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The following publication Yu, Peiheng; Chan, Edwin H.W.; Yung, Esther H.K.; Wong, Man Sing; Chen, Yiyun(2023). Open space fragmentation in Hong Kong's built–up area: An integrated approach based on spatial horizontal and vertical equity lenses. Environmental Impact Assessment Review, 102, 107174 is available at https://doi.org/10.1016/j.eiar.2023.107174.

Open space fragmentation in Hong Kong's built–up area: An integrated approach based on spatial horizontal and vertical equity lenses

Highlights:

•Understanding open space fragmentation via horizontal and vertical equity lenses.

•Various open space fragmentation forms are characterised by spatial heterogeneity.

•Old towns are embedded in more spatial horizontal inequalities than new towns do.

•Vulnerable groups are exposed to more fragmented open spaces, notably in old towns.

•New knowledge is gained regarding open space fragmentation and related inequalities.

Abstract:

Spatial equity embeddedness in fragmented open space has long been neglected but is now becoming a pivotal topic in sustainable urban development. It is unclear whether open space fragmentation has widened existing spatial inequalities. Thus, this study proposes an integrated methodological framework of open space fragmentation and its associated spatial equity issue in towns at different stages of urbanisation development. Hong Kong's built–up area could provide a typical case to unveil this topic due to the high shortage of open space, continued urbanisation, high immigrant rate, large wealth gap and aging population. The characteristics of open space fragmentation forms in old and new towns are elaborated through landscape pattern analysis and principal components analysis. Spatial horizontal equity and spatial vertical equity based on

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demographic characteristics and social economic status are portrayed by means of the Theil index and spatial matching. The findings indicate that the heterogeneity of open space fragmentation is evidenced by the uneven distribution of residents' environments in the old and new towns. Statistics reveal that in addition to shape fragmentation, the mean values of use fragmentation, internal fragmentation, extensive fragmentation and location fragmentation in old towns are all larger than those in new towns. Additionally, internal fragmentation overall is embedded in more spatial horizontal inequalities, and there is a higher level of spatial horizontal inequality in old towns than in new towns. Vulnerable groups that rely more on open spaces, including children, the elder, low education groups, immigrant groups and unemployed groups, suffer more from spatial vertical inequalities in old towns than in new towns. The knowledge gained from this research could provide a valuable reference for open space planning at home and abroad.

Keywords:

open space fragmentation; spatial heterogeneity; spatial equity; open space planning; built–up area

1. Introduction

Open space is an urban landscape that provides residents with social, environmental and economic benefits (Yung et al., 2016; Høj et al., 2021). Considering these advantages, it is of great significance to examine the provision of appropriate and equitable open space for all residents. Nevertheless, anthropogenic interference has led

to the development of urban open space from a homogeneous, unified and contiguous pattern to a mosaic form of heterogeneity, segmentation and discontinuity (Yang et al., 2014; Yu et al., 2022a). This mosaic form of open space fragmentation is expressed in morphological segmentation and inefficient connectivity of landscapes (Yu et al., 2023a), which could lead to urban ecosystem degradation, animal habitat destruction and social isolation (Kim and Pauleit, 2007; Kowe et al., 2021). Open space fragmentation is increasing recognition of urban environmental degradation worldwide (Fahrig, 2003; Atasoy, 2018). Hence, understanding open space fragmentation and its forms has been regarded as a critical component of sustainability, especially in the context of rapid urbanisation.

Urbanisation plays a crucial role in determining open space patterns, leading directly to a general loss and fragmentation of open space (Vergnes et al., 2012; Lin et al., 2015; Chen et al., 2023). Angel et al. (2012) have demonstrated that when towns have experienced considerable construction and redevelopment, the density is higher, the spatial pattern of open spaces is more refined and logical, and the level of open space fragmentation is lower. In contrast, Wagtendonk and Koomen (2019) have recognised that old towns have too small and non–intensive open spaces with more fragmentation as a result of the growing lack of space for development. These opposing views that consider different fragmentation forms highlight an integrated methodological framework to elaborate on the heterogeneous characteristics of open space fragmentation at different stages of urbanisation development (Tian et al., 2011;

Tannous et al., 2021). While a more accurate and realistic understanding of open space fragmentation forms in old and new towns remains challenging to some extent, this topic is particularly relevant for built–up areas, where the conflict between the development of old and new towns is more apparent.

In addition to the unequal distribution of open space physical fragmentation, the relationship between open space fragmentation and residents also affects residents' equitable access to open space in densely populated and transitioning built–up areas (Xiao et al., 2017; Xu et al., 2018; Shen et al., 2022). The disproportionate distribution of open space fragmentation may benefit more wealthy communities, while more socioeconomically deprived areas may have more fragmented open spaces (Badland et al., 2010; Wu, 2016). Specifically, disadvantaged groups have a greater reliance on open space due to a lack of private land, yet always face more fragmented open space (Lin et al., 2015; Verbeek and Tempels, 2016). This process may in turn amplify spatial inequalities and even result in the spatial segregation of social groups (Xiao et al., 2019; Liu et al., 2022). It further highlights spatial equity as an effective lens to elaborate the relationship between open space fragmentation forms and disadvantaged groups in built–up areas.

This study proposes an integrated methodological framework for understanding open space fragmentation forms through spatial horizontal and vertical equity lenses. In particular, this research addresses these three questions: (i) what are the spatial

89 characteristics of the various forms of open space fragmentation? (ii) how do the
90 various open space fragmentation forms relate to the urbanisation process? and (iii) to
91 what extent does the spatial distribution of open space fragmentation express strengths
92 or weaknesses for socioeconomic characteristics? To ascertain these research questions,
93 the built–up area of Hong Kong is selected for the case study. Five types of open space
94 fragmentation forms are simulated. The characteristics of open space fragmentation
95 forms in towns at different urbanisation development stages are explored. Spatial
96 horizontal and vertical equity is then investigated based on demographic characteristics
97 and social economic status. Evidence–based open space interventions for the health
98 promotion of urban residents.
99

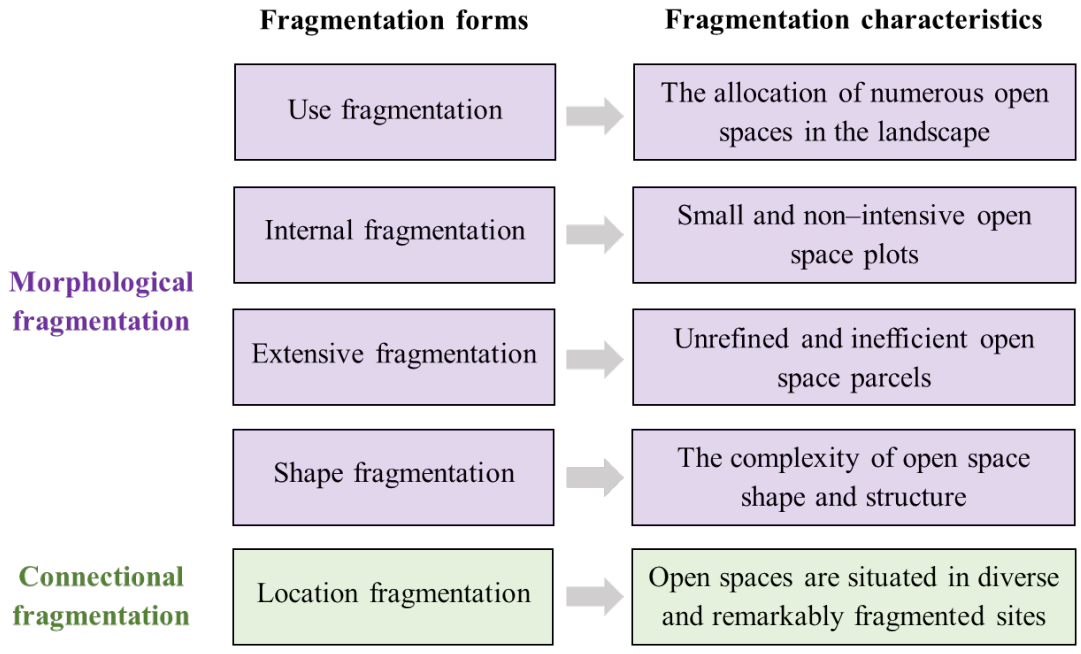
100 **2. Literature review**

101 *2.1. Dual attributes of open space fragmentation*

102 There is little overlap between the two in contemporary literature, although open
103 space fragmentation generally covers both physical and social attributes (York et al.,
104 2011). Open space physical fragmentation refers to the spatial isolation, incoherence
105 and disorder of open space that threatens the built environment and landscape integrity
106 (Larbi, 1996; Jenks et al., 2013; Zhu et al., 2018). Forman (1999) and Geneletti (2004)
107 have highlighted the physical attribute of open space fragmentation and have proposed
108 that it is the dissection of open space into a series of small and spatially separated
109 fragments. On this basis, open space fragmentation is the negative physical spatial
110 heterogeneity of landscapes (Gulinck and Wagendorp, 2002; Verbeek and Tempels,

111 2016). Carvalho et al. (2009) noted that open space fragmentation is an artificial process
112 of breaking up a contiguous habitat, biome or ecosystem, etc. Further, open space
113 fragmentation is considered to be the division of large patch size and continuous open
114 space into smaller and isolated patches and edges of open space surrounded by human
115 settlements, impermeable surfaces and transport networks (Di Giulio et al., 2009; Kowe
116 et al., 2021).
117
118 There is no universally recognised definition of the social attributes of open space
119 fragmentation (Harrison, 2003; York et al., 2011). Nevertheless, the social attribute of
120 open space fragmentation has been alluded to by the strong existing evidence as an
121 unequal form of urban open space (Krellenberg et al., 2017). This concept emphasises
122 the terms 'spatial segregation', 'spatial separation', 'spatial polarisation', 'social
123 exclusion' and 'disconnected cities' (Rodríguez et al., 2001; Gu and Shen, 2003; Mele,
124 2011; Allegra et al., 2012; Romero et al., 2012; Borsdorf et al., 2016; Ogas-Mendez and
125 Isoda, 2021). With the ongoing urbanisation process, the significantly increased level
126 of open space fragmentation has also substantially exacerbated social isolation and
127 social fragmentation in cities (Romero and Ordenes, 2004; Krellenberg et al., 2017).
128 However, studies linking the physical and social attributes of open space fragmentation
129 to tackle the complex environmental challenges in built–up areas have not been
130 insightful enough.
131
132 *2.2. Diverse forms of open space fragmentation*

Previous literature has revealed great diversity in open space fragmentation forms, generally determined by morphology and connectivity (Yu et al., 2022b; Yu et al., 2023a) (**Fig. 1**). Morphological fragmentation comes in the form of use, internal, extensive and shape fragmentation (Ntihinyurwa and de Vries, 2020; Ntihinyurwa and de Vries, 2021). Use fragmentation is defined as the allocation of numerous open spaces in the landscape (Su et al., 2018). Internal fragmentation is associated with small and non–intensive open space plots (Tang et al., 2006). Extensive fragmentation is characterised by unrefined and inefficient open space parcels (Enaruvbe and Atafo, 2019). Shape fragmentation emphasises the complex shapes and structures of open spaces (He et al., 2019; Jia et al., 2019). With respect to connectional fragmentation, it occurs in terms of location fragmentation, where open spaces are situated in diverse and remarkably fragmented sites (Wang et al., 2013; Yu et al., 2022a). While fragmentation forms have been studied individually, they have little been examined jointly within a methodological framework, which poses an environmental challenge to understanding complex urban areas.



148 **Fig. 1.** Open space fragmentation forms and characteristics.

149 Source: Author.

150

151 Prior research has looked at the coexistence and mutual interference of
152 fragmentation forms (Yu et al., 2022a). However, the complicated and elaborated
153 characterisation of open space fragmentation and the diverse fragmentation forms have
154 not been fully captured and examined (Yu et al., 2023a). This predicament could result
155 in the design of ineffective open space fragmentation management policies that ignore
156 the specificity of fragmentation forms and thus produce controversial results that cause
157 failure. As such, it is necessary to clarify the varied forms of open space fragmentation,
158 which could assist in the more accurate selection of indicators and the development of
159 locally adapted coping strategies.

160

161 *2.3. Relationship between open space fragmentation and spatial horizontal and*
162 *vertical equity*

163 Spatial equity is not only a production of the Spatial Turn and the New Social
164 Movement, but also an expression of social equity (Lefebvre, 1992). Spatial equity
165 involved spatial horizontal equity and spatial vertical equity lenses and was initially
166 described as an assessment of tax reform (Boisjoly et al., 2020). The horizontal equity
167 lens has been widely stated as a minimum regulation that requires equal consideration
168 of all individuals (Durrant, 2017; Yu et al., 2022b). Spatial horizontal equity focuses on
169 equal coverage and non–discriminatory treatment. The vertical equity lens calls for a

distinction between these different populations (He et al., 2020). However, the concept of spatial equity is still new in built–up areas, and the investigation of spatial vertical equity related to fragmented open spaces is more limited (Kabisch et al., 2015; Wu et al., 2020; Liu et al., 2022). The association between open space fragmentation and spatial vertical equity has not been conceptualised theoretically, so the synergy of the two characteristics remains poorly understood.

More precisely, the relationship between use and location fragmentation forms and socioeconomic characteristics has been observed (Bahrini et al., 2017; Egidi et al., 2020; Liu et al., 2022). Byrne (2012) has suggested that open space is not equally and formally distributed within the cities, and that open space is related to urban demographic characteristics and class inequalities during the history of urban development. However, previous studies have given insufficient attention to the internal, extensive and shape fragmentation forms of open space in the light of the spatial vertical equity lens. Recent literature has reported on the equity of access to open space linked to the age and education level of residents (Xing et al., 2018; Rigolon et al., 2021). Scholars held a polarised view, either that disadvantaged groups are favoured over more affluent citizens (Xiao et al., 2017); or that children, the elder and low education groups suffer from lower–quality open spaces (Lersch and Hart, 2014; Frank et al., 2019; Yu et al., 2022b). Yet, the polarisation view ignores the self–organisation process of open space fragmentation and urbanisation. In addition, it is uncertain whether the fragmented open spaces embedded in the built environment have a bias towards disadvantaged groups

such as immigrant groups and unemployed groups under the lens of spatial vertical equity. Thus, it is necessary to propose an integrated methodological framework to ascertain the relationship between urban open space fragmentation and disadvantaged groups under the spatial equity lens.

3. Methodology

3.1. Overall methodological framework

We construct an overall methodological framework that highlights the issue of open space fragmentation through the lenses of spatial horizontal and vertical equity. This study involves four main components to complete the overall methodological framework (**Fig. 2**).

First, we identify the patterns of open space fragmentation forms on the basis of landscape pattern analysis and principal component analysis. Second, we investigate the characteristics of open space fragmentation forms in old and new towns. Third, we assess spatial horizontal equity by means of the Theil index, i.e., whether open space fragmentation produces unequal coverage and discriminatory treatment. Fourth, we scrutinise spatial vertical equity in terms of demographic characteristics and social economic status, including age, educational attainment, place of birth and economic activity status, i.e., whether the heterogeneity of open space fragmentation meets population needs and compensates for overall inequities. This approach can provide necessary guidance on sustainable open space planning.

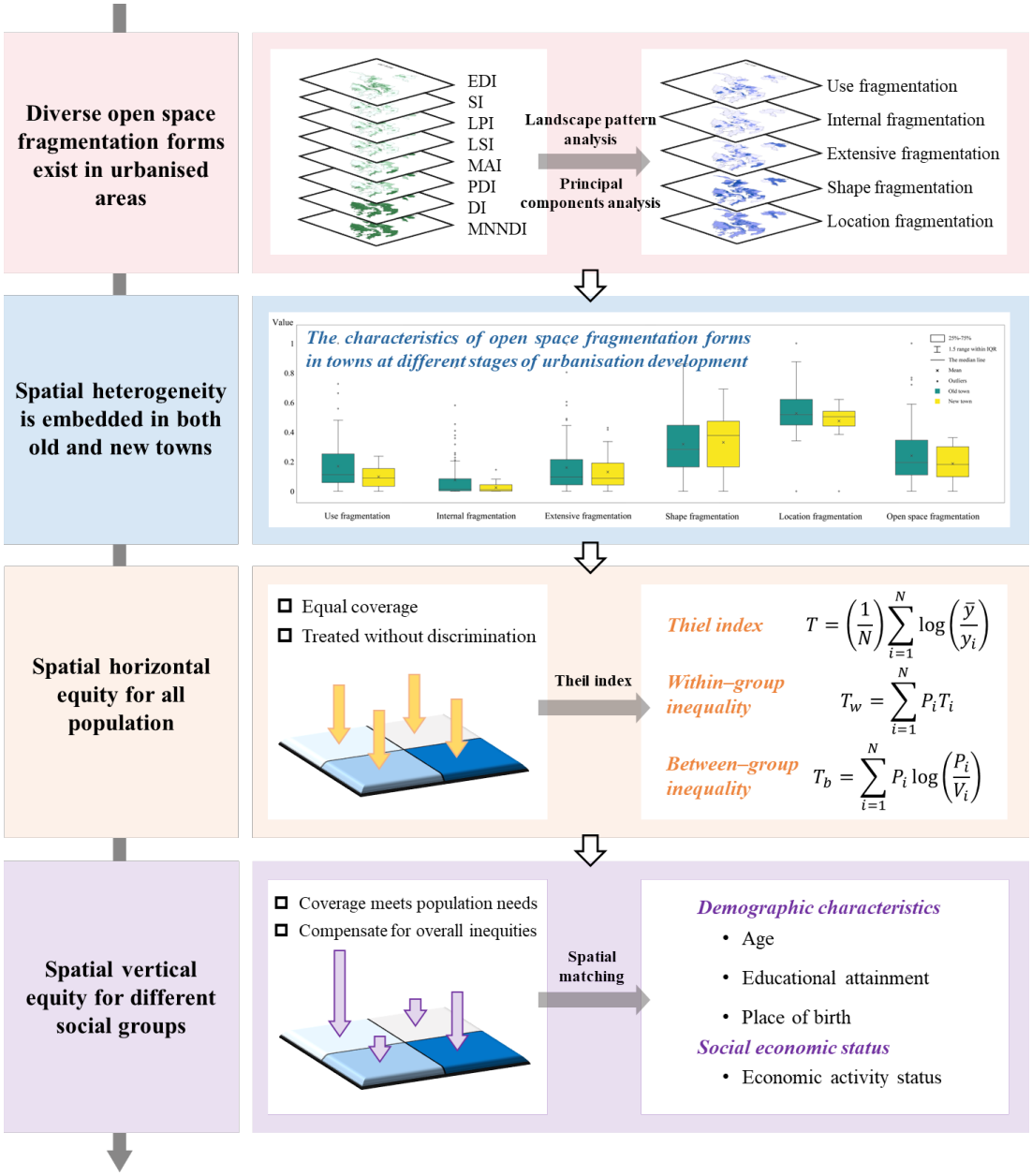


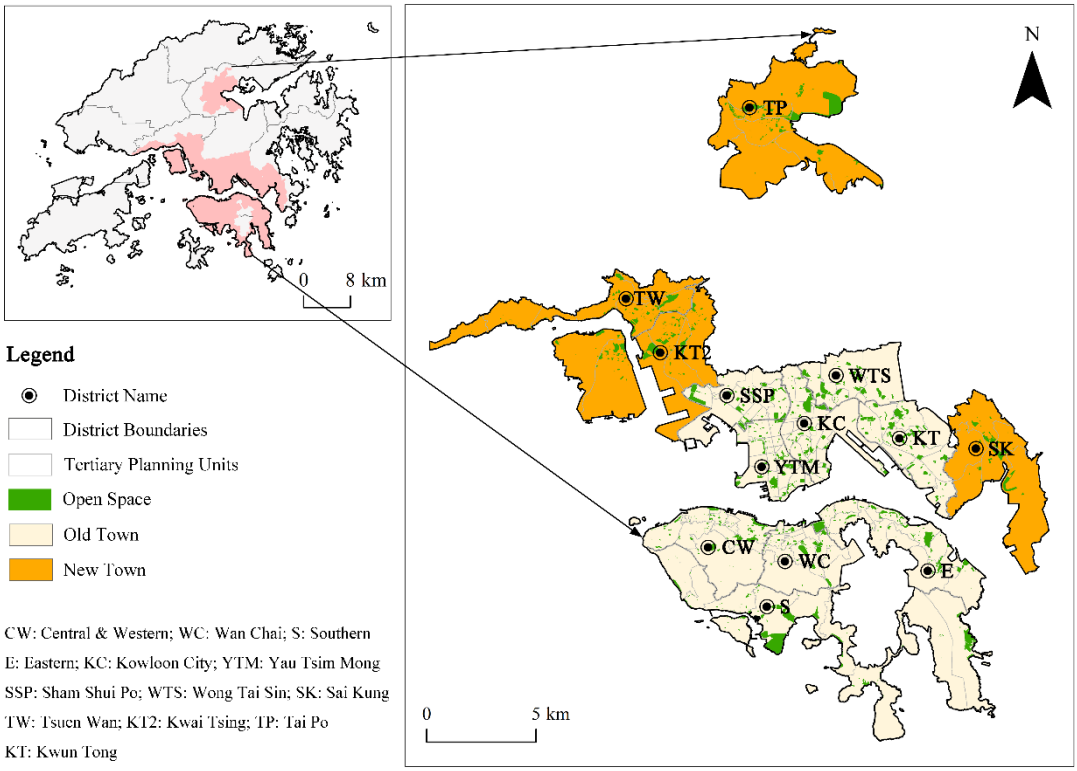
Fig. 2. Overall methodological framework of open space fragmentation through the lenses of spatial horizontal and vertical equity.

Source: Author.

3.2. Study area and data sources

Situated on the eastern side of the Pearl River Delta in southern China, Hong Kong is a rapidly developing special administrative region. With 7.5 million residents of

different nationalities in a territory of 1,104 km^2, it is a densely populated city with limited land resources worldwide (Tang, 2017; Yu et al., 2023a). Hong Kong consists of Hong Kong Island, Kowloon and New Territories, which are the three main regions administered by 18 districts. Thirteen districts, also known as the built–up area of Hong Kong, were selected to reflect the old and new towns (**Fig. 3**). The Central & Western (CW), Wan Chai (WC), Southern (S), Eastern (E), Kowloon City (KC), Yau Tsim Mong (YTM), Sham Shui Po (SSP), Wong Tai Sin (WTS) and Kwun Tong (KT) districts are old towns. Tsuen Wan (TW), Kwai Tsing (KT2), Tai Po (TP) and Sai Kung (SK) districts are new towns. The study area consisting of these 13 districts has been classified into 160 Tertiary Planning Units (TPUs) by the Planning Department. On the one hand, the extreme lack of open space in the built–up area of Hong Kong is a severe challenge due to continued population and urbanisation growth. Hong Kong has significantly less open space in its built–up area than other Asian cities such as Singapore, Seoul and Tokyo (Planning Department, 2016). On the other hand, given the high immigrant rate, large wealth gap, aging population and population growth, Hong Kong's built–up area could provide an interesting and typical case for exploring the topic of open space fragmentation and its associated spatial equity in built–up areas.



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240 **Fig. 3.** Location of the built–up area of Hong Kong.

241 Source: Author.

242

243 In this study, the 2020 open space data was obtained from the Planning Department
244 (http://www.pland.gov.hk/pland_sc/info_serv/open_data/landu). In addition,
245 socioeconomic data on age, educational attainment, place of birth and economic activity
246 status in the TPUs were derived from the Demographic Profiles of Population in the
247 Whole Territory (http://www.bycensus2016.gov.hk).

248

249 *3.3. Measurement of open space fragmentation forms*

250 Open space fragmentation could be quantified by looking at morphology and
251 connectivity. There are three criteria in selecting open space fragmentation metrics: (i)

comparability with prior open space fragmentation studies; (ii) capability to identify open space fragmentation features; and (iii) low redundancy between fragmentation metrics (Yu et al., 2023a; Yu et al., 2023b). Therefore, this paper selected edge density index (EDI), split index (SI), largest patch index (LPI), landscape shape index (LSI), mean area index (MAI), patch density index (PDI), division index (DI) and mean nearest–neighbour distance index (MNNDI) as metrics according to open space fragmentation forms. These eight metrics could provide a comprehensive description of open space morphological and connectional fragmentation forms (**Fig. 4**).

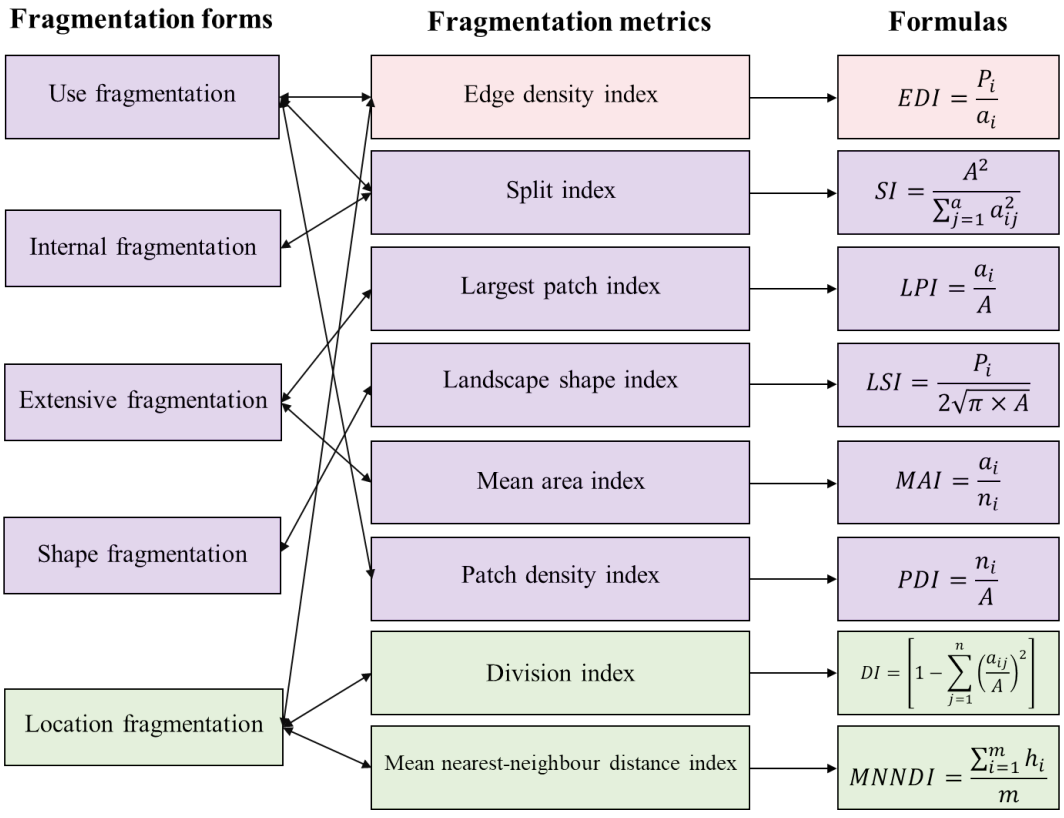


Fig. 4. Open space fragmentation forms and their corresponding metrics.

Note: P_i and a_i are the total perimeter and area of open spaces in the TPU i. A is the TPU area. a_{ij} is the area of open space j in the TPU i. n_i is the total number of open spaces in the TPU i. n is the number of open spaces. h_i is the distance from

each patch to its nearest neighbour. m is the total number of nearest neighbours to this patch.

Source: Author.

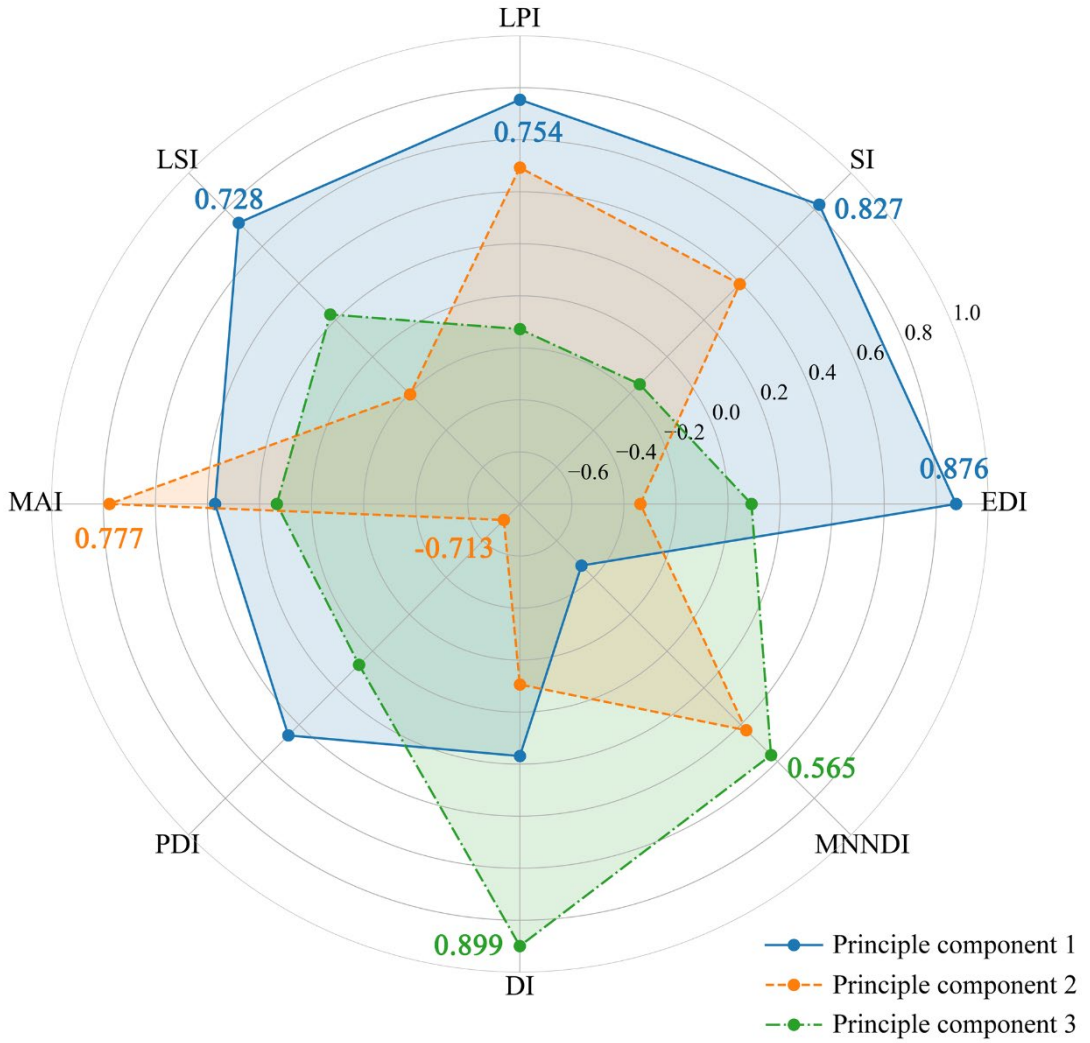
The eight metrics were standardised for extreme values to eliminate dimensionality between metrics. Principal components analysis (PCA) with the varimax rotation method was then adopted to derive the weight (eigenvalue) for each metric (Demšar et al., 2013). Three principal factors with high metric loadings were extracted (Cumming and Vernier, 2002). The results revealed that the first three principal factors had eigenvalues larger than 1, explaining 78.196% of the variation. Principal factor 1 denotes the edge and internal features, maximum patch and shape of open space, which includes EDI, SI, LPI and LSI. Principal factor 2 indicates the mean area and density of open space: MAI and PDI. Principal factor 3 expresses the division and distance among open spaces and includes both DI and MNNDI metrics. **Fig. 5** shows the metric loadings for each factor. By means of the eigenvalues of the three principal factors and the associated loading scores for each metric, the open space fragmentation index of each TPU i ($OSFI_i$) can be assessed.

$$OSFI_i = E_{i1} \times (S_1 \times EDI_i + S_2 \times SI_i + S_3 \times LPI_i + S_4 \times LSI_i) + E_{i2} \times (S_5 \times MAI_i + S_6 \times PDI_i) + E_{i3} \times (S_7 \times DI_i + S_8 \times MNNDI_i) \quad (1)$$

E_{i1}, E_{i2} and E_{i3} indicate the eigenvalues of the first principal factor, second principal factor and third principal factor. S_1, S_2 and S_3 represent the loading values for the first principal factor, second principal factor and third principal factor. EDI_i, SI_i, LPI_i,

287 LSI_i, MAI_i, PDI_i, DI_i and $MNNDI_i$ reflect the standardised values of the EDI, SI,

288 LPI, LSI, MAI, PDI, DI and MNNDI.



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290 **Fig. 5.** The metric loading on each component in the principal components analysis

291 (PCA).

292 Source: Author.

293

294 In addition, open space fragmentation forms could also be assessed, i.e., use

295 fragmentation, internal fragmentation, extensive fragmentation, shape fragmentation

296 and location fragmentation.

$$UF_i = E_{i1} \times (S_1 \times EDI_i + S_2 \times SI_i) + E_{i2} \times (S_6 \times PDI_i) \quad (2)$$

$$IF_i = SI_i \quad (3)$$

$$EF_i = E_{i1} \times (S_3 \times LPI_i) + E_{i2} \times (S_5 \times MAI_i) \quad (4)$$

$$SF_i = LSI_i \quad (5)$$

$$LF_i = E_{i1} \times (S_1 \times EDI_i) + E_{i3} \times (S_7 \times DI_i + S_8 \times MNNDI_i) \quad (6)$$

UF_i, IF_i, EF_i, SF_i and LF_i refer to the fragmentation forms of each TPU i that could be employed to evaluate use fragmentation, internal fragmentation, extensive fragmentation, shape fragmentation and location fragmentation. These indexes were normalised to eliminate the dimensions amongst indexes. $\widehat{UF_i}$, $\widehat{IF_i}$, $\widehat{EF_i}$, $\widehat{SF_i}$, $\widehat{LF_i}$ and $\widehat{OSFI_i}$ were obtained.

3.4. Theil index for spatial horizontal equity measurement

The Thiel index is a general measure of inequality and is often employed in both economics and geography to capture the variation and extent of regional inequality (Silver and Theil, 1967; Harper et al., 2008; Chen and Haynes, 2017). The Theil index is adopted because it has advantages over other indexes such as Gini, Atkinson, Standard Deviation and Coefficient of Variation in terms of decomposability. The Thiel index is able to divide spatial horizontal inequality into between–group inequality and within–group inequality (Frosini, 2012), hence can provide more information and advantages. A higher Thiel index represents more inequality.

$$T = \left(\frac{1}{N}\right) \sum_{i=1}^{N} \log\left(\frac{\bar{y}}{y_i}\right) \quad (7)$$

$$T_w = \sum_{i=1}^{N} P_i T_i \quad (8)$$

$$T_b = \sum_{i=1}^{N} P_i \log\left(\frac{P_i}{V_i}\right) \quad (9)$$

T denotes the Thiel index. N is the number of TPUs. $\bar{y}$ indicates the mean value of the open space fragmentation index in the study area. y_i is the open space fragmentation index value of the ith TPU. T_w is the within–group variation. T_b represents the between–group variation. P_i denotes the population of the ith TPU as a proportion of the study area population. T_i refers to the Thiel index of the ith TPU. V_i is the open space fragmentation index of the ith TPU as a proportion of that of the study area.

3.5. Spatial matching for spatial vertical equity measurement

Spatial matching approach is the matching of one set of objects and another so that the cost of measuring the 'goodness' of such a match is optimised (Egidi et al., 2020; Yao et al., 2021). The two sets of objects are various forms of open space fragmentation and socioeconomic characteristics, respectively. As shown in **Table 1**, socioeconomic characteristics include demographic characteristics (age, educational attainment and place of birth) and social economic status (economic activity status). Such a spatial matching approach allows measuring the supply and demand match between open space fragmentation and population distribution characteristics.

337 **Table 1**

338 Descriptive statistics of socioeconomic variables.

Socioeconomic characteristics		Explanations
Demographic characteristics		
Age	Children	Under age 18
	Youth and adults	Over age 18 and under age 60
	The elder	Over age 60
Educational attainment	Low level education group	Population with no schooling, pre–primary and primary education
	Middle level education group	Population with secondary education
	High level education group	Population with post–secondary education
Place of birth	Resident group	Chinese (place of domicile–Hong Kong)
	Immigrant group	Chinese (place of domicile–other than Hong Kong), Filipino, Indonesian, British and others
Social economic status		
Economic activity status	Unemployed group	Home–makers, students, retired persons, of independent means and other economically inactive persons
	Economically active group	Employees, employers, self–employed and unpaid family workers

339 Source: Author.

4. Results

4.1. Pattern characteristics of open space fragmentation forms

In this study, five fragmentation forms (use, internal, extensive, shape and location fragmentation) and the index of open space fragmentation were assessed on the basis of the pattern characteristics of open spaces (**Fig. 6**). Open space fragmentation reveals complex physical spatial heterogeneity (**Fig. 6–f**). Open space fragmentation indexes for the Kowloon region, Hong Kong Island and the New Territories regions are 0.259, 0.237 and 0.187. From a district perspective, the WTS district in the Kowloon region has the highest open space fragmentation index of 0.351, which is followed by the CW district (0.336) and E district (0.272) in the Hong Kong Island region. In contrast, the KT2 district, SK district, TP district and TW district belonging to the New Territories region have the lowest open space fragmentation indexes, which are 0.215, 0.202, 0.195 and 0.122.

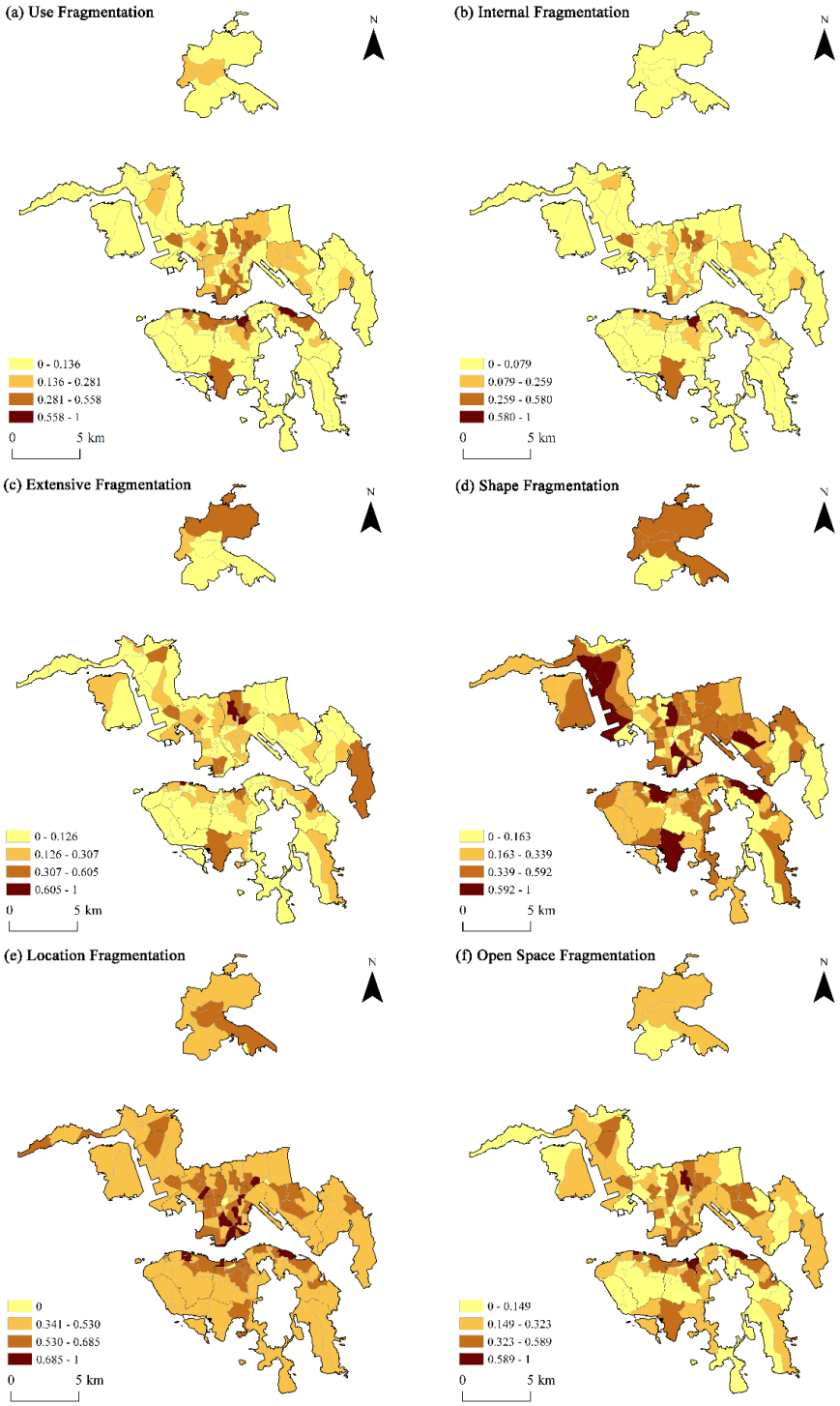


Fig. 6. Spatial distribution for different fragmentation forms and the index of open space fragmentation in the built–up area of Hong Kong: use fragmentation (a), internal fragmentation (b), extensive fragmentation (c), shape fragmentation (d), location fragmentation (e) and open space fragmentation (f).

Source: Author.

359

360 *4.2. Open space fragmentation forms in old and new towns*

361 **Fig. 7** reveals the characteristics of open space fragmentation forms in towns at
362 different stages of urbanisation development. In general, the heterogeneity of open
363 space fragmentation manifests itself in the heterogeneous allocation of inhabitants'
364 living circumstances between old and new towns. Statistics reveal that in addition to
365 shape fragmentation, the mean values of use, internal, extensive and location
366 fragmentation are all larger in old towns than in new towns.

367

368 The high–income areas of old towns have contributed to extensive fragmentation
369 by unjustifiably expanding open space near strategic waterfronts and commercial areas
370 for the purpose of local marketing and urban competition. Due to the large population,
371 limited land resources and ongoing development pressures, the open spaces in the low–
372 income areas of old towns are narrow, inefficient, scattered and segmented. The level
373 of use, internal and location fragmentation has been exacerbated. In contrast, many new
374 towns with relatively low population densities place more emphasis on enhancing open
375 space cover and its contiguity. There is a low level of use, internal, extensive and
376 location fragmentation. However, a few new towns are being transformed from densely
377 developed industrial areas into science parks and commercial and tourist areas. In these
378 new towns, open space coverage is low and of poor quality and irregular shape.

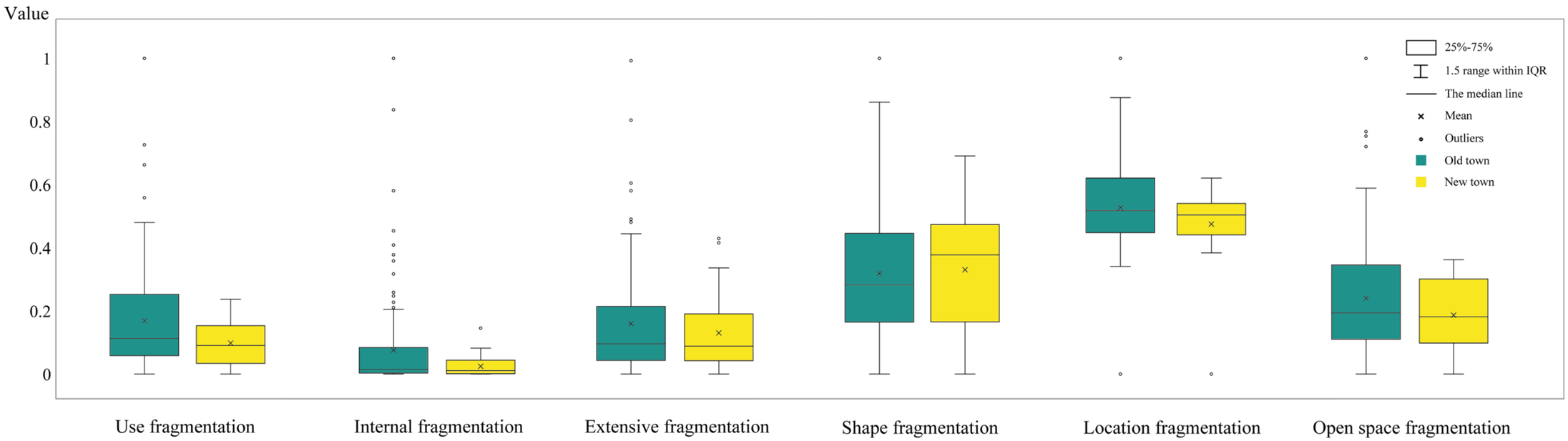


Fig. 7. Different fragmentation forms in old and new towns.

Source: Author.

382 *4.3. Spatial horizontal equity for all population*

383 **Table 2** shows the Thiel indexes for each form of open space fragmentation to
384 reflect spatial horizontal inequity. In terms of overall Thiel index values, the coefficients
385 for internal fragmentation, use fragmentation, extensive fragmentation, shape
386 fragmentation and location fragmentation are 0.567, 0.223, 0.210, 0.085 and 0.003,
387 respectively. This suggests that in overall, internal fragmentation is embedded in more
388 spatial horizontal inequities, followed by forms of use fragmentation, extensive
389 fragmentation, shape fragmentation and location fragmentation.

390

391 The between–group and within–group Thiel index values for open space
392 fragmentation are 0.021 and 0.108, respectively, indicating that open space
393 fragmentation is more inequitable within groups than between groups. In terms of the
394 within–group Thiel values, internal fragmentation is the most inequitable form in both
395 old and new towns, with values of 0.387 and 0.213, respectively. In contrast, location
396 fragmentation has the lowest Thiel index in both the old and new towns, with values of
397 0.007 and 0.006, respectively. In addition, the open space form of the old towns is more
398 equitable than that of the new towns. Compared to new towns, the old towns contain
399 many low–income regions with a large population and limited land resources, which
400 results in narrow, inefficient, fragmented and scattered open spaces.

401 **Table 2**

402 Theil index for open space fragmentation in the old and new towns.

Type	Use fragmentation	Internal fragmentation	Extensive fragmentation	Shape fragmentation	Location fragmentation	Open space fragmentation
Overall	0.223	0.567	0.210	0.085	0.003	0.102
Between group	0.151	0.222	0.104	0.067	0.089	0.021
Within group	0.236	0.600	0.216	0.087	0.012	0.108
Old towns	0.153	0.387	0.152	0.064	0.007	0.068
New towns	0.083	0.213	0.065	0.022	0.006	0.040

403 Source: Author.

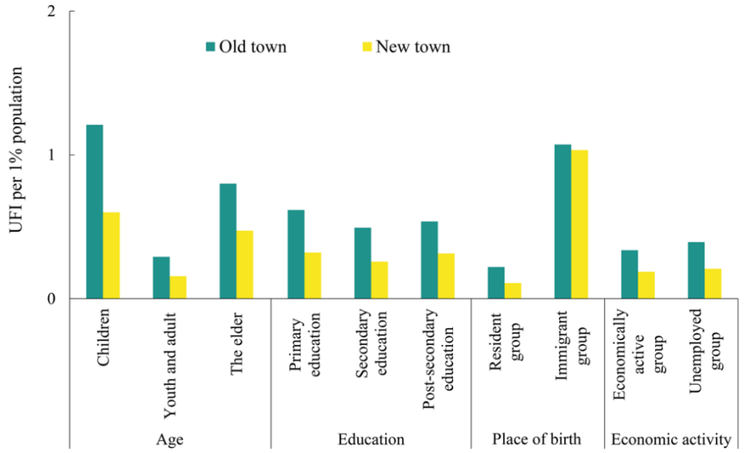
404 *4.4. Spatial vertical equity for different social groups*

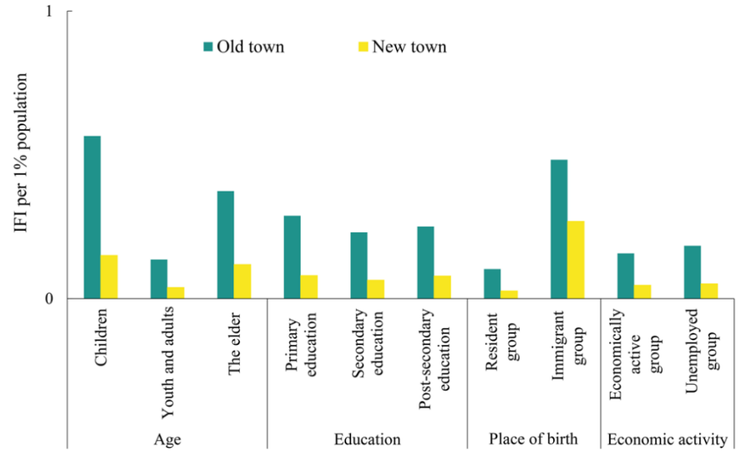
405 Open space fragmentation forms could affect the wellbeing of residents, which
406 varies by age, educational attainment, place of birth and economic activity status (Li et
407 al., 2019; Cheng et al., 2020). The vertical equity levels of use fragmentation, internal
408 fragmentation, extensive fragmentation, shape fragmentation, location fragmentation
409 and open space fragmentation corresponding to each 1% of the population in the built–
410 up area of Hong Kong are depicted in **Fig. 8**.

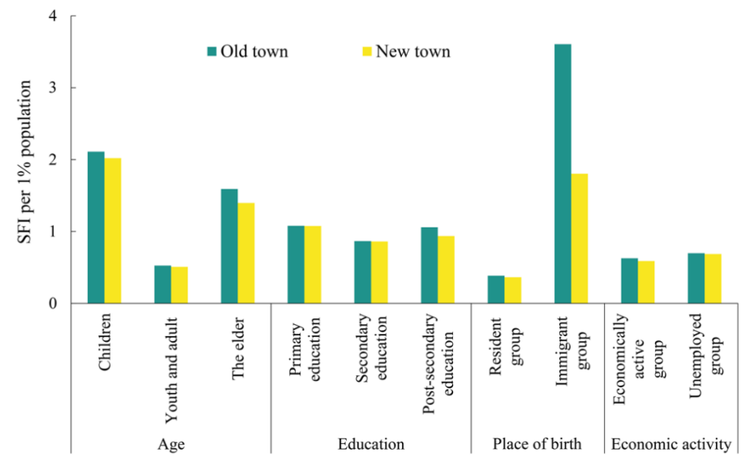
411

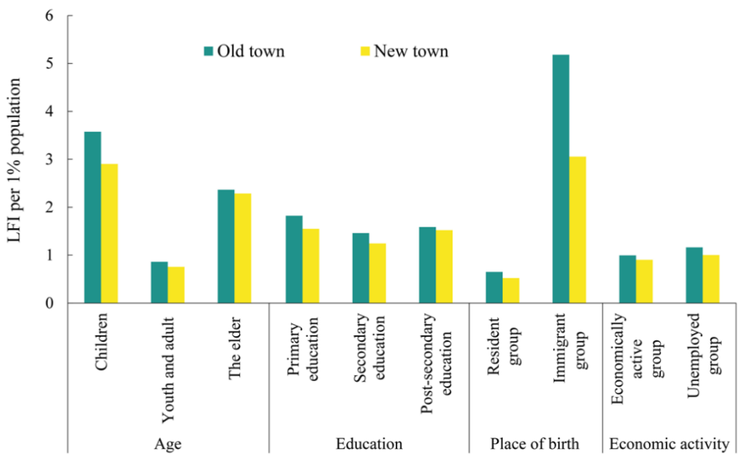
412 In terms of age, children and the elder have the highest levels for all open space
413 fragmentation form values. This suggests that compared with youth and adults, children
414 and the elder are in a more unfavourable status with regard to open space fragmentation
415 forms, especially in old towns. Aside from the findings on inequalities in urban open
416 spaces for disadvantaged age groups, it was also confirmed that children face more
417 inequalities than the elder. In terms of educational attainment, the values for all open
418 space fragmentation forms are significantly higher for the primary education population
419 than for the other groups, which indicates that the primary education population tends
420 to be closer to fragmented open spaces both in old and new towns. Furthermore, all
421 values of various fragmentation forms correspond to higher values for the primary
422 education population in old towns than in new towns, suggesting that the primary
423 education population in old towns is more exposed to more fragmented open spaces. In
424 terms of place of birth, the immigrant group corresponds to a much higher level of any
425 open space fragmentation forms than the resident group, indicating that the immigrant

group suffers from larger spatial vertical inequalities in open space, especially in old towns. In terms of economic activity, the unemployed group are more likely to live near more fragmented open spaces than the economically active group. The level of open space fragmentation corresponding to the unemployed group is significantly higher in old towns than in new towns.









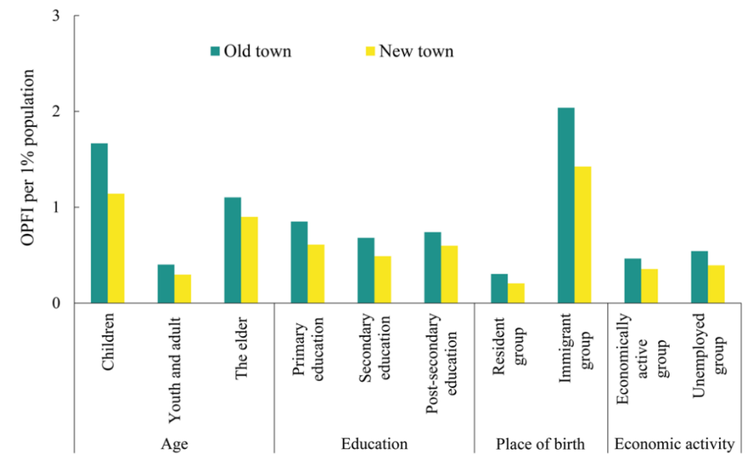


Fig. 8. Vertical equity of use, internal, extensive, shape, location fragmentation and open space fragmentation in the built–up area of Hong Kong.

Source: Author.

5. Discussions

5.1. Open space fragmentation is affected by the urbanisation process

Unprecedented population growth and urbanisation have created intergenerational and heterogeneous environments, leading to urban open space fragmentation (Sharifi and Hosseingholizadeh, 2019; Ahn et al., 2020). Our study results echo that in built–up areas, the morphology of open space is increasingly segmented and the connectivity of open space is decreasing, especially in old towns (Dewaelheyns et al., 2014; Cui et al., 2020). More specially, old towns have a more fragmented form of open space than new towns. Such a discovery supports the argument of Tang and Wong (2008) that planners always prioritise other 'profitable' land–use areas at the expense of open space because of limited land. Such pro–growth planning mindset and revenue–maximising land sales policies have been deemed detrimental to sustainable open space planning (Tang and Wong, 2008). As in many western cities, the multiple forms of open space fragmentation in the built–up area of Hong Kong allude to a trend towards the privatisation of public space, resulting in environmental degradation in urban areas (Régnier, 2020). Therefore, actions are needed to mitigate the impact of fragmented open spaces from further urbanisation tendencies (Verbeek and Tempels, 2016).

5.2. Spatial equity concerning vulnerable groups

Urban open spaces may create barriers to equitable access if they are not explicitly targeted to take into account the age, education, place of birth and economic activity status of urban residents (He et al., 2020; Ma, 2020). Our research has proven that

456 vulnerable groups such as children, the elder, low education groups, immigrant groups
457 and unemployed groups are exposed to more fragmented open spaces. Such open space
458 fragmentation embedded in capital deprivation weakens the identity between different
459 social classes (Bahrini et al., 2017; Yu et al., 2022b). These results accord with prior
460 studies on the long–term evolutionary nature of historical urban socio–spatial patterns,
461 resulting in open space not tending to be created by and for disadvantaged groups nor
462 captured by them (Huang et al., 2022).
463
464 In terms of age, our study not only confirms the findings of previous studies on
465 inequalities in urban open spaces among vulnerable age groups (Lin et al., 2021; Zhang
466 et al., 2022), but also further provides a new finding that children face more inequalities
467 than the elder by considering open space fragmentation forms. This echoes the results
468 of the UNICEF Report suggesting that few countries accord each child the right to feel
469 safe and secure in the built environment, with access to essential services and clean air
470 (UNICEF, 2022; Yu et al., 2022b). In terms of education, many less–educated people
471 tend to live in neighbourhoods where the environment is poor and open space
472 morphology and connectivity are fragmented, in line with prior studies (Wolch et al.,
473 2005; Pearce et al., 2010; Shrestha et al., 2016; Liu et al., 2022). We suggest that more
474 educated groups can better avoid fragmented open spaces and participate in open space
475 planning decisions related to their wellbeing. In terms of place of birth, we have
476 confirmed that immigrant groups are closer to fragmented open spaces, in contrast to
477 the conclusion of Xiao et al. (2017) that open spaces do not favour resident groups or

478 immigrant groups. These diverse insights are attributed not only to the fact that previous
479 studies have considered the quantity of open space more than the morphology and
480 connectivity, but also to the extent of the government's dominant role in urban planning
481 and the cultural inclusion of immigrants in the treatment of local policies. In terms of
482 economic activity, unemployed groups who are more sensitive to open space
483 fragmentation have long been clustered in poorer and more fragmented living
484 conditions, in contrast to other economically active groups who can afford to purchase
485 private recreational facilities or ay higher values to access quality open space away
486 from their neighbourhoods. This confirms Mullin et al.'s (2018) view that areas with
487 lower quality natural surroundings tend to be closest to lower socioeconomic
488 neighbourhoods. Without appropriate foresight and regulation, the fragmented spatial
489 pattern of open space could crowd out disadvantaged groups, so it is necessary to
490 propose policy and practical implications for sustainable open space planning.
491
492 *5.3. Implications for sustainable open space planning*
493 In terms of the physical environment, it is beneficial to connect open spaces by
494 means of a multi–level and multi–dimensional approach, such as elevated platforms on
495 floors, roof gardens, sky corridors and vertical walls, which weakens the issue of use
496 fragmentation. In addition, it is recommended that priority be given to open space
497 planning and systematic provision of open space to create open spaces of moderate
498 spatial scale and ecological value. The consolidation of small open spaces in this way
499 could reduce internal fragmentation. In order to alleviate extensive fragmentation,

given the extreme scarcity of land resources in old towns, it is essential to achieve a mix–use model of open space to increase the attractiveness of open space. Appropriate and well–designed open space shapes such as strips or rings help to create sustainable landscapes and reduce shape fragmentation, especially in new towns. In addition, it is necessary to maintain appropriate areas of open space, to create continuity between open spaces and to make them accessible to the public in order to mitigate the level of connectional fragmentation.

In terms of the social environment, spatial equity should be strongly reflected in the planning process of urban open space. Whilst some open space plannings may consider population distribution, most of them ignore the population's socioeconomic characteristics. Hence, adopting both spatial horizontal and vertical equity lenses in urban open space decision–making can help built–up areas make open space an important tool to address existing inequalities, as well as to build local resilience and wellbeing. Instead of the open space as a 'melting pot', we need the 'salad bowl', where different groups can find individual expression (Thompson, 2002). The government could intervene in open space planning to promote more favourable policies for disadvantaged groups in neighbourhoods with more fragmented open space forms, as opposed to excluding them. The matching of various open space forms and the socioeconomic status of the population needs to be fully considered to build more equitable built–up areas, particularly where disadvantaged groups are concentrated.

5.4. Contributions and limitations

The findings of this study updated our knowledge base regarding open space fragmentation forms through the spatial equity lens both theoretically and methodologically. Theoretically, it is significant that this research assists in pushing the boundaries of open space fragmentation by conceptualising spatial horizontal and vertical equity lenses. It effectively unravels the physical and social attributes of open space fragmentation to tackle the complex environmental challenges in built–up areas. Open space fragmentation forms have been well evidenced and quantified, which are generally regarded as allowing for a more accurate selection of indicators and the development of locally adapted coping strategies. Adding to this contribution, we have revealed that fragmented open spaces embedded in the built environment are biased against children, the elder, low education groups, immigrant groups and unemployed groups, highlighting the importance of the self–organisation process of urbanisation. Methodologically, our approach relies solely on publicly available data, in contrast to previous related studies that required substantial resources, labour and time to scale up. The methodological flow of open space fragmentation is feasible, producible and applicable for other built–up areas internationally with a similar political or socioeconomic background to Hong Kong. Most importantly, our methodological framework could be adopted to identify the location of open space fragmentation and to assess the effectiveness of relevant policies targeting inequalities. It could also be employed as a guide for governments to optimise their policy systems to reduce inequalities, considering long–term environmental development.

However, we must also note the shortcomings in our research. First, future research could investigate the long–term open space fragmentation and its relationship to the urbanisation process from a temporal scale. Second, a more generalised set of indicators could be developed in the future for exploring cities of other sizes and other development contexts. Third, due to data limitations, some vulnerable groups have not been fully considered, and future studies could combine questionnaires and interviews for a more comprehensive assessment. In the future, understanding open space fragmentation forms in a spatial equity lens could be more meaningful through consideration of temporal scale, indicator evaluation and social difference.

6. Conclusion

This study suggests a new methodological framework to investigate the physical attribute and social attribute of open space fragmentation in built–up areas. Following this methodological framework, we unveil the forms of open space fragmentation in towns at different stages of urbanisation development via spatial horizontal and vertical equity lenses. The conclusions of this article are as follows.

Rapid population and urbanisation have caused intergenerational and heterogeneous environments, which have resulted in open space fragmentation. This is a significant spatial heterogeneity in open space fragmentation manifested by the fact that all fragmentation forms are unequal in both old and new towns. The results indicate

566 that open space fragmentation is characterised by morphological (use, internal,
567 extensive and shape) and connectional (location) fragmentation. Apart from shape
568 fragmentation, the mean values of use fragmentation, internal fragmentation, extensive
569 fragmentation and location fragmentation are all larger in old towns than in new towns.
570
571 Additionally, internal fragmentation overall is embedded in more spatial
572 horizontal inequities and is the most inequitable form in both old and new towns. Open
573 space fragmentation is more inequitable within groups, evidenced by more equitable
574 open space forms in old towns than in new towns. Vulnerable groups who are more
575 dependent on open spaces are more exposed to fragmented open spaces considering age,
576 educational attainment and place of birth and economic activity status. More
577 specifically, compared to new towns, children, elderly people, low education groups,
578 immigrant groups and unemployed groups suffer more spatial vertical inequalities in
579 old towns. These findings provide guidance for open space planning policies and
580 practices that promote spatial equity, sustainable cities and social development.
581
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