to identify the spatial features of relatively equal settings of already-existing facilities, and to explore location-specific design interventions that achieve spatial equality for urban renewal or future urban planning.

2.2. Framework of interpreting spatial equality of UPFs from a spatial perspective

As a key dimension of equality, spatiality has triggered scholarly discussions, especially on its extent, dimension, morphological concern, and consequence [60]. Relevant research in the spatial equality of UPFs is highly related to the per capita distribution of facilities caused by uneven urban development; the accessibility of different UPFs; the location-allocation of facilities; as well as an equality and guaranteed standard of services for everyone with variation above the minimum based on personal choices and expressed personal preferences [8,61]. From the spatial design perspective, extensive attempts have been made to parse and emphasize the attributes and organization of UPFs, which can be distinguished from three main dimensions: 1) quantity and distribution of UPFs supplied across the city; 2) equal access to the UPFs; 3) the spatial composition and configuration of UPFs and urban fabric (see Fig. 1).

2.2.1. Quantity and distribution of UPFs

Citywide numerical allocation and distribution of UPFs plays a vital role in building an equal and inclusive living environment [8]. A few research pointed out the quantity variance of UPFs by uneven urban development such as between old urban districts and newly developed areas, urban central district and outer suburbs, directly cause spatial inequality. Li, Wang [62] and Zhao, Zhang [63] revealed that urban fringe areas normally contained fewer services (e.g. medical, geriatric facilities, and recreational facilities) and public transportation connections [48,64,65]. While, the dilemma of megacities started emerging in high-density urban areas through urban shrinkage, by where increasing residents gathered in the older urban districts also undergo inadequate and unequal opportunities to local services [66]. Moreover, the uneven distribution regarding to the aggregated and disaggregated manner of UPFs is also one of the most predominant research subject to reflect the spatial inequality. For example, Zhang, Li [67] analyzed the distribution pattern of community-based service centers in 11 administrative districts in Nanjing, and identified the weakness areas which represent heavy spatial disparities and marginalization for certain people to receive the resources. Gao, Wang [68] pointed out that the geographical concentration of high-quality hospitals would cause tidal traffic phenomenon, which would further decrease the accessibility of these facilities. The previous findings have important implications for investigating and evaluating the interplay of UPFs in a certain district, as well as the relationship between geographical and socioeconomic factors and the spatial organization of UPFs between administrative districts. It could help urban planners to draw an intuitive understanding of current urban development situations, and consciously brings the concern of distributional justice in the early stage of spatial planning and design process.

2.2.2. Spatial accessibility of UPFs

In addition to quantity, efficiency is another central issue needs to be emphasized and trade-off during the assessment of the usability and reachability of UPFs [69]. To represent the efficiency, accessibility as a spatial feature is commonly used to figure the equality in the distribution of a UPF among people [70], and assess the interaction between the UPFs and transportation system [7]. For example, Xiao, Wang [71] revealed that large-scale concentrated landscape areas could provide a few benefits for the living environment, however, they were always distributed remotely and difficult for the people to access due to the high travel and time costs. Cortés [72] noted the uneven coverage of the transportation network or poorly developed transportation system across the city decreased the accessibility of large-scale recreational facilities, such as sports centers, museums, and municipality libraries. Kompil, Jacobs-Crisioni [73] stated improving spatial accessibility to UPFs can effectively result in the reduction of social and spatial inequalities. Though extensive efforts have been made to measure the accessibility of UPFs through spatial scales from local to regional and eventually national, to guide the constructive-detailed plan and indicate the appropriate location-allocation of UPFs, the spatial accessibility of UPFs still mainly remains to three components, which are residential location, facility location, and the connected transportation opportunities [74]. As a main pillar, it is valuable for policy and decision makers to ensure equal access to the desirable services, so as to evaluate the effectiveness of the provision of urban services and facilities.

2.2.3. Spatial composition and configuration of UPFs and urban fabric

The above research has contributed to a status-quo understanding of spatial equality in UPFs with quantification as a basis to allow for more precise and accurate clues for the interpretation of spatial attributes. However, they are mostly concentrated on communication by geographical, management, and urban planning points of view. The core of urban design focuses on the construction and articulation of outdoor space and results in the spatial forms [75]. It is essential to thoroughly comprehend how equal a site or place can be from a design perspective by describing the spatial composition and configuration of urban fabric, which mainly includes the road network, buildings, landscapes, and other infrastructure. For example, Gehl Institute [76] published Public Life Diversity Toolkit revealing a relationship between public space metrics and spatial equality, which indicates a low quality of facilities and the neighboring environment would limit people's accessing options and affect people's preference in using the services. Wu & Liu (2022)

Table 1
Multi-scale approach analyzing the attributes and organization of UPFs in terms of spatial equality.

Approach and implemented scale	Strengths
Quantity and distribution of UPFs (citywide and district scale)	Drawing an overview and comparison the geographical heterogeneity of UPFs' supply across the city Identifying the aggregated and disaggregated manner of UPFs regarding to the uneven distribution within the district
Spatial accessibly of the UPFs (district and sub-district scale)	Analysing the degree of accessibility to UPFs through a sub-district scale Understanding the neighboring impact based on the inner autocorrelation of accessibility between adjacent sub-districts
Spatial composition and configuration of UPFs and urban fabric (sub-district and neighborhood scale)	Revealing spatial equality from a design perspective

developed a framework that displays a hierarchical process of interpreting the spatial inequality/injustice/inequity in UPFs from an ambiguous concept to detailed design interventions. Studies on urban fabric have been always focusing on the shape, form, size, and relative allocations of spatial elements as a whole [77]. In this regard, to understand and explain these built forms, qualitative analysis together with graphic mapping techniques of traditional morphology were widely used within the field of urbanism [78–80].

Summing up, to conduct a designerly and analytical lens to explore the spatial equality of UPFs towards urban planning and design practices, a multi-scale approach can be presented with analyses of the numerical allocation and distribution of UPFs, spatial accessibility of UFPs, and spatial composition and configuration formed by UPFs and the surrounding urban fabric from both quantitative and descriptive dimensions (see Table 1).

3. Materials and methods

3.1. Study area

Shenzhen is a coastal city located in Guangdong province in south-eastern China. After it was named one of the first Special Economic Zones for foreign investment in 1980, Shenzhen has experienced rapid urbanization and economic development [81,82]. According to Chinese Academy of Social Sciences, Shenzhen ranks at the top of concerning "overall economic competitiveness". The official data [83,84] shows the city's permanent resident population has increased from 10.42 million (in 2010) to 17.56 million (in 2020). In 2020, its GDP amounted to 437.4 billion dollars, which is about 14 times the GDP of 2001.

Due to this accelerated urbanization, Shenzhen has an increasing demand for all kinds of UPFs to better satisfy human needs, and to achieve a fairer living environment. Based on the China's 13th and 14th plan of five-year national development, the local government intends to append at least 5 square kilometers of land for UPFs through urban design processes. However, since local governments are pressured to act very quickly, there is a lack of in-depth investigation for those urban designs (plans) which are supposed to foster spatial equality [85,86]. This paper thus adopts Shenzhen as a case city to analyze the spatial equality of UPFs, and aims to provide insights into the formation of equal UPFs for other cities in developing countries as well.

Shenzhen is made up of 10 districts and 74 sub-districts and each district initiates its own development priorities. For example, Nanshan District, has focused on high-tech industries, research, and education, whereas Futian and Luohu Districts are known the financial hubs of Shenzhen, while Yantian District is well-known for logistics industries. These functional localizations cause significant differences between the spatial distribution and configuration of the nearby residence zones and supporting amenities.

3.2. Data resources

Multiple-source open data were used in this study to explore the spatial equality of UPFs in Shenzhen. First, for the measurement of accessibility, single line map of road systems were prepared in ArcGIS 10.8 based on the network data from OpenStreetMap (OSM) with an attribute showing one or two way streets. Besides, area of interest (AOI) data sources of apartment complex and some of the UPFs were collected from UDP (Urban Data Party, www.udparty.com), a Chinese big data platform specialized in urban studies. Apartment complex is defined as a group of buildings that contain apartments set up more like a community and staffed with the same property manager. In Chinese context, it is normally built with physical barriers such as gates, walls, or fences, and few points of entry and exit which are only for residents [87]. AOI data marked the boundaries of Shenzhen's apartment complex represented the status of 2021 ($n = 4249$) were collected, and linked with the gridded population counts (100 m resolution raster) obtained through WorldPop (www.worldpop.org) to gain the total residential population of each complex.

The UDP AOI data including educational facilities, cultural and sports facilities, and hospital facilities documented attributes with the location, name, ground floor area, floor, sub-category and represented the status of 2021. Besides, it is worth noting that commercial facilities are always mixed with other functions, while they only occupy certain floors of a building. To collect the exact area and coordinate of each commercial facility, data from 2020 was sourced via Python from Win Shang Wang (www.winshang.com), the biggest Chinese commercial estate database, and geo-located them into ArcGIS 10 (See Supplementary Document for the detailed processing code). As for the landscape facility, green spaces listed in the Statistic Book for Green Parks in Shenzhen were searched through Amap (https://ditu.amap.com). Data with full-sided attributes including boundary, altitude and longitude, name, area, subcategory were extracted using web scraping with python, which iterated all over the list of addresses fetched in each iteration or page.

Table 2
Scope, sub-category, and service radius of each type of UPFs.

Type	Scope	Sub-category	Service radius
Commercial facility (n = 265)	Structures used for providing commercial services, which include shopping malls, department stores, and mercantile facilities.	Commercial facility (less than 5ha)	5000 *m*
		Commercial facility (less than 10ha)	10000 *m*
		Commercial facility (more than 10ha)	20000 *m*
Educational facility (n = 715)	Structures providing compulsory educational purposes, including primary schools and middle schools.	Primary school	500 *m*
		Middle school	1000 *m*
Landscape facility (n = 258)	Landscape facilities refer to the UPFs that provide landscape services to the public, containing pocket parks, community parks, and urban parks.	Pocket park (less than 10ha)	500 *m*
		Community park (0–10ha)	1000 *m*
		Urban park (20–50ha)	2000 *m*
		Urban park (more than 50ha)	5000 *m*
Healthcare facility (n = 97)	Healthcare facilities refer to the services that directly relate to public health including different tiers of hospital. Medical centers, nursing centers, and geriatric care centers are being excluded in this research.	Tier 1 hospital	1000 *m*
		Tier 2 hospital	15000 *m*
		Tier 3 hospital	50000 *m*
Cultural and sports facility (n = 603)	Recreational facilities refer to urban amenities for culture, sports, and entertainment, which includes community sports hubs, museums, libraries, and different kinds of public activity space.	Neighborhood center	1000 *m*
		Senior center	10000 *m*
		Cultural square/plaza	15000 *m*
		Small-sized stadium (less than 1ha)	1000 *m*
		Middle-sized stadium (1–3ha)	4000 *m*
		Large-sized stadium (more than 3ha)	6000 *m*
		Small-sized library (0.12–0.5ha)	2500 *m*
		Middle-sized library (0.5–1.3ha)	6500 *m*
		Large-sized library (1.3–1.8ha)	9000 *m*
		Museum	50000 *m*

Then, the point of interest (POI) data indicating entrances to the landscape facilities were artificially generated in ArcGIS. According to Code for Urban Public Facilities Planning (GB 50442–2008) published by Ministry of Housing and Urban-Rural Development and Shenzhen Urban Planning Standards and Guidelines proposed by General Office of the People's Government of Shenzhen Municipality, the sub-category and service radius of each type of UPF used in this research were determined (shown as Table 2).

3.3. Measures

3.3.1. Kernel density analysis and nearest neighbor index

In this study, to identify the quantity and enable the comparison of the UPF's supply densities through the city, Kernel density analysis were used to measure and map the geospatial cluster of UPFs relative to each other [88–90]. It calculates a magnitude-per-unit area from point using a kernel function to fit a smoothly tapered surface to each point, in short it measures the density of features around each output raster cell. Thus, Kernel density analysis taking known quantities of distributional phenomenon and spread them across the city is an effective tool to gain intuitive understandings of geographical heterogeneity of UPF's allocation caused by uneven urban development. The predicted density is determined by Eq. (1):

$$\lambda(s) = \sum_{i=1}^{n} \frac{1}{\pi r^2} k\left(\frac{d_{is}}{r}\right) \tag{1}$$

where $\lambda(s)$ is the density at UPF's location s, r is the search radius, k modeled as kernel function is the weight of a certain facility point i at distance d_{is} to location s. All the points represented UPFs within the bandwidth r of location s, weighted depending on their distances to s, are summarized for calculating the density. In addition, to compare the spatial distribution of a variety of UPFs within a fixed area and explore the spatial aggregation of homogeneous facilities, this study uses average nearest neighbor (NN Ratio) to measure the distance between each UPF and its nearest neighbor's location [91]. The results would reveal the dispersed-clustered circumstance of each type of facilities and the associations with residential communities and apartment complex in a district level.

3.3.2. Two-step floating catchment area (2SFCA) and local spatial autocorrelation

Two step floating catchment area (2SFCA) method was one of the most commonly used gravity models for the interpretation of spatial equality to measure the accessibility to facilities. It is easy to implement in a GIS environment and visualize the findings in a spatial way. Through the calculation, road network was involved as a basis to calculate service scopes of facilities referring to different service radius and then estimate each facility's supply-demand ratio. To enhance the accuracy, distance decay function was considered to indicate the supply attractiveness of different levels of facilities to residents [92,93]. In this research, the 2SFCA proposed can be formulated as Eqs. (2) and (3):

$$R_j = \frac{S_j}{\sum\limits_{i\in\{d_{ij}\ll d0\}}^{k} D_i} \tag{2}$$

$$A_i = \sum_{i\in\{d_{ij}\ll d0\}}^{m} R_j \bullet f(d_{ij}) \tag{3}$$

where, R_j is the ratio of the supply-demand radio, S_j is the size of supply of facility j, D_i is the population of the demand spot i, d_{ij} is the travel cost measured by distance, d_0 is the service radius of the facility, k is the number of apartment complex within the catchment area. A_i is the accessibility at location i, f is distance decay function. The Gaussian function is adopted to model the distance-decay effects as suggested by existing studies. Furthermore, considering the publicity of UPFs and mutual influence between sub-districts, measures of spatial autocorrelation were applied here to identify local clusters and local spatial outliers [94]. Univariate local Moran statistic and LISA cluster map were conducted here via GeoDa focusing on relationships between each sub-district's accessibility and its surroundings, in order to show the inner autocorrelation for understanding the neighboring impacts.

3.3.3. *Urban morphological analysis*

To disclose the multi-scale structuring of urban form, designers proposed to study urban fabric constituted by the combination of spatial elements made up of streets, buildings, landscapes, and other infrastructure and their spatial organization [95]. To describe and analyze the distinctiveness of physical characters in terms of spatial equality, urban morphological analysis can be implemented in such spatial analysis procedures to study the characteristics, patterns, and formation of urban components. It primarily includes the typology of road pattern, the diversity of UPFs, and the spatial relative position between UPFs and the surrounding apartment complexes. In this regard, this study extracted and analyzed top ten percent of the sub-districts with best accessibility in order to understand the characters of the area. Those urban elements and the corresponding spatial compositions and configuration they conducted would provide supplements the body of knowledge from a neighborhood scale, which enables spatial planners and urban designers to become more conscious about fundamental spatial inequality effects relevant to the design of UPFs.

4. Results

4.1. *Quantity and distribution of UPFs*

A breakdown of the different categories of UPFs allocation in each district has been summarized through a radar chart shown as Fig. 2. It performs the quantity of UPFs which varies greatly from administrative districts in Shenzhen. After comparing the general holding levels, Bao'a and Longgang contain the largest number of UPFs in total, by which both of these districts have the biggest occupied areas and largest population (i.e. 396.61 km^2 and 388.22 km^2, 334.25 million and 250.86 million). In addition, the polygonal shapes show each type of UPFs allocated in Nanshan are more balanced than the others, while the eastern and the northwestern sides of the city including Yantian, Pingshan, Dapeng, and Guangming have much less UPFs than other administrative districts, which indicates certain difficulties for the residents living there to achieve public services.

Then, based on the Kernel density calculation, the spatial distribution and geospatial cluster of UPFs relative to each other has been mapped and analyzed. Firstly, the geographical concentrations of ***commercial facilities*** are centrally aggregated and mainly located in the financial center, cultural center, inter-city transportation center, as well as science and technology center, respectively (Fig. 3-a). The area with the highest density of commercial facilities is Luohu along the south coast of Shenzhen with major ports. It was the starting point of implementing the Chinese reform and opening up policy, which contains well-developed transportation infrastructure, major ports, and a large number of financial institutions facilitating the cooperation between mainland China and Hong Kong.

Another denser area is Nanshan, which is known as the Chinese Silicon Valley. It has attracted numerous well-known high-tech industry headquarters, in which GDP per capita amounts to 60.32 thousand US dollars. Also, Longhua District with North Railway Station, the largest transportation hub in Shenzhen, has a high density of commercial services for the transit passengers and the residents nearby. Within all the districts, nearest neighbor indicator (R) are less than 1 (from 0.238 to 0.763), which means that commercial facilities in each district are in clustering geographical phenomenon ($R < 1$, the pattern exhibits clustering; $R > 1$, the trend is toward dispersion).

Educational facilities in Shenzhen are evenly distributed in combination with residential areas. Density analysis shown as Fig. 3-b demonstrates except for the distribution of educational facilities in the eastern Shenzhen, which is characterized by a point-like clustering pattern, the rest of the amenities in the administrative districts are mostly distributed continuously and evenly. The earliest developed areas, Futian and Luohu with a high population density, have the densest educational facilities, which have formed a continuous strip-like spatial pattern. In addition, both the density of educational facilities in the south-western area (Nanshan and

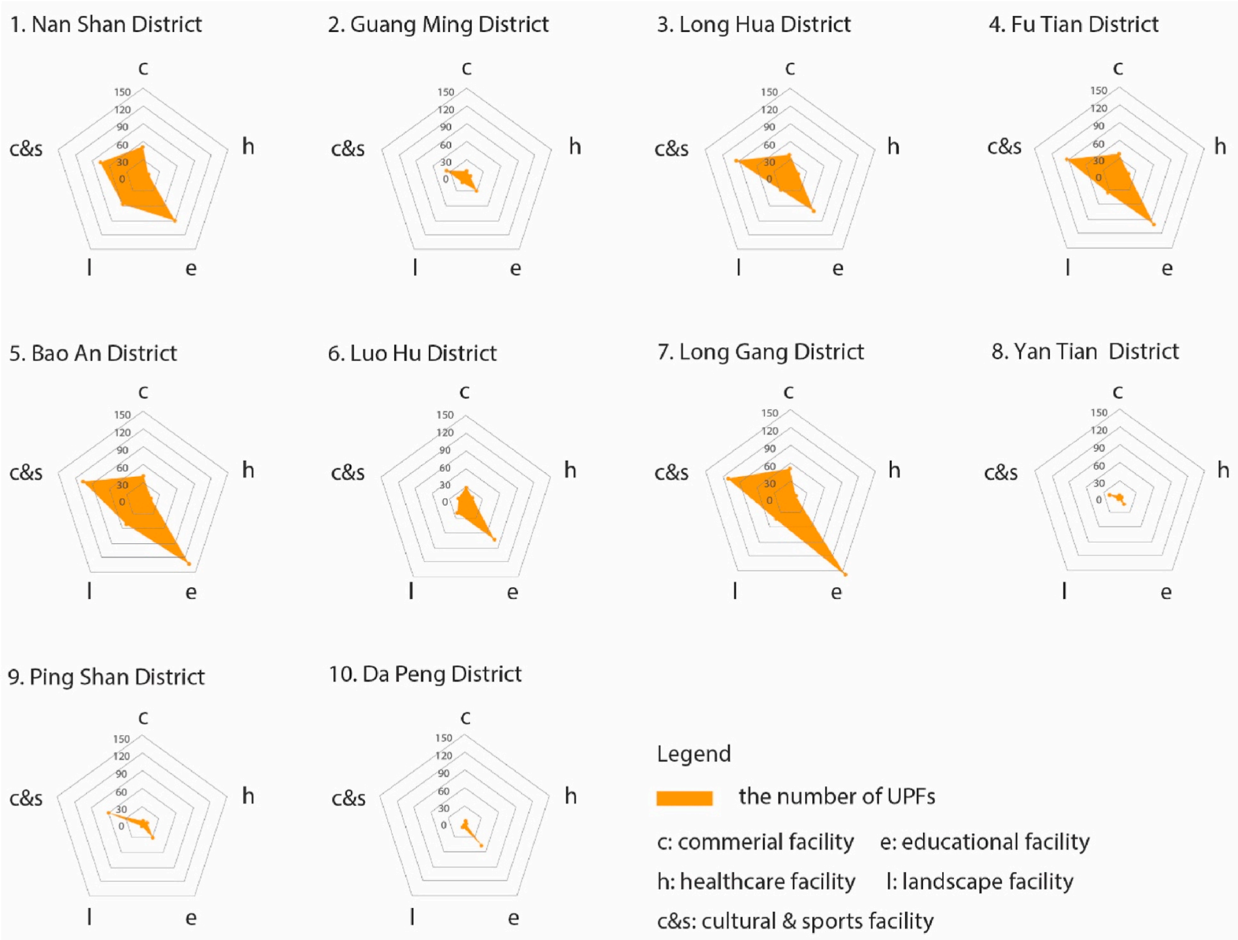

Fig. 2. Radar chart displaying the quantity and allocation of different UPFs in each administrative district (1-NanShan District, 2-Guang Ming District, 3-Long Hua District, 4-Fu Tian District, 5-Bao A District, 6- Luo Hu District, 7-Long Gang District, 8-Yan Tian District, 9-Ping Shan District, 10-Da Peng District) in Shenzhen (check supplementary document for the high resolution image).

Bao'an) of the city are relatively high, which constitute a band-like spatial distribution to the northwest. The nearest neighbor index of educational facilities in each administrative region is from 0.510 to 0.894, which shows as significant clustered distributions.

As for ***healthcare services***, each administrative district contains a certain number, besides Dapeng a new district under initial development which does not have a local hospital (Fig. 3-c). Based on the nearest neighboring index, healthcare facilities in Pingshan, Yantian, Futian, and Longgang districts are dispersed ($R > 1$, from 1.018 to 1.286), while in the other districts these facilities are organized into clusters ($R < 1$, from 0.348 to 0.815). Generally, healthcare facilities are house denser in the old town. They are evenly allocated in the highest density on the west side of Luohu. Together with the eastern part of Futian which also has a high density of healthcare services, a continuous belt-like spatial form has appeared. By comparison, Longhua District has a rather high density of healthcare facilities, but they are aggregately distributed, for example Longhua Sub-district which includes about 10% (10/97) of healthcare facilities in Shenzhen. In addition, healthcare amenities are always densely arranged on the edge of adjacent administrative districts. For instance, hospitals are concentrated at the junction of western Nanshan and eastern Bao'an, as well as between Bao'an and Guangming.

The quantity and aggregation of ***cultural and sports facilities*** in the southwest coastal area are higher than in any other region (Fig. 3-d). To be specific, Futian as the political and cultural center of Shenzhen has a large number of cultural and sports facilities (93/603, 15.4%) which are evenly distributed in the entire administrative district. Then, expanding to the west, a continuous belt-like spatial form a dense cultural and sports facilities has been shaped. In addition, in the north part of Shenzhen containing a high density of sport facilities which are in a clustered spatial distribution. Meanwhile, the nearest neighbor indicators of cultural and sports facilities at a district level are all less than 1 (from 0.448 to 0.797), which indicates non-randomly clustered distributions all across the city.

In Shenzhen, the area of ***landscape facilities*** occupies 43.4% of the built-up area. Almost all the administrative districts have different levels of green spaces (Fig. 3-e). The nearest neighbor index of landscape facilities in Pingshan, Dapeng, Yantian, and Longhua are all greater than 1 (from 1.087 to 1.516) indicating a discrete distribution pattern, while facilities in the rest administrative districts

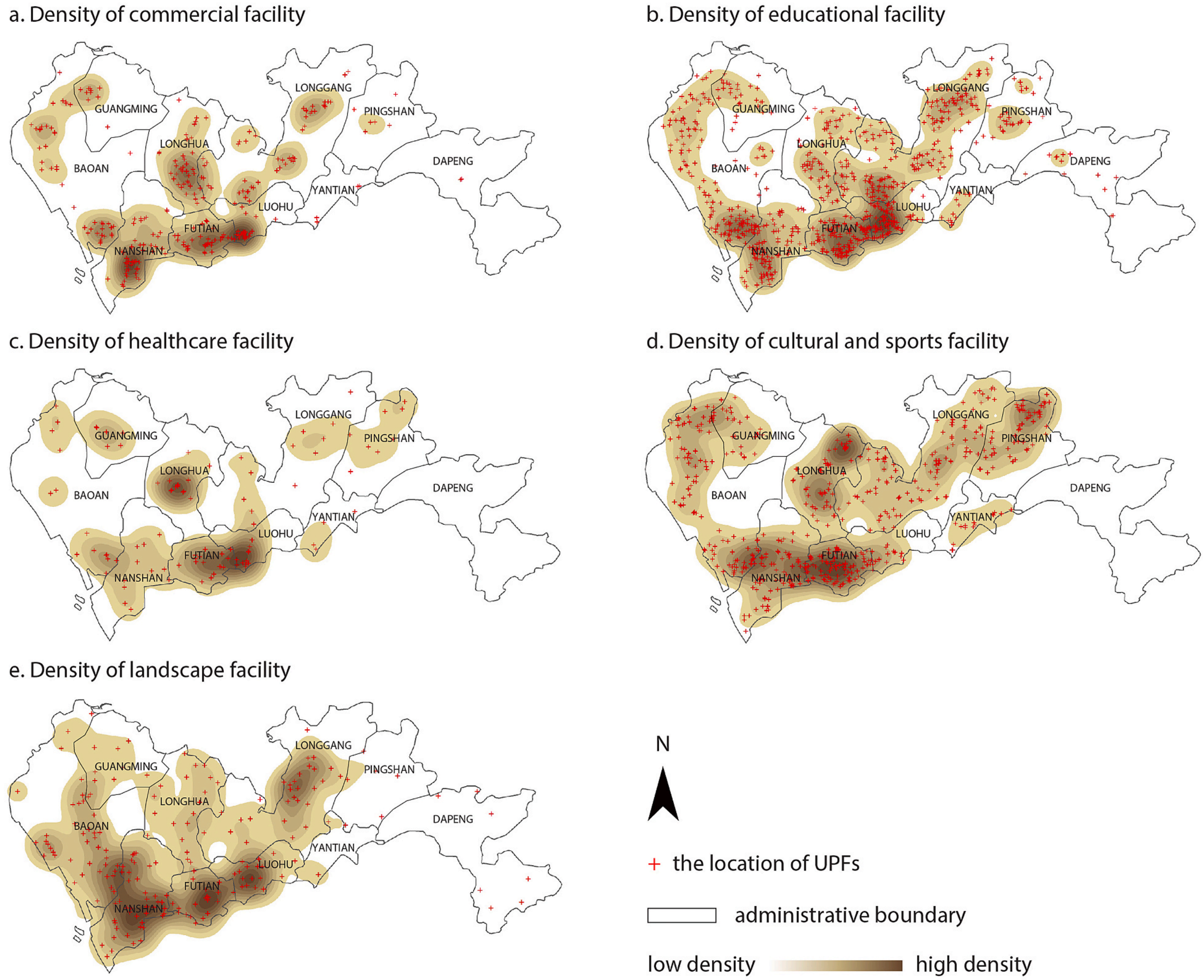

Fig. 3. Citywide spatial distribution and density map of different types of UPF (a-commercial facility, b-educational facility, *c*-healthcare facility, d-cultural and sports facility, e-landscape facility) in Shenzhen (check supplementary document for the high resolution image).

show clustered distributions (from 0.315 to 0.842). Overall, a series of large-scale urban landscapes are allocated in the central part of the city running through in an east-west direction. By contrast, in the southern coastal area and northern side of the built-up area, a large number of small patchy green spaces are dispersed. Density analysis shows that in Nanshan, landscape facilities which are mostly at the community and the urban park level, are densely distributed in a continuous belt-like spatial form, while landscape facilities in the central old town (i.e. Futian and Luohu) are in a high density with point-like clustering. In addition, in the northeast (i.e. Longgang) there is a high-density of landscape spaces distributed in clusters.

4.2. Spatial accessibly of the UPFs

In addition to the overall quantity allocated in each district, it is also necessary to evaluate the efficiency of equal access to the desirable services from the sub-district level. Accessibility maps have been drawn to figure the equality people could gain based on the interaction between the UPFs and transportation system. Particularly, Fig. 4-a shows sub-districts with better economic growth are much more accessible to ***commercial facilities*** than any other areas. As LISA cluster map and Moran's I indicated, several areas show significant relationships on accessibility among adjacent sub-districts (Fig. 5-a). The sub-districts (i.e., Nanshan and Zhaoshang sub-districts) at the southwest corner of the city show a high accessibility surrounded by high accessible sub-districts, while sub-district (i.e. Dongmen Sub-district) in the center of Shenzhen presents low-low relations. As for the accessibility of ***educational facilities***, people living in the northeast and southwest regions of Shenzhen can access primary and middle schools better than those living in other regions (Fig. 4-b). The areas with high accessibility are more concentrated, and mainly distributed at the central part of the city, as well as the sub-districts along the southern coast. In addition, Fig. 5-b shows in south-eastern and north-western Shenzhen sub-districts with low accessibility are significantly aggregated. Furthermore, in terms of ***healthcare facilities***, the analysis of spatial accessibility points

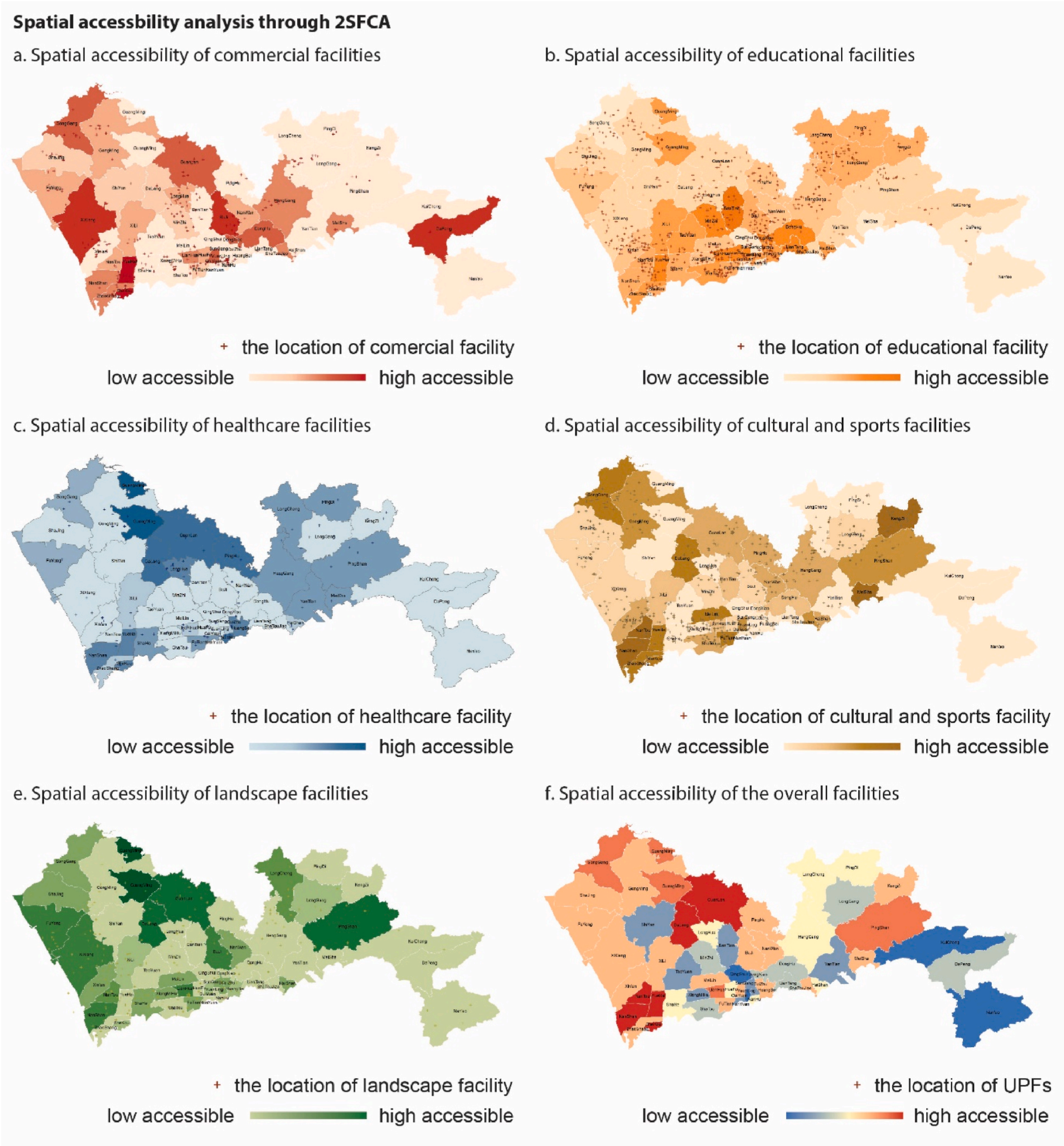

Fig. 4. The spatial accessibility of each type of UPFs and the overall accessibility of UPFs (a-commercial facility, b-educational facility, *c*-healthcare facility, d-cultural and sports facility, e-landscape facility, f-the overall facility) in Shenzhen from a sub-district perspective (check supplementary document for the high resolution image).

out that most of the areas in the central and eastern parts of Shenzhen have low accessibility to hospitals. The local spatial auto-correlation analysis reveals an aggregation of sub-districts with high accessibility in the northern area of Shenzhen, while areas in the west (i.e. Xixiang Sub-district) and middle east of Shenzhen (i.e. Meilin Sub-district) reveal low-low accessibility rates (Fig. 5-c). Also, sub-districts with high accessibility of the ***cultural and sports facilities*** are relatively scattered, respectively locating in the northwest, northeast, southwest, and southeast sides of Shenzhen (Fig. 4-d). Both the accessibility map and LISA cluster map show that the sub-districts along the southern coastal lines show distinct differences in accessibility to cultural and sports facilities (Fig. 5-d).

Last but not the least, the measurement of accessibility regarding to **landscape facility** shows that landscape spaces in the western sub-districts are more accessible than those located in the eastern sub-districts, while ones in the sub-districts along the southern

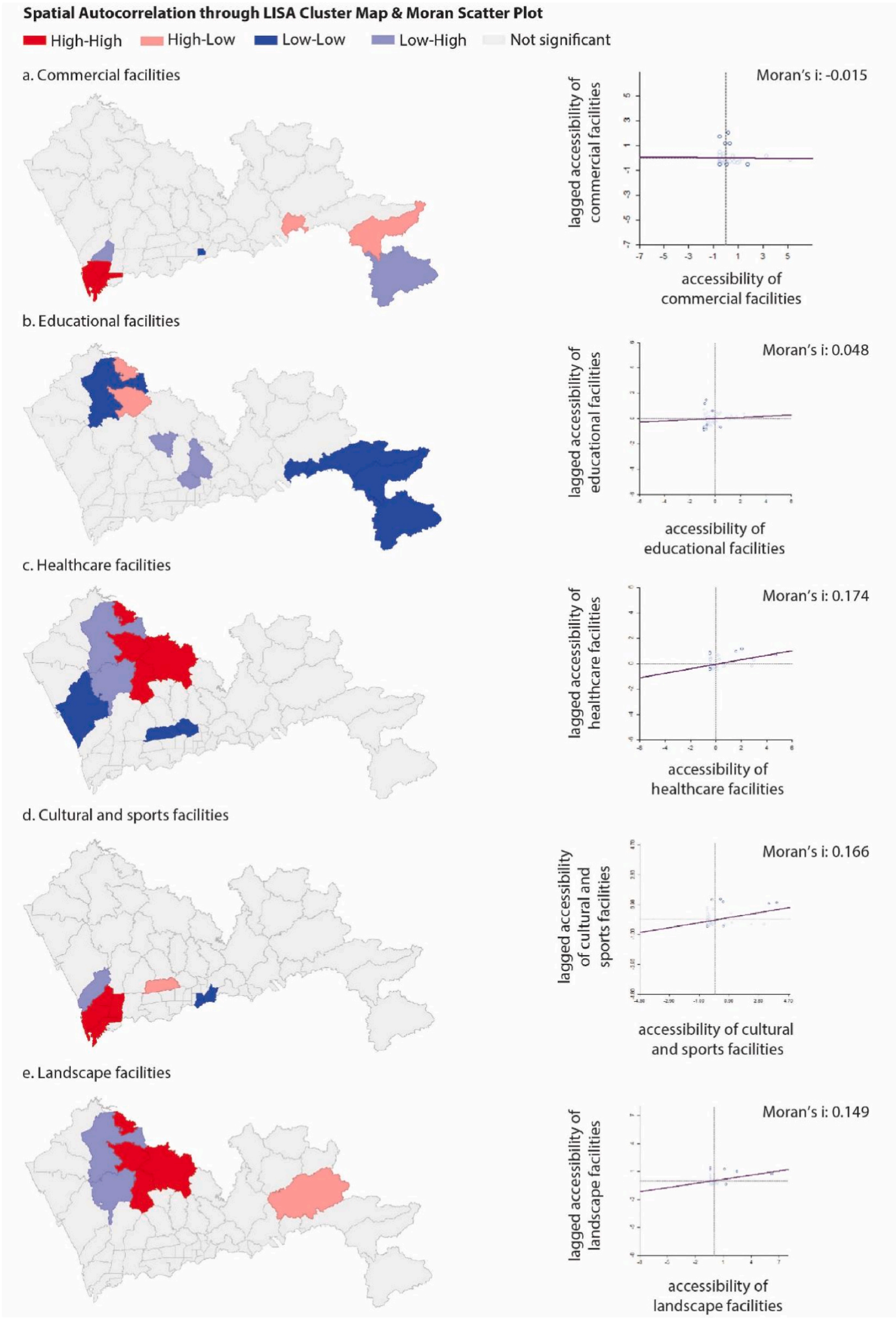

Fig. 5. Significant local spatial autocorrelations referring to the accessibility of UPFs (a-commercial facility, b-educational facility, *c*-healthcare facility, d-cultural and sports facility, e-landscape facility) from a sub-district level (check supplementary document for the high resolution image).

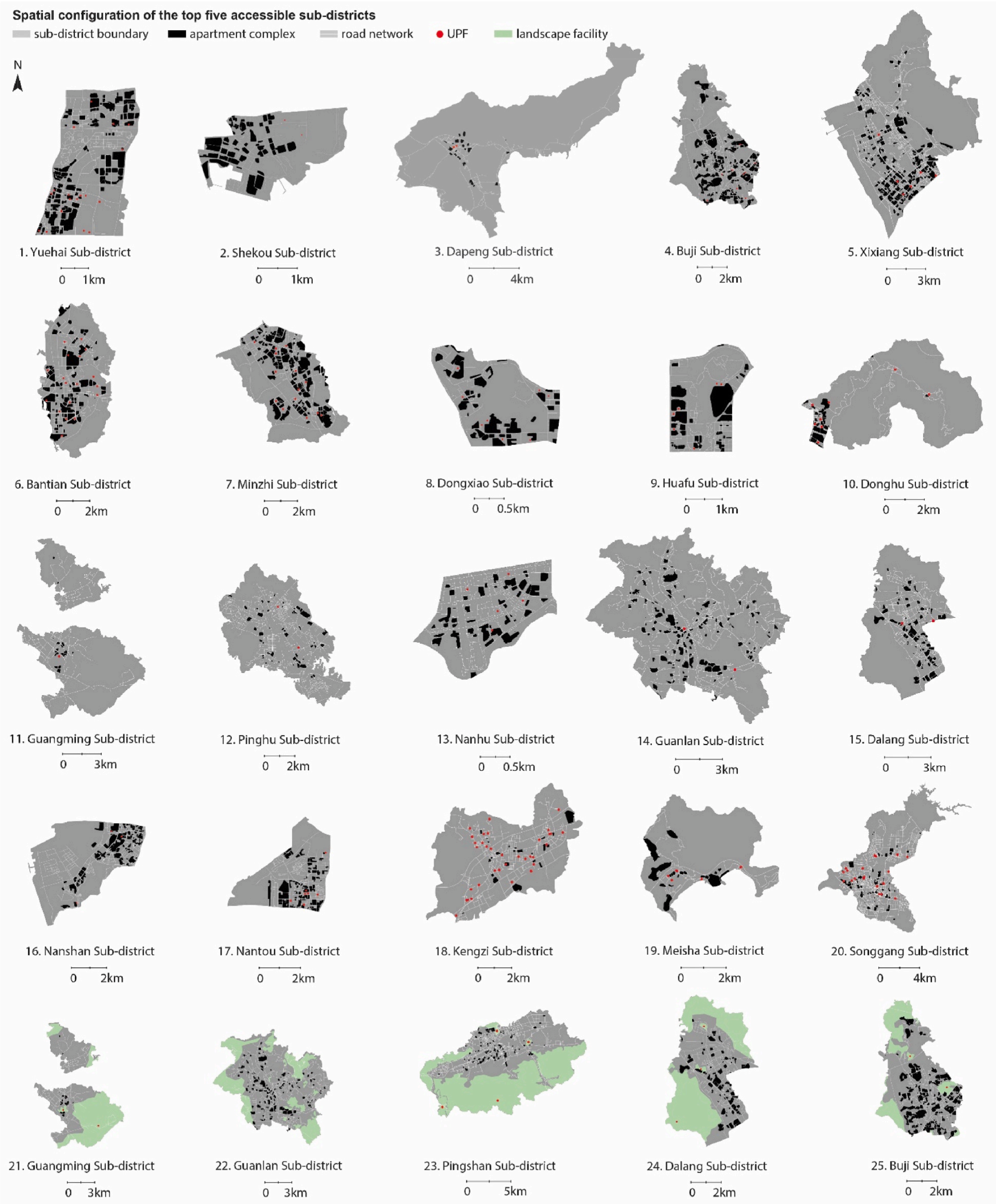

Fig. 6. The spatial composition and configuration and urban fabric of well-accessed sub-districts (No.1-25) to UPFs at a neighborhood scale (check supplementary document for the high resolution image).

coastal area is generally not high. Through the LISA cluster map, sub-districts in north-western Shenzhen show high-high spatial correlations referring to the accessibility to landscape facilities (Fig. 5-e).

4.3. Spatial composition and configuration of UPFs and urban fabric

To understand the relationship between spatial equality and characters of the area from an urban design point of view, sub-districts with a higher accessibility of certain types of UPFs were selected to analyze, in order to extract how urban elements and the corresponding spatial compositions and configuration conduct the usability from a neighborhood scale (shown as Fig. 6 and Table 3). To be summarized, several disciplines in term of spatial attributes and layouts of well-accessed sub-districts to ***commercial facilities*** (between 25.17 and 7.05) can be generalized. Firstly, when residential areas are distributed as clusters, commercial facilities with various sub-categories and service radii placed in the middle of residential clusters, including mixed-used with the living areas are easy for the local to be achieved. Even though most of them are not located along the primary urban roads, the density of road network is high, which leads to good accessibility. In addition, if residential areas in the sub-district are located and combined with those in the adjacent sub-district as a large living cluster in an aggregated spatial form, commercial facilities distributed on the edge of the residential areas and are closed to the main roads can create more equal opportunities and services for locals to reach. Taking the geolocation into consideration, what is similar is that a sub-district adjacent to multiple sub-districts can effectively receive positive impact on the provision of services and accessibility from others.

After analyzing the sub-districts with highest accessibility (from 57.96 to 21.98) to ***educational facilities***, with large total area of educational amenities and high supply and demand ratio, it is better to allocate the educational facilities evenly surrounded by residential areas, and closed to the main roads. The corresponding proximity and adequate connectivity across sub-districts can increase the spatial equality of using educational amenities within regions. By means of gathering and grouping residential communities with those in the neighboring sub-district(s), evenly distributed educational facilities among residential clusters and configured them closely to the main roads can help improve the accessibility to UPFs for local residents. Also, high road density connecting adjacent sub-districts provides good connectivity and more equal chances for the residents throughout the region to use facilities.

In addition to density, road pattern plays an important role on increasing the accessibility for local residents to reach ***healthcare facilities***. In particular, the ring and radial road network with good road density could enhance the service range, which makes the accessibility between the residential areas and the healthcare facilities sufficient. Due to the level of care, people might prefer to travel to high-level hospitals rather than receive treatment nearby. Allocating healthcare facilities along the main urban roads which crosses several administrative districts and residential communities would effectively create a positive impact on spatial equality in terms of accessibility.

Table 3
Characteristics of the top five accessible sub-districts including the total area, population, road density, number of facilities, supply-demand ratio, and accessibility.

Name of the sub-district	Population density	Road density	Sum supply-demand ratio	Average accessibility
Commercial facility				
Yuehai	0.0079	0.00998	805.12	25.17
Shekou	0.0045	0.00597	200.98	16.7
Dapeng	0.0001	0.00123	109.22	9.94
Buji	0.0031	0.00575	321.53	7.98
Xixiang	0.0017	0.00355	598.76	7.05
Educational facility				
Bantian	26,739	0.0033	1807.54	57.96
Minzhi	23,301	0.0043	1378.32	31
Dongxiao	15,600	0.0034	584.26	25.44
Huafu	11,491	0.0065	494.16	23.6
Donghu	12,607	0.0005	77.41	21.98
Healthcare facility				
Guangming	0.0001	0.00185	152.57	61.21
Pinghu	0.0005	0.0053	116.29	40.91
Nanhu	0.0065	0.01485	159.05	38.48
Guanlan	0.0007	0.00331	392	29.48
Dalang	0.0013	0.00341	8.16	23.94
Cultural and sports facility				
Nanshan	0.0038	0.00584	61.77	15.73
Nantou	0.0051	0.00834	188.72	13.95
Kengzi	0.0002	0.00364	170.33	12.79
Meisha	0.0002	0.00241	42.71	9.95
Songgang	0.0006	0.00481	314.31	5.64
Landscape facility				
Guangming	0.0001	0.00185	42348.2	4215.32
Guanlan	0.0007	0.00331	32111.7	1793.08
Pingshan	0.0002	0.00209	125,438	1061.16
Dalang	0.0013	0.00341	31,895	978.23
Buji	0.0031	0.00575	35083.8	824.62

As for the ***cultural and sports facilities***, when separated residential areas are well-connected or residential areas of the adjacent sub-districts are banded by an internal traffic system, such integration could cause positive effect from surrounding services efficiently enhance the spatial equality of the local sub-district. Moreover, despite connectivity containing multiple levels of cultural and sports facilities with high road, distributing them along primary urban road and next to the residential areas can provide direct access and increase the spatial equality for the residents.

In regard to ***landscape facilities***, it is effective to improve spatial equality by allocating landscape spaces closely to the administrative boundary, preferably in a continuous shape, which encloses the residential areas and the whole sub-district with nature. Also, sandwiching the residential communities in the middle makes the distance from all residential areas to the landscape facilities relatively close, while the potential for the residents to reach these facilities could be more equal.

4.4. Design guidelines promoting equal accessibility

This research explores the level of spatial equality for local residents in their ability to access and use urban pubic facilities. This was done through the measurement of spatial accessibility, together with the interpretation of spatial allocation and configuration of relevant urban elements including residential community, UPFs, and transportation. The results demonstrate that, from a design perspective, within highly accessible sub-districts, spatial clues sometimes overlap and are not mutually exclusive. After extracting and synthesizing these findings, a series of location-specific design interventions referring to relatively equal accessibility can be refined as follows.

a. To facilitate resource sharing, proximity, and the accessibility of facilities, it is possible to allocate residential communities from neighboring sub-districts into an integrated residential cluster, or to organize residential communities along primary urban roads which effectively connects people to the neighboring facilities.
b. When the location of residential communities reveals an aggregated distribution pattern, configuring facilities within the residential clusters, preferably closed to urban main roads, would promote accessibility to amenities.
c. When residential communities are evenly distributed in a scattered manner, the accessibility of facilities could be improved by arranging plenty of small-sized public services together with the dispersive residential areas and urban main roads.
d. The diversity of facilities with different service radii play an important role in improving service capacity and the corresponding spatial equality.
e. Developing the overall road density within the sub-district can effectively increase accessibility between residential areas and facilities.
f. Some types of facilities (e.g., high-tier hospital, large urban park, large-scaled shopping center, and museum) are commonly used to serve the public from a city level rather than the nearby residents. Therefore, the "cross-district impact" of these facilities especially rely on a sufficient transportation network.
g. In terms of spatial layout, allocating facilities in the center of the ring and radial road system could be beneficial for accessibility.
h. Unlike other facilities, landscape facilities covers larger areas and often spans multiple sub-districts or administrative districts. Continuous distribution of landscape facilities surrounding residential areas could improve people's accessibility to nature.

5. Discussion

Studies about spatial equality analysis have appeared in abundance [23,74,94]. However, these studies have primarily focused on accessibility analysis [see, for example, 32, 37, 55, 73]. Although accessibility analysis is critical, urban design involves more than just accessibility analysis as it concerns the arrangement, appearance, and function of urban areas [19]. Therefore, to serve the public interest, spatial equality analysis for urban design must also consider how to design and configure specific physical urban elements. While studies such as those by Dovey [17] and Moughtin, Cuesta [3] have emphasized the importance of spatial composition and configuration strategies, few have incorporated them into their research design and analysis. This paper addresses this gap by proposing specific spatial design strategies.

In the academic literature, accessibility analysis can be conducted through two primary approaches, namely place-based and individual-based analysis [96,97]. The place-based analysis approach involves the use of density or proximity measurements to assess the availability of nearby facilities. This method relies on models like cumulative-opportunity models and gravity-type models to evaluate the accessibility of a specific reference location [32,98,99]. In contrast, individual-based analysis, exemplified by time-geographic accessibility metrics, accounts for individual mobility constraints and examines an individual's capacity to access facilities [100]. This paper adopts the 2SFCA method, which is anchored in the gravity model, as it combines the features of both place-based and individual-based analysis. This method considers both the distance decay effect, whereby the level of interaction between two locales decreases as the distance between them increases, and the demand and supply of facilities to provide a more comprehensive assessment of accessibility [92].

This paper studies five main categories of UPF (commercial facilities, educational facilities, landscape facilities, healthcare facilities, and cultural and sports facilities) and successfully adopts multi-source open data to conduct the analysis. Compared to the majority of the existing studies which focus on only one or two types of UPFs [52,64], this study can provide a more comprehensive understanding of the UPFs within the studied city. Moreover, such a study can help policymakers and urban planners make more informed decisions about how to allocate resources and prioritize investments in public infrastructure.

The existing national *Code for Urban Public Facilities Planning* only suggests and sets requirements about the quantity and total area

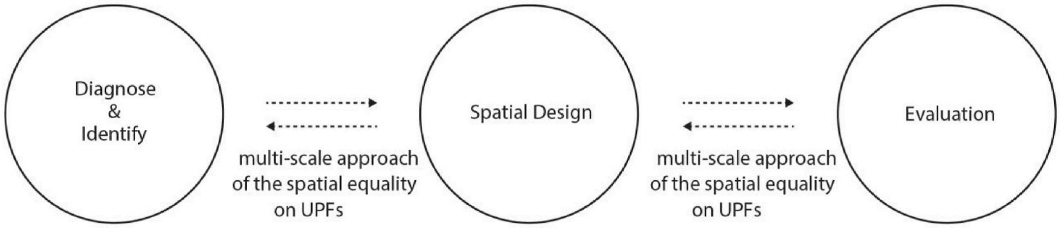

Fig. 7. The role of the multi-scale approach on the spatial equality of UPFs throughout an iterative design process.

of each type of facility. To complement it, this research provides a multi-scale approach as a toolbox to describe, measure, and interpret spatial equality of UPFs, which has the potential to be applied in the whole planning and design process. It is helpful for practitioners, such as urban designers and decision makers, to understand the spatial distribution and the configuration of public amenities, and also guide location-specific design interventions to increase equal accessibility to the urban services. Appraisal from a city/district scale could help build up an overview of the status quo and identify particular spatial distribution features of different facility types, for example the spatial aggregation, evenness, and dispersed-clustered situation of the congeneric facilities [8]. Analyses from the sub-district scale are able to identify unequal areas and reveal the matter of spatial equality in terms of supply-demand relations. From a site scale, design guidelines and principles generated from highly accessible projects enable urban designers to layout the facilities, address the relationship between residential areas and amenities, and provide effective transportation links. As shown in Fig. 7, this multi-scale approach could act as tools for analysis, design, and evaluation in an iterative design process, which aids to study the status of UPFs, evaluate the effectiveness of the design changes or refinements, and review the improvement of spatial equality. On the other hand, a thorough interpretation of the spatial equality of UPFs can help urban planners and designers to gain new insights in the form and functioning of urban spaces in order to become more conscious about the spatial equality relevant to urban services.

6. Conclusion

In recent decades, urban design has witnessed a shift from 'making good places' to 'making good places in the public interest'. In other words, current urban design practice not only deals with the placement of buildings and spaces in between, but also about serving the public interest through creating better spaces. Therefore, for urban designers and policy makers, the analysis of spatial equality, as an indispensable concern, is a necessity for achieving good urban design results. Since UPFs widely distributed in the city are the most relevant physical elements for the public interest, this paper aims to understand the spatial equality of UPFs, as well as to explore applicable spatial strategies for future urban design. With one of the fastest urbanization processes and greatest economic growth in China, Shenzhen was selected as the case study for this research because of its urgent spatial inequality issues.

To fulfil the aim, this paper proposes a multi-scale approach to analyze the spatial equality of UPFs. This approach consists of three steps: the first step was to investigate the spatial distribution and configuration of UPFs at the district level by measuring the density and aggregation of different types of UPFs; the second step was to analyze the accessibility of UPFs at a sub-district level via 2SFCA, as well as the spatial autocorrelations between adjacent sub-districts; the third step was to zoom in and examine location-specific design strategies for creating greater equality by exploring spatial layouts formed by the road network, residential community, and UPFs.

As the results show, "cross-district impact" plays an important role in facilitating overall spatial equality, for example, allocating residential communities from adjacent sub-districts into integrated residential clusters to share resources and improve the proximity and accessibility to UPFs. Moreover, high-tier and large-sized facilities are commonly used to serve the public from a city level rather than on the local residents, therefore, a sufficient transportation network and reasonable road configurations (e.g., ring and radial patterns) are relatively influential to achieve a holistic equality. Last but not the least, spatial clues of organizing different UPFs sometimes overlap and are not mutually exclusive. According to site conditions, a diversity of facilities with different sizes, service radii, and layout could effectively improve service capacity and the corresponding spatial equality.

As scientific added value, the multi-scale approach proposed in this paper is new to current literature. As a toolbox, it has the potential to be applied throughout the whole planning and design process. This is especially true for urban designers and decision makers to understand the spatial distribution and configuration of public amenities, and also guide location-specific design interventions to increase equal accessibility to the facilities. The analytical framework as such will be useful in other types of analyses as well, as it has two further dimensions: time dimension and space dimension. The time dimension means it can be utilized when conducting longitudinal studies to understand how spatial equality has evolved over time in a given city. The space dimension stresses that the framework can be applied to other cities or regions in or outside China for comparative purposes.

It is worth acknowledging that this paper has some limitations regarding the scope of urban public facilities (UPFs) and data issues. The scope of UPFs has been ever-expanding, from essential livelihood facilities (e.g., schools, hospitals, and fire stations) to higher ideological requirements of humans (e.g., landscape, opera houses), and further concerns about environmental issues, for example, toxic-release facilities and waste management facilities. To fully understand the spatial equality of UPFs, it will be meaningful to take various types of services into consideration in future studies when given more time and staff capacity. Besides, although the paper takes the demand of UPFs into consideration by utilizing the Two step floating catchment area (2SFCA) to calculate the supply-demand ratio for each facility while data on facility supply, population at demand locations, travel cost measured by distance, and facility service radius are collected and analyzed, it does not specifically examine the differences in demand among different population groups. However, it must be pointed out that the main focus of this paper is to develop the multi-scale approach, and thus, the investigation of the specific demand disparities among different groups is not the primary objective. In addition, the mapping approaches employed in this study also have limitations in terms of open data acquisition, processing time, and existing calculation formulas, and the results are dependent on the quality of the data. Nonetheless, as indicated before, this paper's primary contribution lies in its multi-scale approach to comprehensively understanding spatial equality in UPFs from a design perspective. Thus, while the research could benefit from more precise methods and more accurate data, the approach is the core of the research.

Author contribution statement

Mei Liu; Juan Yan: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Tianchen Dai: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e18281.

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