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Three-dimensional walking accessibility to multi-type public open spaces: Spatial equality and planning implications

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Abstract: Accessibility to public open space (POS) is critical for promoting walking and outdoor physical activity. In dense, vertically developed cities, traditional two-dimensional accessibility measures fail to capture the complexities of vertical and slope movement. This study addressed this gap by incorporating three-dimensional (3D) distance into walking accessibility assessment and examining spatial equality across multi-type POSs. A research framework was established integrating Gini index-based equality measurement, regression analysis of influencing factors, and multivariate grouping of street blocks to inform planning strategies for equitable POS distribution. The framework was applied to the case of the Kowloon district in the vertical city of Hong Kong. Spatial (in)equality of 3D walking accessibility for different POSs, including local POSs, district and regional POSs, POSs with children's playgrounds and POSs with fitness equipment for the elderly was measured and interpreted. The results suggested that small-scale local POSs were undersupplied compared to large ones, while accessibility inequality was more pronounced for child- and elderly-oriented facilities. Ethnicity was the most influential social-economic factor in the spatial heterogeneity of POS distribution. Spatial grouping analysis identified only 16.03% of the area as "optimizable zones" suitable for renewal interventions, with the remainder classified as "deadlock" (high-density constraints) or "stagnant" (low renewal urgency) zones. Future urban renewal projects should pay more attention to the improvement of POS quality and spatial equality. The proposed framework offers transferable methodologies for enhancing POS spatial justice in high-density cities through data-informed planning and governance.

Keywords: public open space, three-dimensional walking, children and the elderly, spatial equality, dense city

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1 Introduction

The importance of urban public open space (POS) providing multiple services has been recognised by cities worldwide, while differences in the quality or accessibility attributes of POS are receiving increasing attention from researchers. Access to an attractive, large POS is associated with higher space quality and higher levels of active use (Coombes et al., 2010; Giles-Corti et al., 2005). Accessible POSs may promote

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public physical exercise and deliver ecosystem services for mental benefits (Wang et al., 2021; Wood et al., 2017). In recent studies, accessibility to POSs not only means frequently adhering to "park minimum standards" but also considering the variations in forms and functions of multi-type POSs (Kimpton, 2017; Sharifi et al., 2021), as well as spatial (in)equality regarding socioeconomic disparities in distribution (Chen et al., 2020; Csomos et al., 2021).

The impacts of POS features on accessibility have been evaluated from different dimensions. For example, POSs in Brisbane were classified according to 12 functional and physical characteristics to understand their association with social equity (Kimpton, 2017) while in Sheffield, POS distribution was found to vary with socioeconomic deprivation when concerning publicly accessible POSs, POSs providing health benefits and POSs specifically for children and young people (Mears et al., 2019). However, research explaining the ambiguity around the causes of POS inequality is still insufficient (Sharifi et al., 2021).

In addition, despite extensive studies on POS accessibility, three-dimensional (3D) walking accessibility has rarely been studied, except for a study of Hong Kong (HK), where both horizontal and vertical distances were included in measuring POS accessibility (Tang et al., 2021). This may be because (1) HK is a vertically built city with a considerably dense population and buildings whose POS accessibility is overestimated by conventional two-dimensional (2D) measurements, thus deviating from real walking distances and (2) the newly established 3D Pedestrian Network database published by the HK government in 2020 has not yet been used in other cities. It contains street topographies, physical impedances and formal crossings that enable researchers to incorporate vertical distances into accessibility analysis. However, 3D accessibility analysis based on the relationship between multi-type POSs and the diverse demands of groups of people (e.g., children, youth and the elderly) is still lacking.

Urban renewal plays a dominant role in improving the built environment and the service quality of POSs of cities confronting spatial inequality worldwide. Nevertheless, for dense cities such as HK, plot ratio schemes, conducive to fuelling redevelopment and relieving the government deficit, are challenging to implement in favour of residents in highly dense and expensive areas (Lin et al., 2022). Therefore, confronting the difficulties in increasing large areas of POS in a dense urban core, there is a need to understand the potential of improving POS equality through feasible redevelopment or renovation in the long-term renewal process.

Focusing on how the equality of POS 3D walking accessibility could be optimized, this study aims to evaluate the spatial (in)equality of multi-type POS accessibility based on 3D analysis, explain spatial heterogeneity and propose actionable strategies for enhancing POS equity through urban renewal. Three sub-questions will be explored: (1) How does 3D walking accessibility vary across different POS types in terms of spatial equality? (2) Which socioeconomic and built-environment factors are significantly associated with POS accessibility inequality? (3) How can urban renewal projects be prioritized to reduce spatial inequities in POS accessibility?

Taking Kowloon District in HK as an example, 3D accessibility and spatial inequality (Gini index) were measured for different types of POSs and explained by regression models, considering the impact of socioeconomic, spatial and land-use factors. Multivariate grouping analysis was conducted to compare equality among street blocks and to target potholes with relatively low accessibility. Strategies for improving POS provision in different clustered zones were finally discussed. This study contributes a research framework for measuring and understanding 3D accessibility, which could be generalised to other dense cities aiming to enhance the spatial equality of multi-type POS.

2 Literature review

2.1 Factors relating to POS accessibility and spatial inequality

POS accessibility is shaped by a complex interplay of spatial, socioeconomic, and policy factors, which collectively contribute to systemic spatial inequalities. At the spatial level, POS accessibility is influenced by multi-scalar determinants. Macro-scale urban structure studies indicate a general decline in accessibility from central urban cores to peri-urban areas (Chen et al., 2020), though some city centers paradoxically concentrate high-quality resources, creating localized inequities (Tian et al., 2021). Micro-scale factors further modulate these patterns: proximity to commercial areas and green spaces (Guo et al., 2019), building density and vertical stacking (Tang et al., 2021), street connectivity, and pedestrian infrastructure design (Park & Guldmann, 2020) collectively shape accessibility. Natural features such as rivers and forests also play a role, with their presence or absence altering spatial dynamics (Liang et al., 2021). However, even strategically located POS may fail to deliver equitable access if entrance designs are poorly integrated with pedestrian flows or arterial streets create physical barriers (Tang et al., 2021).

Socio-economic factors shape POS accessibility through dual mechanisms: as direct supply-side determinants and as spatial inequality indicators. Housing markets exemplify this duality, where higher property prices drive superior POS provision in affluent areas through market mechanisms (Guo et al., 2019; Tang et al., 2021), while reinforcing exclusionary hierarchies that marginalize low-income communities (Chen et al., 2020). Vulnerable groups face compounded effects: elderly residents' 20-30% reduced mobility ranges (Guo et al., 2019) and children's inadequate playground access (Yu et al., 2023) reflect both technical design challenges and systemic neglect in disadvantaged neighborhoods. Ethnically, linguistic-cultural barriers directly limit POS engagement (Mushangwe et al., 2021), while spatially concentrated segregation patterns (Reyes et al., 2014) institutionalize these disparities, creating self-reinforcing cycles of exclusion in urban planning process (Rigolon et al., 2024). Low-income communities endure fragmented POS provision coupled with limited influence over planning decisions (Chen et al., 2020; Wang et al., 2022), explaining socioeconomic factors' dominance in accessibility variability in cross-city studies (Tang et al., 2021; Wu & Kim, 2021).

Spatial inequality stem from historical policy trajectories. Private governance regimes further entrenched exclusion by creating gated POS catering to affluent groups (Rigolon et al., 2024). while marginalized communities in high-density, low-yield areas were systematically underserved (Yu et al., 2023). In Hong Kong, market-oriented urban renewal approach has historically favored commercial development over POS provision, resulting in significant POS deficiencies in densely populated, economically disadvantaged areas (Yu et al., 2023). The factors that relating to POS accessibility were shortlisted and shown in Table 1.

Table 1. Factors relating to POS accessibility and spatial equality

Dimension	Factor	Study area	Reference
Spatial	Distance to the nearest commercial area Distance to the nearest green space	Beijing, China	(Guo et al., 2019)
	Number of building units	HK, China	(Tang et al., 2021)
	Locality (job density, street density, built area to dissemination area ratio)	Montreal, Canada	(Reyes et al., 2014)
	Urban heritage Natural landscape	Ohio and Georgia, US	(Park & Guldmann, 2020)
	Communities within the inner, middle, or outer ring road	Shanghai, China	(Chen et al., 2020)
	Distance to rivers, forests, wetlands, lakes, roads, road intersections, or residential areas	Dongguan, China	(Liang et al., 2021)
Social-Economic	Country of birth Spoken language (English or not)	Australia	(Mushangwe et al., 2021)
	Racial and lifestyle diversity Income	Ohio and Georgia, US	(Park & Guldmann, 2020)
	Deprivation level	Sheffield, UK	(Mears et al., 2019)
	Gender, income, and family structure	Montreal, Canada	(Reyes et al., 2014)
	Mean property price Percentage of residents <15 years old Percentage of residents >64 years old	HK, China	(Tang et al., 2021)
	Disadvantaged/advantaged groups Minority groups	Macau, China	(Ye et al., 2018)
Policy	Past planning	Shanghai, China	(Fan et al., 2017)
	Temporal evolution of housing policy	Lodz, Poland	(Laszkiewicz et al., 2021)
	Building age	HK, China	(Tang et al., 2021)
	Policies for upgrading micro-scale POS	Macau, China	(Ye et al., 2018)

2.2 Planning interventions for spatial equality of POS

Contemporary planning strategies address the challenges of spatial inequality through spatially innovative and policy-driven approaches. In land-constrained urban cores, micro-scale interventions in residual spaces such as demolition zones and vacant street corners are repurposed into pocket parks (<0.5ha) to incrementally improve local access (Guo et al., 2019), while vertical connectivity enhancements—including rooftop gardens, vertical green walls, and sky corridors—mitigate spatial fragmentation (Yu et al., 2023). Pedestrian infrastructure upgrades informed by 3D network analysis, particularly in slope-intensive areas, have shown measurable improvements in walking accessibility (Tang et al., 2021). Integrating POS with transit-oriented development further amplifies accessibility benefits, particularly for car-free populations (Wang et al., 2022).

Policy innovations are equally vital. Inclusionary zoning mandates requiring POS provision in redevelopment projects ensure baseline public space allocation (Verheij et al., 2023), while participatory planning processes empower marginalized communities in decision-making, countering historical biases in resource allocation (Rigolon et al., 2024). Macau’s policy interventions demonstrate the efficacy of such approaches, with before-after studies showing significant accessibility improvements following targeted upgrades (Ye et al., 2018). Successful implementation also includes comprehensive activity mapping to identify usage patterns (Park & Guldmann, 2020) and optimization of public transport routes (Wang et al., 2022). These strategies collectively represent a paradigm shift from quantity-based standards to equity-driven planning, and offer actionable pathways to enhance POS accessibility in high-density cities globally.

3 Materials and methods

This study evaluated the spatial (in)equality of multi-type POSs accessibility based on 3D analysis, analysed the socio-spatial heterogeneity of accessibility and discussed planning implications. The methodological framework of this study is illustrated in Figure 1. The research framework was applied to the case of Hong Kong. The supply of multi-type POSs includes local POSs, district and regional POSs, POSs with children's playgrounds and POSs with fitness equipment for the elderly. The demand of POSs was calculated based on the population in Large Street Block Group (LSBG).

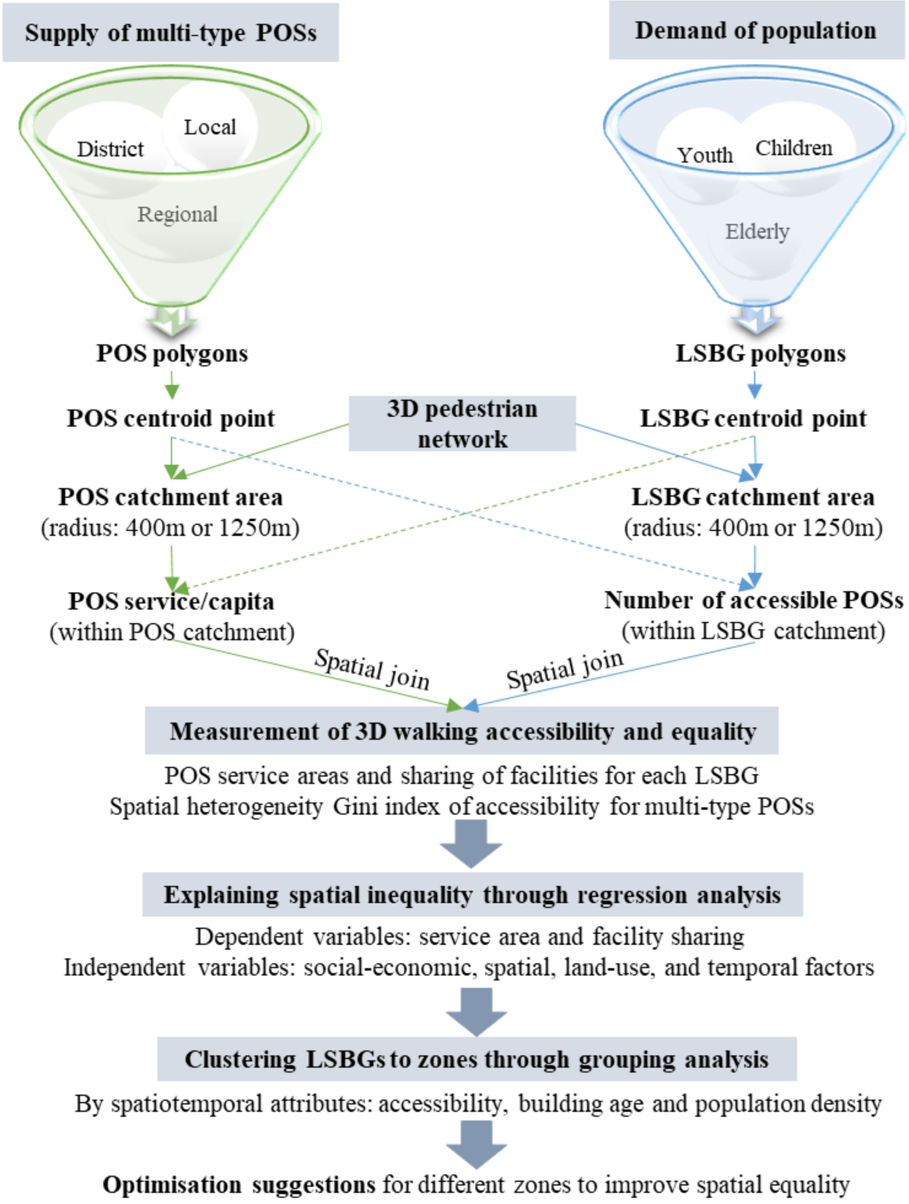


Figure 1. Research framework for analysing the equality of 3D accessibility of multi-type POSs

3.1 Data collection

3.1.1 Multi-type POSs

According to the *Hong Kong Planning Standards and Guidelines* (“the Standard”), POS category was defined in Chapter 4, “Recreation, Open Space & Greening” as follows:

- Local POS: at least 500m2 in urban areas and a maximum building site coverage of 5%;
- District POS: at least 1 ha in size and a maximum building site coverage of 10%;
- Regional POS: at least 5 ha in size and a maximum building site coverage of 20%.

POS data from the Leisure and Cultural Services Department (LCSD) of HK was collected from the List of Facilities & Venues on the official website of the LCSD. Data regarding POSs managed by the Housing Department (HD) in public housing estates was collected via email from the HD and Housing Authority. Except for the type and size of POS, facilities for conducting activities were also identified. Parks, gardens, playgrounds and promenades provide play facilities for children. POSs with elderly fitness equipment were identified following information from the Elderly Fitness Corner on the official website of the LCSD. POSs in public estates have facilities for both children and the elderly.

Overall, the dataset of POSs in Kowloon consisted of 367 POSs providing general fitness stations, including 288 local POSs (500 m2~1 ha), 66 district POSs (1 ~5 ha) and 13 regional POSs (>=5 ha). Two hundred forty-five POSs in the dataset had children’s playgrounds, and 208 POSs had fitness equipment for the elderly.

(a) General fitness station (b) Children’s playground (c) Fitness equipment

Figure 2. Different public open space facilities in Hong Kong for physical exercises

3.1.2 Spatial-temporal data

Spatial data collected from the Public Sector Information Portal (https://data.gov.hk/en/) consisted of the following three datasets: (1) the 3D Pedestrian Network provided by the Lands Department for 3D distance measurement, (2) spatial elements such as buildings, roads, railways and stations extracted from the digital typographic map provided by the Lands Department and (3) land utilization in Hong Kong provided by the Planning Department.

Unlike accessibility in 2D measured through the Euclidean distance or Manhattan path distance (Zhang et al., 2021), the walking distance measured, based on the 3D Pedestrian Network, considered the vertical distance generated when walking aboveground through footbridges or underground through subways. The inclusion of vertical distances means that a specified travel distance, such as 100 meters in a 2D environment, accounts for elevation changes resulting in a shorter radius (<100 meters) that differs from those generated by a purely 2D analysis. This method captures the complexity of urban environments, where elevation can significantly impact accessibility. Consequently, the

3D path distance is more accurate to reflect the actual travel behavior and walking accessibility to places, particularly in vertical and dense cities such as HK, which is well known for its footbridge connectivity between tower blocks.

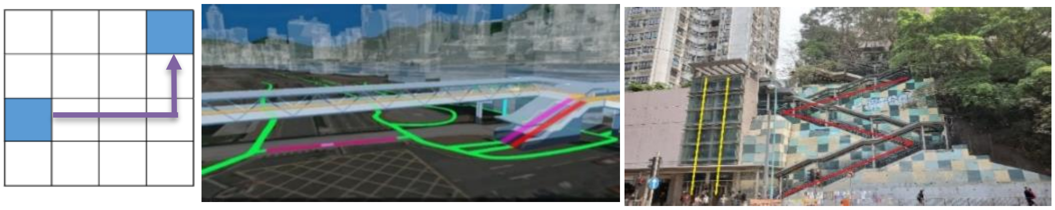

(a) 2D Manhattan distance (b)3D Pedestrian Network (c)The vertical walking environment in HK

Figure 3. Illustration of two-dimensional (2D) versus three-dimensional (3D) distance measurements.

Temporal data implying the ages of buildings was collected from Name of Buildings published by the Rating and Valuation Department (https://www.rvd.gov.hk/en/) and from the website of Centaline Property (https://hk.centanet.com/estate/index). The mean age of each street block was calculated by the average age of the buildings within the boundary.

3.1.3 Demographic characteristics of street blocks

The statistical data for the populations of the Large Street Block Group (LSBG) in 2016 was collected from the official website of population-by-census published by The Census and Statistics Department. LSBG is the basic unit for population statistics, with rich demographic data. The whole city of Hong Kong comprises three main regions (Hong Kong Island, Kowloon and the New Territories), which were subdivided into 18 District Council divisions, 291 TPU divisions and 1622 LSBGs in a top-down way. The LSBGs in Kowloon with a mean area of 8.3 hectares are suitable for measuring walking accessibility. In Kowloon, 537 LSBGs were adopted as the analytical units in this study.

The populations of the LSBGs were characterised by age group (below 15, 15–64, and 65 above), median monthly domestic household income (HK$) and domestic household by tenure of accommodation (owner-occupier, tenant and others). Boundaries of Tertiary Planning Units & Street Blocks / Village Clusters provided by the Planning Department were retrieved from the Public Sector Information Portal.

3.2 Equality measurements regarding the 3D walking accessibility of POSs

3.2.1 Service areas of POSs per capita

The Two-Step Floating Catchment Area (2SFCA) method has become a gold standard for accessibility analysis due to its unique ability to: (1) dynamically balance supply-demand relationships through bidirectional searching (unlike static buffer approaches) and (2) reveal spatial mismatches across population subgroups These advantages have made it widely applicable in healthcare accessibility studies and recreational resource evaluations (Chen & Jia, 2019; Cui et al., 2022; Yang et al., 2006). This study advances the 2SFCA method in two key aspects for vertical cities: (1) vertical impedance in walking networks (e.g., elevation change) and (2) type-specific POS capacity metrics (e.g., playground units for children's POS). This enhanced approach allows more precise equity assessments in high-density environments where traditional 2D methods overestimate accessibility for disadvantaged groups residing in topographically challenging areas, such as those hillside communities in Kowloon.

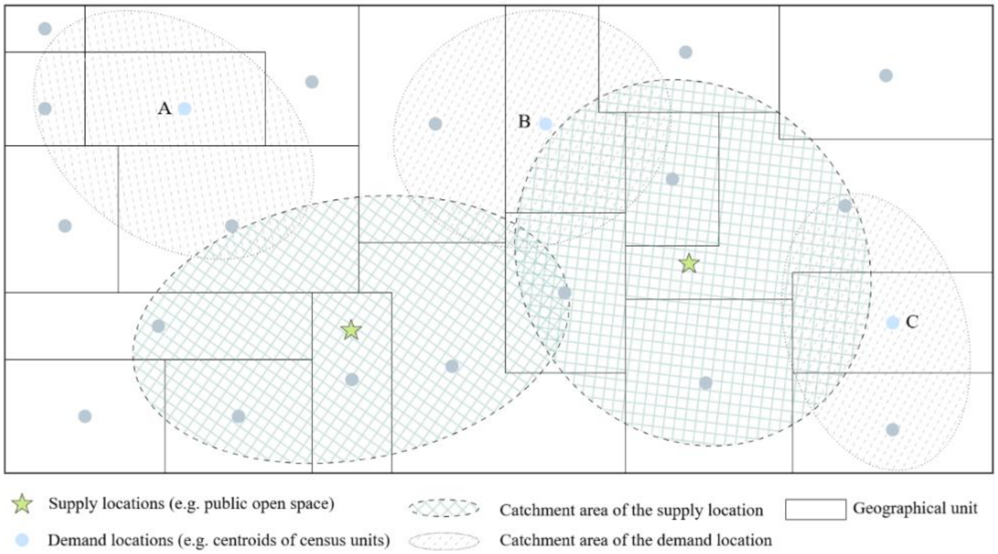


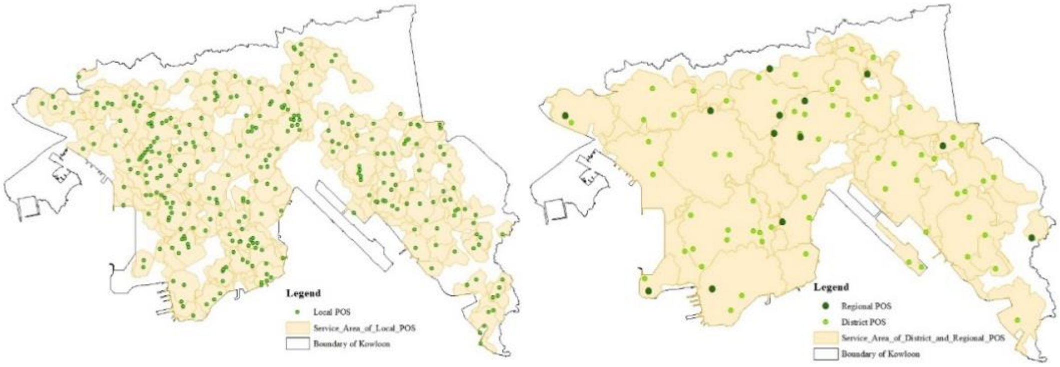
Figure 4. Bidirectional supply-demand catchment areas in the 2SFCA

For data modelling in 2SFCA, demand points were represented by centroids of demographics units to reflect the spatial distribution of population demands. Supply points were denoted by the geographic centroids of service facilities. As illustrated in Figure 4, the dashed lines around the demand and supply locations indicate their respective catchment areas, which define the accessibility thresholds. The catchment area of the supply location is used to identify the demand locations that can access that supply, while the catchment area of the demand location is used to identify the supply locations that can serve that demand.

The 2SFCA method involves two sequential spatial operations to quantify walking accessibility to public open spaces (POS). Firstly, for each POS, a pedestrian catchment area (shown as green cross hatch ellipse) was defined based on a threshold walking distance. For each catchment area: (1) sum the population (demand) from all intersecting statistical units, and (2) calculate the supply-to-demand ratio $R_j = \frac{S_j}{\sum_k P_k}$, where S_j is the POS capacity and P_k is the population within the catchment.

For each population unit, a walking catchment (grey dashed ellipse in Fig.5) was defined using the same distance threshold as applied to POS locations, and sum the R_j values of all POS within this zone to compute accessibility $A_i = \sum_j R_j$.

In this study, "service area per capita" was calculated using ArcGIS Pro following the rules of the 2SFCA method that quantifies the distribution of POS supply versus population demand. The term "service area per capita" refers to the area of a POS within a catchment that can serve one person. The distance thresholds of 0.4 km and 1.25 km were adopted for identifying the catchment area (A_w) of small-scale and large-scale POSs, respectively. According to the "the Standard," a local POS "should be located within short walking distance from the residents it intends to serve, preferably within a radius of not more than about 0.4 km." The threshold distances of large-scale district and regional POSs were assigned as 1.25 km (15 min * 5 km/h) since a 15-minute walking time to access living facilities is an objective in urban planning proposed for social well-being by many cities (Sugiyama et al., 2010; Zhang et al., 2021), while 5 km/h is the average person’s walking speed on flat terrain for accessibility analysis (Tang et al., 2021).



(a) Local POSs (0.4km radius) (b) District and regional POSs (1.25km radius)

Figure 5. Service areas of public open spaces (POSs) within three-dimensional walking distances

For each $LSBG_i$, the served population of each POS (P_j) was calculated with Equation 1:

$$P_j = \sum_{i=1}^{n} \frac{Pi}{A_i \times A_{iw}} \qquad (1)$$

where P_i and A_i are the population and area of $LSBG_i$, A_{iw} is the overlapped area between $LSBG_i$ and A_w of POS_j, and n is the number of LSBGs that overlap with A_w.
The service area per capita (S_i) for $LBSG_i$ was calculated with Equation 2:

$$S_i = \sum_{j=1}^{m} \frac{A_j}{P_j} \qquad (2)$$

where A_j is the area of POS_j, while m is the number of POSs, of which the catchment area (A_w) overlaps with $LBSG_i$. The unit of S_i is m^2/person.

According to “the Standard,” in the metro area, a minimum of 1 m^2/person for a district POS and a minimum of 1 m^2/person for a local POS are regulated. Regional POS provision is regarded as a bonus above the minimum standard, which can be counted by half area as district POS. Accordingly, the overall service area per capita was calculated with Equation 3.

$$Area_{overall} = 0.5 \times Area_{Regional} + Area_{Local} + Area_{District} \qquad (3)$$

3.2.2 Service of facilities per child/elderly person

Linking the supply of children’s playgrounds to the population of children (aged below 15), the sharing number of facilities per child (NC_i) for $LSBG_i$ was calculated with Equations 4 and 5:

$$PC_j = \sum_{i=1}^{n} \frac{PC_i \times A_{iw}}{A_i} \qquad (4)$$

$$NC_i = \sum_{j=1}^{m} \frac{1}{PC_j} \qquad (5)$$

where PC_j is the population of children served by POS_j that provides the facility of a playground, PC_i is the total population of children in $LBSG_i$, n is the number of LSBGs that overlap with A_w of POS_j, and m is the number of POSs, the catchment area (A_w) of which overlaps with $LBSG_i$. Considering children do not visit POSs alone but are taken by their parents, the walking distance threshold to a playground was assigned as 1,250 m to identify the catchment area (refer to Section 2.2.1).

Similarly, focusing on the supply of elderly fitness equipment and the population of the elderly (aged above 65), the sharing number of facilities per elderly person (NE_i) for $LSBG_i$ was calculated with Equations 6 and 7:

$$PE_j = \sum_{i=1}^{n} \frac{PE_i \times A_{iw}}{A_i} \qquad (6)$$

$$NE_i = \sum_{j=1}^{m} \frac{1}{PE_j} \qquad (7)$$

where PE_j is the population of the elderly served by POS_j that provides the facility of a playground, and PE_i is the total population of the elderly in $LBSG_i$. The walking distance threshold (A_w) POS with elderly fitness equipment was assigned as 400 m since the elderly normally walk short distances.

3.2.3 Lorenz curve and Gini index

The Lorenz curve is a visual representation of equality, whereas the Gini coefficient is a mathematical metric representing the overall inequality degree. The Gini coefficient, initially proposed for measuring the inequality of incomes, is the ratio of the area between the line of equality and the Lorenz curve divided by the total area under the line of equality (Gini, 1921). In this study, Lorenz curves were applied to visualise the service area of POS and the service facility cumulated across the population. The distribution of different Lorenz curves regarding 3D walking accessibility to multi-type POSs and facilities was delineated and mathematically compared using the Gini coefficient.

3.3 Regression analysis of factors associated with accessibility inequality

This analysis systematically examines the factors associated with spatial inequities in 3D POS accessibility through a staged regression framework. (1) Initial unidimensional screening evaluated four variable categories—socioeconomic, spatial, land-use, and temporal dimensions (Table 2), using General Liner Model, accompanied by variance inflation factor diagnostics (VIF < 5 threshold) to address multicollinearity. (2) Selected variables subsequently entered multivariate regression analysis employing stepwise selection with robust standard errors to screen the significant variables. (3) Model specification was adapted to distributional characteristics: Gamma regression for right-skewed dependent variables, Tweedie regression (power parameters: 1.3–1.7) for zero-inflated distributions, and Box-Cox transformations where applicable. Model selection between Gamma and Tweedie regression is guided by the Kolmogorov-Smirnov (K-S) test, with Gamma preferred for data conforming to its distribution ($p >= 0.05$) and Tweedie applied otherwise to address dispersion or zero-inflation. All statistical analyses were performed in Python using the statsmodels library for regression modeling. The analytical sample comprised 536 LSBGs, representing all residential areas in Kowloon District, Hong Kong, after excluding one LSBG in the Kai Tak development area due to its ongoing construction status during the study period. Detailed algorithmic implementations are available in Research Material.

Table 2. List of variables in regression analysis

Dimension			Name of Variable
Dependent variable (accessibility)	Area-based		Average service area of local POS/person
			Average service area of district POS/person
			Average service area of regional POS/person
			Average service area of overall POS/person
	Facility-based		Average sharing no. of facilities/1,000 children
			Average sharing no. of facilities/1,000 elderly
Independent variable (32 variables)	Social-economic (18 variables in this dimension)	By Age	Percentage of population aged <15 (%)
			Percentage of population aged 15–24 (%)
			Percentage of population aged 25–44 (%)
			Percentage of population aged 45–64 (%)
			Percentage of population aged >=65 (%)
		By Ethnicity	Percentage of Chinese (%)
			Percentage of Whites (%)
			Percentage of Filipinos (%)
			Percentage of Indonesians (%)
			Percentage of Others (%)
		By Educational Attainment	Percentage of Primary and below (%)
			Percentage of Secondary (%)
			Percentage of Post-secondary (%)
		By tenure of accommodation	Percentage of Owner-occupier households (%)
			Percentage of Tenant households (%)
			Percentage of Others (%)
			Median monthly domestic household income (HK$)
			Population density (number of people/km2)
	Spatial (5 variables in this dimension)		Distance to highway
			Distance to main road
			Distance to railway
			Distance to railway above ground
			Distance to railway underground
	Land-use (8 variables in this dimension)		Percentage of private residential land
			Percentage of public residential land
			Percentage of commercial land
			Percentage of industrial estates
			Percentage of government, institution and community land
			Percentage of roads and transportation
			Percentage of railway land
			Percentage of cemetery land
	Temporal (1 variable)		Mean "year of built" of buildings in the LSBG

3.4 Grouping analysis and planning implications

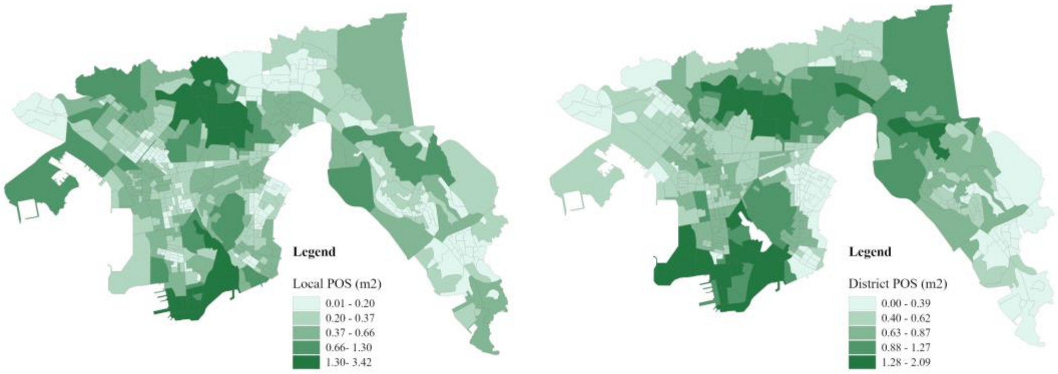
Grouping analysis was conducted to cluster the LSBGs by feature attributes to explore how future planning may improve the accessibility of POSs considering the differences in LSBGs, and enhance the spatial equity of the whole district. The Kowloon District comprises 537 LSBGs with diversified features, so one approach for improving POS accessibility could not fit all. Grouping analysis facilitates decision-makers to understand the differences in LSBGs, which ones (in clusters) should be effectively improved in the urban renewal process, and what actions should be taken for different clusters of LSBGs.

The age and population density of a block were the determinants for urban development and renewal, as ageing blocks are more likely to undergo the renewal/redevelopment process sooner, through which POS accessibility may be improved. By contrast, blocks with dense populations can hardly spare extra spaces for providing more POSs during urban renewal. Therefore, grouping analysis was conducted using ArcGIS to construct clusters with three attributes of the measured accessibility of POS, the age of the LSBG and the population density of the LSBG to categorize a district into several zones. It helps to identify the LSBGs that (1) have poorly performed in accessibility, (2) are not very dense and are able to provide more spaces for POS, and (3) are old enough to conduct urban renewal projects in coming years so that a new plan for the area may be implemented. The implications for urban planning to improve POS accessibility and spatial equity were discussed.

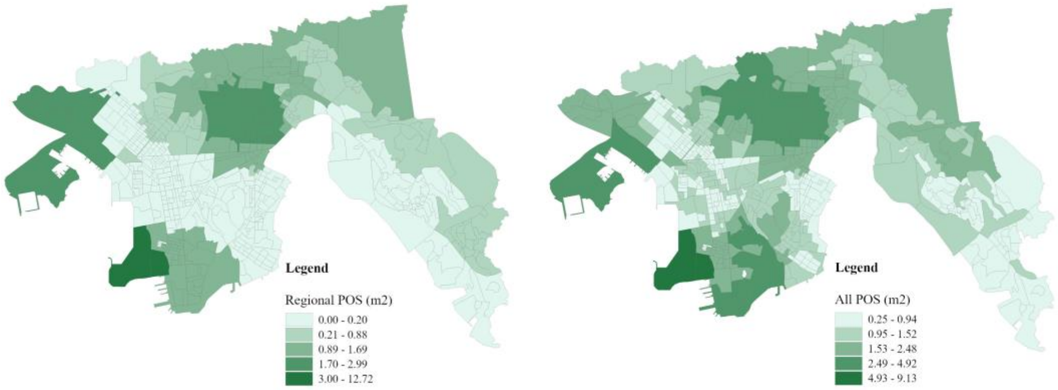
4 Results

4.1 Inequality in 3D walking accessibility of multi-type POSs

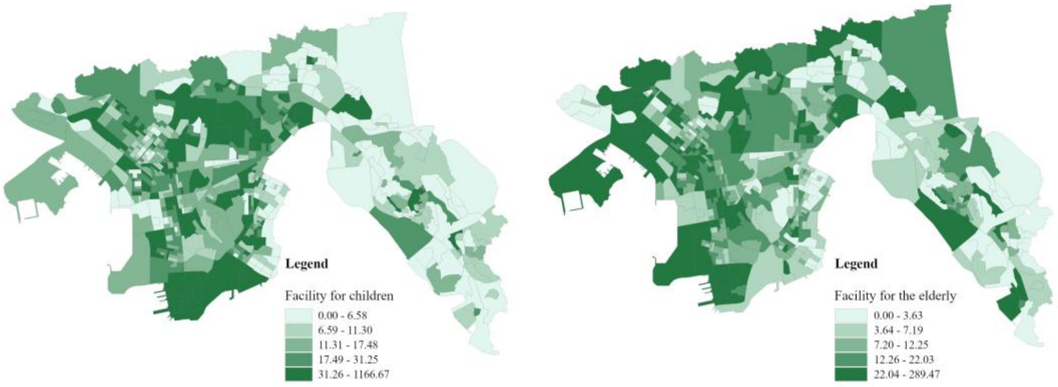
The analysis results showed that in Kowloon, the mean value service areas of local, district and regional POSs were 0.35 m^2/capita, 0.63 m^2/capita, and 0.53 m^2/capita, respectively. The overall service area of these three types of POSs calculated by Equation 3 was only 1.24 m^2/capita. Regarding the facilities, the average sharing number of playgrounds for children was 23.12 facilities/1,000 children, while the average sharing number of elderly fitness facilities was 15.77 facilities/1,000 elderly. Spatial heterogeneity in accessibility to multi-type POSs and facilities is shown in Figure 6. Inequality in accessibility illustrated by the Lorenz curve and Gini index is shown in Figure 7.



(a) Average service area of local POS (b) Average service area of district POS



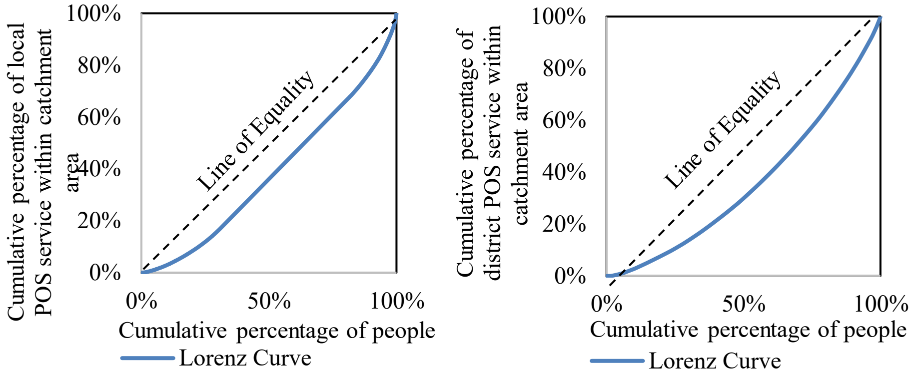
(c) Average service area of regional POS (d) Average service area of overall POS



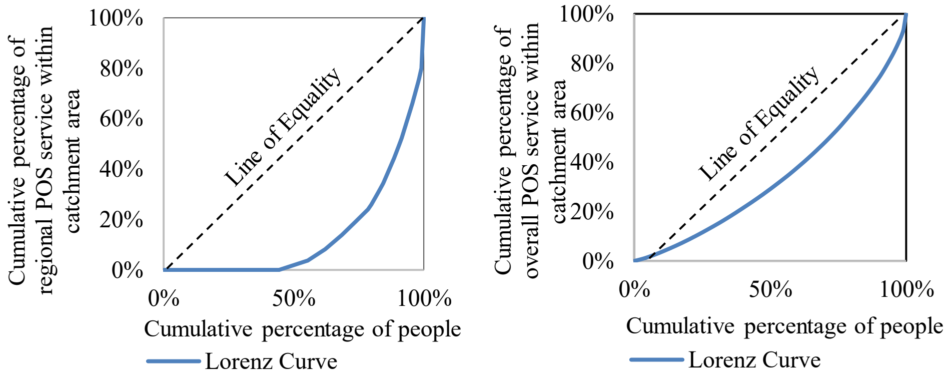
(e) Average sharing no. of facilities/1,000 children (f) Average sharing no. of facilities/1,000 elderly

Figure 6. Spatial heterogeneity in 3D walking accessibility to multi-type POSs and facilities

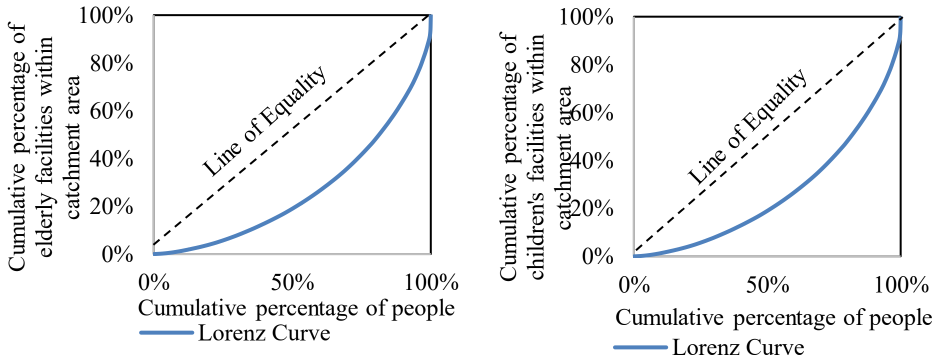
According to Figure 6, spatial heterogeneity in accessibility was evident within the study area and varied among different types of POSs and facilities. According to Figure 7, the equity of the regional POS distribution was the worst due to the highest value of its Gini index (0.72), indicating that walkability to large POSs in Kowloon needs improvement. The equity of children's facilities (Gini index = 0.47) and elderly facilities (Gini index = 0.56) was much worse than local POSs (Gini index = 0.23) and district POSs (Gini index = 0.28), as well as the overall POS (Gini index = 0.31). Therefore, more attention should be given to the provision of facilities in POSs to support the physical activities of people, particularly the vulnerable groups of children and the elderly.



(a) Lorenz curve of local POS (Gini index = 0.23) (b) Lorenz curve of district POS (Gini index = 0.28)



(c) Lorenz curve of regional POS (Gini index = 0.72) (d) Lorenz curve of overall POS (Gini index = 0.31)



(e) Lorenz curve of children's facilities (Gini index = 0.47) (f) Lorenz curve of elderly facilities (Gini index = 0.56)

Figure 7. Lorenz curve and Gini index of multi-type POSs and facilities

4.2 Regression analysis of associated factors

Based on variable screening through staged regression, variables demonstrating meaningful associations with POS accessibility were retained for regression modeling, with Gamma or Tweedie distributions selected based on K-S test results and data distribution characteristics. Table 3 shows the significant factors associated with accessibility inequality across POS types and the performance of each regression model.

Table 3. Significant factors associated with accessibility inequality across POS types

Dependent Variable (accessibility)	**Local POS**	**District POS**	**Rgional POS**	**Overall POS**	**Children Facilities**	**Elderly Facilities**
Ethnicity_White	6.20***	6.85***		0.02**	327.44***	0.07*
Ethnicity_Chinese	-0.70**	-0.98***	-0.10***	-0.60**	-50.31***	-0.08**
Education_primary	0.90**	0.63***	0.03*	0.02*		
Income_median	0.09***		0.06***	0.02*		
Distance_highway	0.00***	0.00***	0.03**	0.05***	-0.00***	
Land_private_ residence	-0.10***	-0.52***	-0.05**	-0.08***		
Land_public_ residence	-0.66***	-0.17*		-0.03**	-0.03*	
Land_commercial	0.70*				55.72***	
Road_density			-0.01*			
Model Performance						
K-S test (p-value)	0.02	0.15	0.00	0.12	0.05	0.01
Box-Cox transformations$^{\#}$	N	N	Y	Y	Y	Y
Model Type$^{\#\#}$	Tweedie	Gamma	Tweedie	Gamma	Tweedie	Tweedie
Pseudo-R^2	0.36	0.18	0.24	0.27	0.23	0.05

Note: *$p<0.1$, **$p<0.05$, ***$p<0.01$. $^{\#}$Data preprocessing included Box-Cox transformation (Y) with Tukey correction to adjust the data distribution pattern before standardization. $^{\#\#}$Gamma regression was used if the K-S test for Gamma distribution fit yielded $p > 0.05$; otherwise, Tweedie regression (with optimized power parameter) was employed.

According to Table 3, the variable Ethnicity_White exhibited strong positive associations with accessibility for Local POS, District POS, POS with children's facilities, and POS with elderly facilities, suggesting that predominantly white neighborhoods tend to have better access to these spaces. Conversely, Ethnicity_Chinese showed negative associations across most POS types, particularly for District POS and POS with children's facilities, indicating disparities in access for areas with higher Chinese populations. Socioeconomic factors such as Education_primary and Income_median were positively correlated with accessibility, with Education_primary having notable effects for Local POS and District POS, and Income_median showing significance for Local POS and Regional POS. These results underscore the influence of social-economic disparities on accessibility.

Spatial and land-use variables also played a role, though their impacts varied. Distance_highway had a consistent positive yet weak association with accessibility (for Local and District POS), while Land_private_residence and Land_public_residence displayed negative effects for Local POS. Land_commercial showed a positive association with accessibility for children's facilities, as commercial-dominated areas typically have fewer children.

Model performance was evaluated using pseudo-R² values, ranging from 0.18 to 0.36 for Local POS, District POS, Regional POS, Overall POS and POS with children facilities, indicating moderate explanatory power across these types of POS. The model of POS with elderly facilities showed notably lower fit, suggesting unaccounted factors influence its accessibility patterns. Overall, the findings emphasize that accessibility inequalities are predominantly shaped by demographic and socioeconomic factors, with land use and spatial variables contributing secondary effects, which call for targeted policy interventions to address these disparities, particularly in underserved communities.

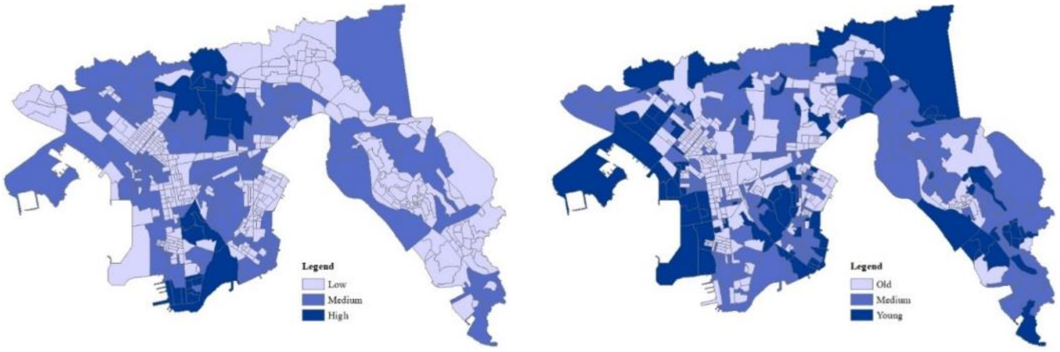
4.3 Grouping analysis by spatiotemporal variables

Since the performance of local POS accessibility was far below the minimum standard of planning among the other accessibility indexes, the improvement of local POS accessibility is the focus of this section. Three attributes were adopted for grouping analysis: accessibility, block age and population density. For each attribute, three groups (i.e., high, medium and low) of LSBGs were constructed without spatial constraints through grouping analysis in ArcGIS. Four zones were categorized, namely optimizable zone, deadlock zone, stagnant zone and comfort zone, corresponding to different statuses/potentials for accessibility improvement. Table 4 demonstrates the clusters of accessibility improvement zones, and Figure 8 illustrates the results of grouping analysis.

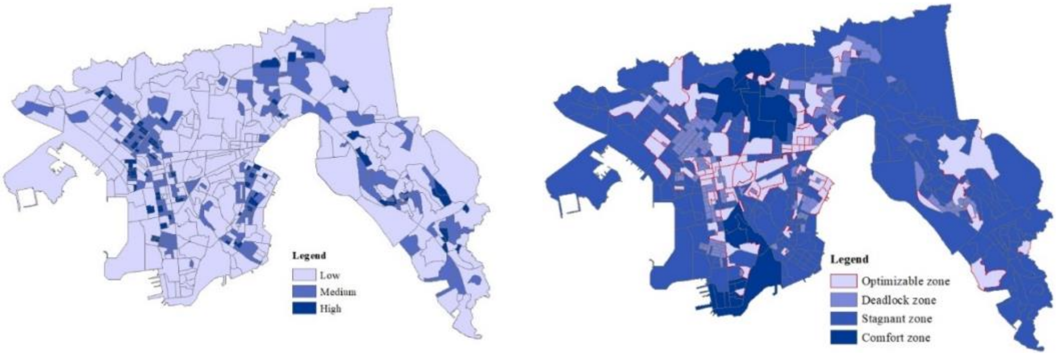
Table 4. Clusters of accessibility improvement zones by related attributes

Name of zone	**Definition**	**Feature of attribute**			**Percentage by area**
		Local POS accessibility$^{(a)}$	**Block age**$^{(b)}$	**Population density** $^{(c)}$	
Optimizable zone	Old areas that are not very dense, where POS accessibility can potentially be improved in the forthcoming renewal process	Low or medium	Old	Low	16.03%
Deadlock zone	Densely built old areas, where POS accessibility can hardly be improved in the forthcoming renewal process		Old	Medium or high	6.35%
Stagnant zone	Areas without pressing renewal requests yet did not perform well in POS accessibility		Medium or young	(N.A. #)	68.16%
Comfort zone	Areas with good performance in POS accessibility	High	(N.A.)	(N.A.)	9.46%

The groups' means of each attribute were identified through grouping analysis in ArcGIS:
Local POS accessibility – high (1.71 m^2/capita), medium (0.54 m^2/capita) and low (0.20 m^2/capita)
Block age – young (24.5 years), medium (40.7 years) and old (53.8 years)
Population density – high (273,690 population/km^2), medium (152,870 population/km^2) and low (46,477 population/km^2).
#N.A.: The attribute is not a key determinant for categorizing the specified zone.



(a) Groups by accessibility performance of local POSs (b) Groups by mean age of street blocks



(c) Groups by population density (d) Zones by potential for accessibility improvement

Figure 8. Groups of large street block groups regarding three attributes and the potential for accessibility improvement.

5 Discussion

5.1 Inequality in accessibility to multi-type POSs

According to the findings, the mean service areas of local POSs (0.35 m²/capita) and overall POSs (1.24 m²/capita) were much less than the minimum requirement of 1.0 m²/capita and 2.0 m²/capita in "the Standard." The inequality in facilities for children (Gini index = 0.47) and the elderly (Gini index = 0.56) was relatively higher than the inequality in accessibility to local POSs (Gini index = 0.23) and overall POSs (Gini index = 0.31) for the whole population. These indicated the shortage of POSs, distributional variations among LSBGs and ignorance of the people's demands for facilities, particularly for vulnerable groups. It was consistent with what has been found in HK that some neighborhoods of underprivileged families in old urban tenement buildings cannot reach a neighborhood POS by walking (Tang et al., 2021). This study advanced efforts to demonstrate and explain differentiation in POS service accessibility (whether there is a POS to visit) and facility accessibility (whether there is a POS to conduct physical activities). It also categorized spatial zones for implementing specific planning strategies, offering strategic guidance for the subsequent interconnected improvement of planned spaces.

5.2 Factors relating to spatial equality of POS

The analysis identifies ethnicity and income as key determinants of POS accessibility in Kowloon, reinforcing existing findings on urban environmental inequalities (Lou et al., 2024; Park & Guldmann, 2020). In other international contexts, it can be found that racial segregation is a also root cause of urban inequality, which in turn exacerbates the spatial segregation of disadvantaged groups (Duxbury & Andrabi, 2022; González-Pérez, 2021). Ethnicity_White showed consistent positive associations across all POS types, contrasting sharply with negative correlations for Ethnicity_Chinese. This disparity suggests systemic advantages in predominantly white neighborhoods, aligning with Hong Kong's broader patterns of environmental privilege (Lou et al., 2024). Income levels significantly influenced access to Local and Regional POS, confirming market-driven distribution patterns observed in previous studies (Guo et al., 2019). Spatially, private residential areas exhibited diminished Local POS access, likely constrained by high population density and competing land uses, while commercial zones surprisingly enhanced availability of children's facilities - a phenomenon potentially attributable to lower children population density in these areas.

These results also highlight how historical planning priorities have institutionalized socioeconomic disparities in POS provision. The strong explanatory power of demographic variables challenges conventional zoning-based approaches, underscoring the need for equity-focused interventions in underserved communities (Tang et al., 2021). The findings particularly emphasize addressing accessibility gaps in ethnically diverse, lower-income neighborhoods through targeted planning strategies.

5.3 Planning implications for spatial equality

The existing POS distribution in Kowloon reflects historical planning decisions, with future renewal projects facing significant constraints: deadlock zones (6.35% of area) are too densely built to accommodate new POS, while stagnant zones (68.16%) lack renewal urgency. Only 16.03% of land falls within optimizable zones where targeted interventions could improve spatial equality. However, Hong Kong's top-down renewal paradigm has historically prioritized capital interests over environmental enhancement (Lai et al., 2018), necessitating innovative policy approaches to ensure POS optimization in these limited opportunity areas.

To effectively address POS inequality in high-density urban contexts, an integrated strategy framework must combine revised planning standards, micro-scale interventions, and governance innovations. Moving beyond conventional land-per-capita metrics, planning standards should incorporate demographic-specific needs and POS typologies (Kimpton, 2017), ensuring proximate, well-equipped spaces for elderly populations (Wang et al., 2022) and specialized play facilities for children (Flowers et al., 2020). In space-constrained Stagnant zones where major redevelopment is unfeasible, micro-scale interventions through place-making tactics (Abd El Gawad et al., 2019) and private-sector partnerships (Wang et al., 2023) can activate underutilized spaces. Crucially, these physical interventions must be supported by governance innovations including Transferable Development Rights mechanisms (Wang et al., 2025) and participatory planning processes that counterbalance developer influence (Boulton et al., 2018; Wang & Chan, 2020), creating an institutional environment where spatial justice can be systematically pursued despite land constraints. These multi-pronged approaches recognize that sustainable improvements in POS equality require simultaneous advancements in design standards, tactical urbanism, and decision-making structures.

6 Conclusion

Spatial equality regarding meeting the demands of different demographic groups is a controversial topic for ageing dense cities worldwide, and this topic is particularly overlooked when the 3D accessibility of a vertical city is taken into consideration. This study contributes an innovative methodology to measure and explain the (in)equality in 3D walking accessibility with holistic considerations of the types of POSs and facilities provided for different groups of people. Based on this, zones were then classified, and differentiated optimization strategies for future development were proposed. 3D accessibility is more accurate than 2D accessibility in reflecting people's walking behavior, particularly for vertical cities. The impacts of socioeconomic, spatial and land-use factors on spatial equality of access to POS were investigated comprehensively. The observed ethnic disparities in POS distribution and the mismatch between POS service areas and actual facility accessibility reveal systemic deficiencies in addressing both the functional characteristics of different POS types and the varied needs of demographic groups. Optimizable zones are limited for future development, while stagnant zones need more innovative planning strategies to be optimized. This research can be a useful reference for other dense cities for improving equality in POS accessibility through urban renewal and promoting spatial justice and people's health in the long term. Since this study focuses on accessibility based on walking distance to multi-type POSs, future studies may consider walkable environment analysis and incorporate walking with transportation approaches to further demonstrate the term accessibility from other perspectives.

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Author contribution

The authors confirm their contribution to the paper as follows: conceptualization: A. Wang, Y. Yao, E.H.W. Chan; methodology, software, validation: A. Wang, Y. Yao; formal analysis: A. Wang, Y. Yao, B. Jiang; writing: A. Wang, Y. Yao, B. Jiang, E.H.W. Chan; formatting: B. Jiang; funding acquisition: A. Wang; supervision and project administration: E.H.W. Chan.

Data availability

The data presented in the study are available at https://doi.org/10.5281/zenodo.13730141.

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