Measuring high-density built environment for public health research: Uncertainty with respect to data, indicator design and spatial scale

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Abstract

Uncertainty with respect to built environment (BE) data collection, measure conceptualization and spatial scales is evident in urban health research, but most findings are from relatively low-density contexts. We selected Hong Kong, an iconic high-density city, as the study area as limited research has been conducted on uncertainty in such areas. We used geocoded home addresses (n=5732) from a large population-based cohort in Hong Kong to extract BE measures for the participants' place of residence based on an internationally recognized BE framework. Variability of the measures was mapped and Spearman's rank correlation calculated to assess how well the relationships among indicators are preserved across variables and spatial scales. We found extreme variations and uncertainties for the 180 measures collected using comprehensive data and advanced geographic information systems modelling techniques. We highlight the implications of methodological selection and spatial scales of the measures. The results suggest that more robust information regarding urban health research in high-density city would emerge if greater consideration were given to BE data, design methods and spatial scales of the BE measures.

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Introduction

Public health researchers have started to pay attention to built environment (BE) with regard to preventive approaches against the global pandemic of obesity and related health problems resulting from physical inactivity (Lee *et al.*, 2012; Sallis *et al.*, 2016). Previous studies of relationship between BE and public health have, however, predominantly been conducted in relatively low-density city contexts (Rydin *et al.*, 2012; Barton and Grant, 2013). The is now evidence of uncertainty due to spatial scales and conceptualizing measures (Clark and Scott, 2014), an issue which becomes amplified in high-density cities such as Hong Kong, Tokyo, Mumbai and Shanghai (Low *et al.*, 2016). These megacities are widely known for their geographic and morphological BE heterogeneity, but the uncertainty in relation to constructing and interpreting BE measures needs further examination.

According to Longley *et al.* (2015), uncertainty arises since most representations of the world are incomplete, erroneous, out of date, subject to generalization or aberrant. The absence of complete BE data of high-density cities often hinder inferring the relationship between BE and health outcomes. For example, a cross-national study reported difficulties in measuring accessibility of public transport because of incomplete bus records in Bogotá and Hong Kong (Adams *et al.*, 2014). With efforts focused on the development of street audit instruments to collect objective BE data (Sun *et al.*, 2017), current indicators collected by audit instruments are unlikely to reveal variability of locations (Cerin *et al.*, 2013). Only single scales have been used in studies of Hong Kong, for example research at level of the block (an area bounded by roads and their intersections) for body constitution and sedentary behaviour (Low *et al.*, 2016) or a residence-based buffer and a 15-minutes walking radius for walking and physical activity (Cerin *et al.*, 2013; Lu *et al.*, 2016).

Geographic information systems (GIS) are widely used to measure BE, but conceptualizing such indicators varies considerably across disciplines. For example, street design can be measured and presented as different indicators, *i.e*. block length, block size, intersection density, street density, connected intersection ratio or link node ratio (where node signifies the point where roads meet or cross) (Berrigan *et al.*, 2010; Cerin *et al.*, 2011; Sallis *et al.*, 2016). However, there is a lack of clear and precise operational definitions of BE measures (Handy, 2005; Forsyth *et al.*, 2006) together with limited information issuing from uncertainty analysis of such indicators in high-density cities. Kwan (2012) notes that important ambiguities arise in measuring geographical context due to the spatial and temporal uncertainty of where, when and how long individuals experience environmental influences. Spatially, the uncertainty relates to the discussion of geographic scales in measuring spatial phenomena, as the modifiable areal unit problem (MAUP) of arbitrarily defined boundaries (Clark and Scott, 2014; Longley *et al.*, 2015). Lack of attention in consistency, validity and reliability of spatial scale of the measures could result in mischaracterization of environment exposure of subjects (Handy, 2005; Brownson *et al.*, 2009).

Hong Kong is a typical high-density city, where little research has been conducted on uncertainty analysis of BE indicators and health associations. We aimed to investigate the reliability of a wide spectrum of measures in this city charactering high-density BE in urban health studies across size and morphology of spatial measurement units thereby deriving urban health indicators. The study is expected to provide insights to analyzing uncertainty in BE measures in public health studies with rigorous stratified location sampling from a territorial-wide cohort.

Materials and Methods

The 5-D (density, diversity, design, destination accessibility, and distance to transit) internationally recognized framework (Ewing and Cervero, 2010; Ewing *et al.*, 2015) was used as design conception for constructing BE indicators based on a comprehensive dataset collected from governmental and private sectors. The 5-D approach includes density, measured as the variable of interest per unit of area; diversity, pertaining to the number of land use classes in that area; design, measured as street patterns and related characteristics; destination accessibility, indicating ease of access to trip attractions; and distance to transit, measured as the number of stations or stops per unit area.

Our measures concerned a representative sampling of residential addresses from the Hong Kong FAMILY Cohort which consists of a composite sample from several sources including a population representative random-core sample (Leung *et al.*, 2015). The cohort covers almost all Hong Kong neighbourhoods (99.8%) enabling detailed spatial epidemiological studies linking BE to health and well-being at the individual, household and neighbourhood levels. Cohort studies take a holistic view of health, investigating its different dimensions including socio-demographics, anthropometrics, lifestyle and behavioural factors, measures of social capital and biomaterials, looking for effective public health and preventive approaches to improving physical, mental and social well-being (Leung *et al.*, 2015).

Population and study area

Hong Kong is one of the most densely populated places in the world. According to the latest available census released from the Census and Statistics Department, Government of Hong Kong Special Administrative Region (SAR) (https://www.censtatd.gov.hk/hkstat/sub/so20.jsp), the inhabitation at the end of 20017 was over seven million people in an area covering 1068 km^2. The ubiquitous building design in Hong Kong is a podium serving as a base platform with 2 to 4 floors, with several high-rise residential towers built above the podium (Shelton *et al.*, 2011). More than 75%t of the land comprises of non-BE areas, while most BE exists between the waterfront and the mountains. The dwelling density of Hong Kong urban area is over 1,250 units per hectare. The shortage of flat land together with high land values have prompted buildings to develop vertically (Shelton *et al.*, 2011). Six spatial buffering and zonal techniques and scales were used for each BE measure in order to understand their performance in local contexts.

Data sources

Table 1 shows a summary of data types and sources collected from Hong Kong governmental and private sectors and stored in shapefile format, including building outlines and heights, street

Table 1. Comprehensive data of the built environment in Hong Kong.

Built environment	Data specification	Data source
Building data	Digital topographic maps in iB1000 (Scale 1:1000): http://www.landsd.gov.hk/download.php?file=mapping/en/digital_map/common/feature/ib1_fgdb_mf.pdf	Lands Department of Hong Kong SAR
Destination data	Points of interest (N= 329, 644): GeoCommunity database and an online map services. http://www.landsd.gov.hk/download.php?file=mapping/en/digital_map/common/feature/geocom_mf.pdf	Lands Department of Hong Kong SAR Gaode.com
Street network	Intelligent road network package: i) road network data: http://www.td.gov.hk/filemanager/en/content_4421/121130%20package_rdnet_-mdb_vasp.pdf ii) digitized traffic aids: http://www.td.gov.hk/filemanager/en/content_4421/110527%20package_dtad_-mdb.pdf	Transport Department of Hong Kong SAR
Census tracts	Tertiary planning unit and Street block/village cluster: https://www.devb.gov.hk/filemanager/en/content_384/frv2E.pdf	Planning Department of Hong Kong SAR

SAR, Special Administrative Region.

network, destinations from points of interest (N=329,644) and census tracts. The building density as floor area ratio, *i.e.* the ratio of a building's total floor area to the size of the piece of land upon which it is built, measured using the street-block census tract, is shown in Figure 1. Most land parcels in northern Hong Kong Island and Kowloon have a building density >5, which means that if the land of a block census tract is completely built, the number of floors is greater than 5 with the fifth quantile of building density being between 5 and 108 floors (Figure 1).

The residential addresses of FAMILY Cohort participants as of 2011 were geocoded. The detailed study design of the cohort has been described by Leung *et al.* (2015). The cohort comprised of 20,279 households and 46,001 participants. In this study, we used 5732 geocoded home addresses which excludes repeated addresses (different apartments) within the same building.

Design of built environment measures

Land use patterns refer to the spatial distribution of areas devoted to different purposes. Using the 5-D model, we measured three main dimensions of the high-density built environment: land use patterns, transport and urban design (Handy *et al.*, 2002). The former was estimated, first by calculating the building density (*i.e.* total floor areas of podium and residential towers divided by the catchment area) and then destination accessibility, which were classified into eleven categories as displayed in Table 2. The destination accessibility measures were constructed using density and quantity where the density measure was derived from the quantity of accessible destinations divided by the catchment area.

We also constructed a measure of the mixture of destination and land-use pattern. The formula used to calculate this mixture is a variation of the entropy formula used by Frank and his colleagues (Frank *et al.*, 2005).

$$DM = -1\left(\sum_{i=1}^{n} di * \ln(di)\right)/\ln(n)$$

where *DM* is the mixture index, *di* the percentage of destination category *i* within the study participant's catchment area and *n* the number of destination categories.

We used street connectivity to measure urban design and transport, constructing several measures, including average and median lengths of a block (influenced by the design of the street network, density of the street intersections (a measure of network connectivity) and the link-node ratio (indicator of connectivity, which is equal to the number of links divided by the number of nodes within in a study area.

The shorter the block length, the more connected the community (Leslie *et al.*, 2007), and the higher the intersection density or the link-node ratio, the more connected the network. The transport infrastructure accessibility is measured as the number of density and quantity of accessible transit stops, including public bus stops, metro entrances and ferries.

Spatial scales

Each BE measure was calculated at six spatial scale signified by: street-block group (SG), primary adjacency community (PAC), two circular buffers (CBs) and two network-based service area buffers (SAs) defined as shown in Figure 2 and Table 3. The SG

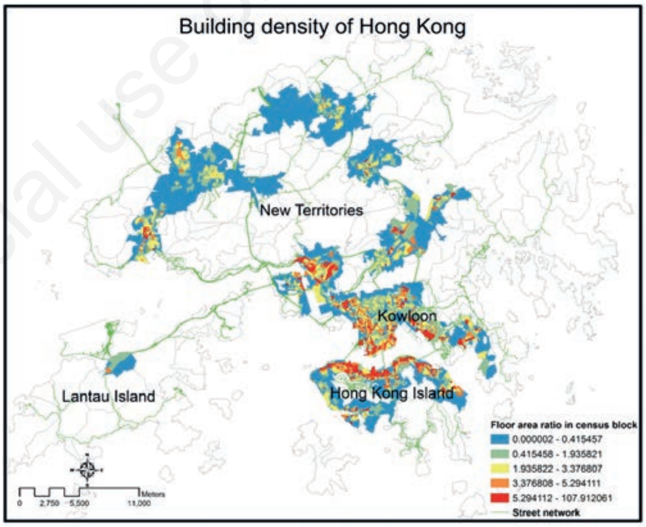

Figure 1. The density of Hong Kong built areas shown as street-block census tract.

Table 2. Taxonomy of destinations.

Destination category	Example
Small business	Real estate intermediaries, small firms, information centres, lottery sales, travel agencies, express centres, *etc.*
Groceries, supermarkets, convenient stores	Groceries, fruit and vegetable shops, farmer markets, supermarkets, convenience stores
Entertainments	Sports & leisure services, cinemas, scenic spots, hair and body spa centres, public green spaces, *etc.*
Government and institutions	Governments, institutions, social organization centres, *etc.*
Educational	Schools, libraries, scientific exhibition halls, training centres, convention centres, *etc.*
Hotels	Hotels, hostels, *etc.*
Retails	Shops, clothing and personal items shops, bookstores, gift shops, *etc.*
Companies	Companies, industry factories, *etc.*
Health care services	Hospitals, private clinics, community health care centres, *etc.*
Financial services	Banks, insurance services, security company and centres, financial firms and service centres, *etc.*
Restaurants	Restaurants, bars, coffees, dessert shops, *etc.*

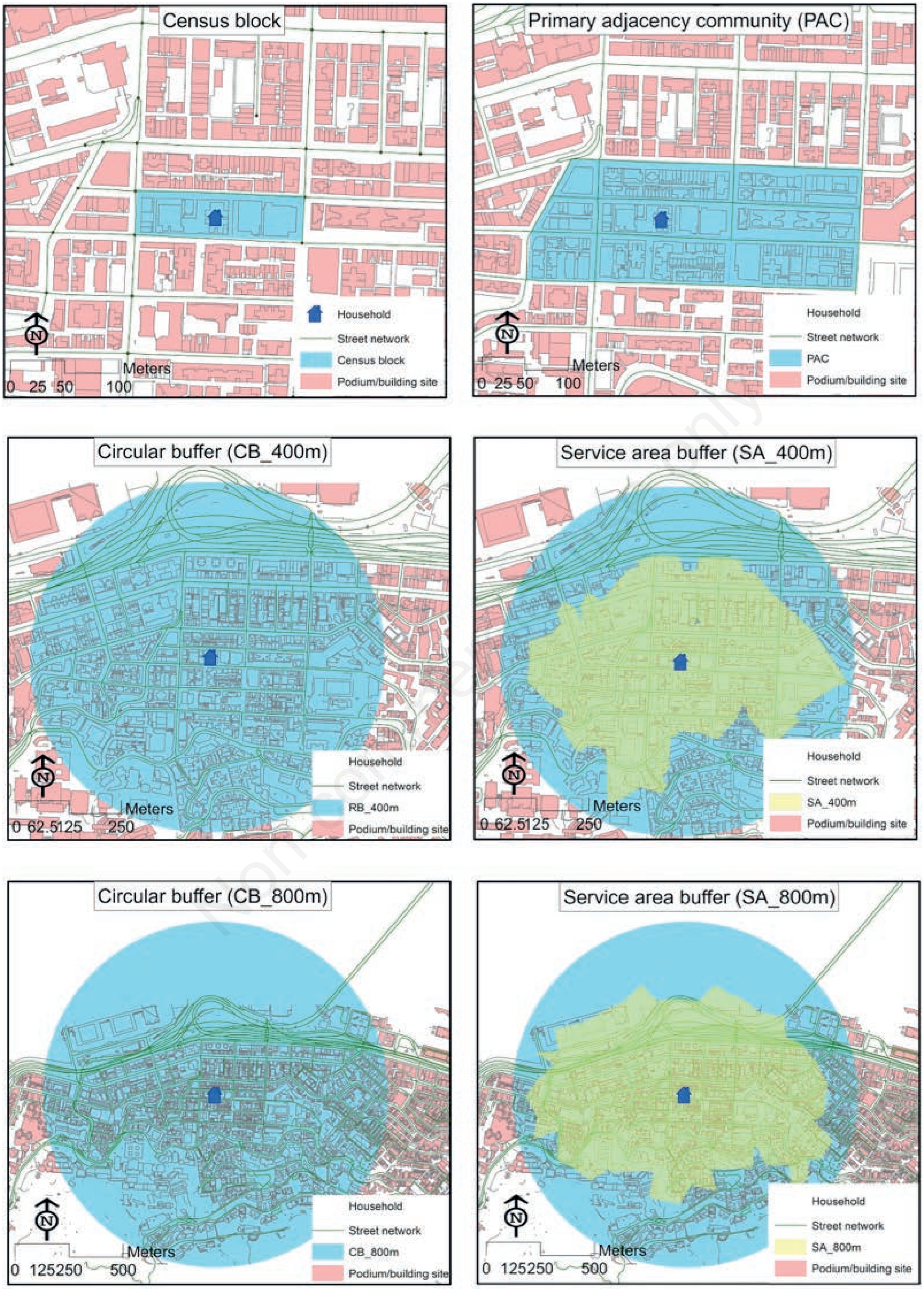

Figure 2. The six spatial scales.

and PAC are zonal buffers consistent with urban design features and statistical census tracts. CBs and SAs are less related to morphological phenomena and more to behaviour using the crow-fly and network distances. In a literature review of studies using behaviour buffers to describe spatial contexts, 65% used CBs while the rest used network-distances (Leal and Chaix, 2011).

Constructing the built environment measures

Density (1 indicator), diversity (1 indicator), design (4 indicators), destinations accessibility (22 indicators) and distance to transit (2 indicators) were calculated in the six spatial scales producing a total of 180 BE indicators, extracted for study participants of the FAMILY Cohort using GIS (ArcGIS 10.31, ESRI, Redlands, CA, USA) and Python scripting with 64-bit desktop background geoprocessing (https://blogs.esri.com/esri/arcgis/2012/11/12/python-scripting-with-64-bit-processing/). Using GIS, we also mapped a destination mixture indicator and a density/quantity indictor of retail (as a destination) across spatial scales as examples to visualize the uncertainty in the design, choice and use of BE measures.

Statistical analysis

Descriptive statistics using Stata (MP 14, StataCorp LP, TX, USA) were applied to the BE measures and Spearman's rank correlation calculated to assess how well the relationships between two variables were persevered across spatial scales. We used various categories to evaluate rank preservation (Strominger *et al.*, 2016) as follows: i) correlation ≥0.7 indicates a well-preserved index; ii) correlation ≥0.5 to 0.7 indicates a moderately preserved index; iii) correlation ≥0.3 to 0.5 indicates a weakly preserved index; iv) correlation <0.3 indicates that the index is not preserved across scales.

Results

The results from the descriptive statistics are shown in Tables 4-6. Judged by the density measures the building density varied between the spatial scales. SA_400m showed the highest building density (4.0). It was different from the CB_400m (2.67) but similar

Table 3. Spatial scales investigated.

Type of spatial scale	Description
Street-block group (SG)	The SG is the smallest census tract (average size 0.22 km^2), which is demarcated by streets containing the 5,732 FAMILY Cohort unique building addresses (in podium/towers buildings). A SG contains one or a few closely adjacent buildings.
Primary adjacency community (PAC)	The PAC includes proximate communities including the home block and adjacent blocks that share boundaries defined by a vertex or a line segment, usually a street (Strominger et al., 2016). The PAC represents the immediate environment of a cohort member, which is formed by the boundary of the closets streets.
Circular buffer (CB)	The CB of the home address using a behaviourally determined impedance value (friction of distance) as radius. In this study, we used impedance values of 400 (CB_400m) and 800 m (CB_800m). These two radii correspond to short and long walking distances and have previously been applied in studies on the linkage of BE and activities such as walking, physical activity, well-being and chronic disease (Oliver *et al.*, 2007).
Network-based service area buffer (SA)	The SA comprises areas that encompass all accessible streets tracing a given impedance value (e.g., 5 min or 400 m) from a home address. SAs aim to provide a more accurate representation of spatial context than CBs. Also here, we used impedance values of 400 (SA_400m) and 800 m (SA_800m) as network radii to extract the BE measures referring to our study participants.

Table 4. Descriptive statistics of built environment characteristics at different scales.

Type of spatial scale	SG		PAC		CB_400m		CB_800m		SA_400m		SA_800m	
	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max
Catchment area(km^2)	0.119 (0.207)	0.000616 1.48	1.07 (1.63)	0.0126 11.600	0.503 (0)	0.503 0.503	2.010 (0)	2.010 2.01	0.144 (0.066)	0.02 0.424	0.437 (0.238)	0.244 (1.38)
Density												
Building density	3.77 (2.14)	0.00 108.00	2.08 (1.67)	0.00 13.00	2.67 (1.33)	0.00 10.03	1.85 (0.97)	0.05 5.54	4.00 (1.91)	0.00-20.74	3.23 (1.53)	0.00 11.09
Diversity												
Destination mixture	0.48 (0.12)	0.00 1.00	0.36 (0.08)	0.07 0.69	0.34 (0.09)	0.07 1.00	0.28 (0.07)	0.08 0.58	0.42 (0.13)	0.00-1.00	0.36 (0.12)	0.00 1.00
Design												
Average block length	118.00 (76.30)	15.00 1130.00	116.00 (37.10)	34.40 680.00	111.00 (36.70)	57.10 1420.00	106.00 (19.50)	68.70 451.00	78.00 (30.40)	29.50-1000.00	78.10 (25.10)	34.20 734.00
Median block length	80.20 (74.50)	10.80 1130.00	64.10 (16.10)	19.70 412.00	65.30 (19.70)	21.30 990.00	60.70 (9.34)	36.80 374.00	52.30 (25.40)	11.10-693.00	51.00 (21.30)	15.80 792.00
Intersection density	0.00041 (0.00042)	0.00 0.00508	0.00034 (0.00029)	0.00 0.00256	0.00038 (0.00022)	0.00 0.00132	0.00030 (0.00017)	0.00 0.00084	0.00145 (0.00087)	0.00-0.00525	0.00118 (0.00063)	0.00 0.00472
Link-node ratio	0.85 (0.36)	0.53 4.00	0.62 (0.09)	0.52 7.00	0.57 (0.03)	0.51 2.50	0.53 (0.01)	0.51 0.63	0.59 (0.07)	0.51-2.10	0.56 (0.04)	0.51 1.12

SG, Street-block group; PAC, primary adjacency community; CB, circular buffer; SA, service area buffer.

Table 5. Destination accessibility. Descriptive statistics of destination accessibility with respect to density of destination *(i, i=1,2,…, 11).*

Category	SG		PAC		CB_400m		CB_800m		SA_400m		SA_800m	
(See Table 2)	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	
Small business	0.00021 (0.00052)	0.00 0.00821	0.00015 (0.00033)	0.00 0.00550	0.00014 (0.00023)	0.00 0.00211	0.00010 (0.00014)	0.00 0.00090	0.00017 (0.00031)	0.00 0.00297	0.00015 (0.00025)	0.00 0.00259
Groceries, and supermarkets	0.00012 (0.00025)	0.00 0.00517	0.00007 (0.00011)	0.00 0.00132	0.00007 (0.00006)	0.00 0.00036	0.00005 (0.00004)	0.00 0.00020	0.00009 (0.00010)	0.00 0.00089	0.00008 (0.00006)	0.00 0.00067
Entertainments	0.00020 (0.00047)	0.00 0.01480	0.00014 (0.00029)	0.00 0.00482	0.00014 (0.00020)	0.00 0.00160	0.00010 (0.00012)	0.00 0.00076	0.00017 (0.00028)	0.00 0.00369	0.00015 (0.00019)	0.00 0.00243
Government and institutions	0.00008 (0.00021)	0.00 0.00969	0.00006 (0.00015)	0.00 0.00252	0.00006 (0.00010)	0.00 0.00071	0.00004 (0.00006)	0.00 0.00033	0.00007 (0.00013)	0.00 0.00180	0.00006 (0.00010)	0.00 0.00130
Education	0.00012 (0.00027)	0.00 0.00667	0.00008 (0.00015)	0.00 0.00302	0.00009 (0.00010)	0.00 0.00079	0.00006 (0.00006)	0.00 0.00039	0.00011 (0.00014)	0.00 0.00131	0.00009 (0.00010)	0.00 0.00119
Hotels	0.00004 (0.00042)	0.00 0.01870	0.00002 (0.00015)	0.00 0.00527	0.00002 (0.00010)	0.00 0.00179	0.00002 (0.00007)	0.00 0.00062	0.00003 (0.00013)	0.00 0.00332	0.00003 (0.00009)	0.00 0.00132
Retails	0.00053 (0.00123)	0.00 0.04210	0.00041 (0.00100)	0.00 0.01600	0.00040 (0.00068)	0.00 0.00563	0.00029 (0.00041)	0.00 0.00237	0.00049 (0.00093)	0.00 0.01250	0.00042 (0.00067)	0.00 0.00835
Companies	0.00062 (0.00296)	0.00 0.05390	0.00073 (0.00210)	0.00 0.03240	0.00070 (0.00150)	0.00 0.01310	0.00060 (0.00096)	0.00 0.00555	0.00076 (0.00201)	0.00 0.02030	0.00075 (0.00161)	0.00 0.01590
Health care services	0.00018 (0.00060)	0.00 0.03820	0.00013 (0.00038)	0.00 0.00953	0.00013 (0.00022)	0.00 0.00238	0.00009 (0.00014)	0.00 0.00084	0.00016 (0.00030)	0.00 0.00426	0.00014 (0.00022)	0.00 0.00247
Financial services	0.00008 (0.00026)	0.00 0.00432	0.00006 (0.00016)	0.00 0.00359	0.00006 (0.00012)	0.00 0.00145	0.00004 (0.00007)	0.00 0.00057	0.00008 (0.00016)	0.00 0.00198	0.00007 (0.00013)	0.00 0.00189
Restaurants	0.00052 (0.00102)	0.00 0.01540	0.00033 (0.00063)	0.00 0.00664	0.00032 (0.00042)	0.00 0.00318	0.00022 (0.00025)	0.00 0.00142	0.00041 (0.00058)	0.00 0.00601	0.00035 (0.00042)	0.00 0.00457

SG, Street-block group; PAC, primary adjacency community; CB, circular buffer; SA, service area buffer.

Table 6. Descriptive statistics of destination accessibility with respect to quantity of destination *(i, i=1,2,…, 11).*

Category	SG		PAC		CB_400m		CB_800m		SA_400m		SA_800m	
(See Table 2)	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	Min Max	Mean (SD)	
Small business	5.6 (7.89)	0.00 85.00	28.30 (32.00)	0.00 375.00	70.60 (118.00)	0.00 1060.00	209.00 (291.00)	1.00 1810.00	29.00 (59.70)	0.00 808.00	86.30 (168.00)	0.00 1640.00
Groceries, and supermarkets	6.52 (6.50)	0.00 65.00	21.80 (12.80)	0.00 108.00	34.60 (29.80)	0.00 179.00	92.00 (72.80)	0.00 411.00	14.50 (17.60)	0.00 143.00	37.20 (43.50)	0.00 275.00
Entertainments	7.66 (9.49)	0.00 116.00	38.50 (29.40)	0.00 398.00	70.80 (98.40)	0.00 802.00	207.00 (238.00)	3.00 1530.00	28.70 (54.60)	0.00 687.00	82.60 (143.00)	0.00 1140.00
Government and institutions	3.88 (4.56)	0.00 53.00	15.50 (13.40)	0.00 134.00	29.50 (49.60)	0.00 355.00	85.80 (123.00)	0.00 662.00	11.60 (24.40)	0.00 281.00	34.50 (69.90)	0.0 559.00
Education	7.55 (7.60)	0.00 100.00	28.10 (18.40)	0.00 161.00	43.00 (49.50)	0.00 398.00	125.00 (127.00)	1.00 789.00	16.80 (27.40)	0.00 340.00	47.50 (73.70)	0.00 597.00
Hotels	0.4 (3.85)	0.00 347.00	2.40 (10.50)	0.00 638.00	12.50 (51.50)	0.00 901.00	40.10 (131.00)	0.00 1260.00	5.99 (32.60)	0.00 887.00	19.00 (81.10)	0.00 990.00
Retails	21.70 (50.00)	0.00 597.00	93.50 (118.00)	0.00 1310.00	200.00 (341.00)	0.00 2830.00	579.00 (825.00)	0.00 4770.00	84.10 (183.00)	0.00 2320.00	247.00 (497.00)	0.00 3880.00
Companies	10.60 (52.00)	0.00 2000.00	149.00 (471.00)	0.00 5170.00	353.00 (753.00)	0.00 6580.00	1210.00 (1930.00)	0.00 11200.00	130.00 (360.00)	0.00 5380.00	443.00 (1010.00)	0.00 0400.00
Health care services	7.13 (8.03)	0.00 149.00	30.60 (29.20)	0.00 522.00	63.60 (112.00)	0.00 1200.00	181.00 (272.00)	0.00 1690.00	27.70 (69.40)	0.00 1200.00	79.70 (175.00)	0.00 1540.00
Financial services	2.99 (5.03)	0.00 61.00	13.20 (16.50)	0.00 242.00	31.10 (58.70)	0.00 730.00	89.20 (138.00)	0.00 1140.00	12.80 (29.80)	0.00 633.00	37.60 (81.30)	0.00 1080.00
Restaurants	19.10 (25.30)	0.00 223.00	83.30 (69.80)	0.00 650.00	162.00 (213.00)	0.00 1600.00	451.00 (507.00)	0.00 2850.00	68.10 (114.00)	0.00 1250.00	187.00 (298.00)	0.00 2100.00
Distance to transit												
Density of transit services	0.00006 (0.00008)	0.00 0.00113	0.00004 (0.00004)	0.00 0.00036	0.00005 (0.00003)	0.00 0.00017	0.00003 (0.00002)	0.00 0.00010	0.00006 (0.00004)	0.00 0.00037	0.00005 (0.00003)	0.00 0.00025
Quantity of transit services	4.50 (5.42)	0.00 28.00	20.70 (14.10)	0.00 104.00	23.70 (13.30)	0.00 84.00	69.40 (39.20)	3.00 208.00	8.90 (8.00)	0.00 61.00	24.80 (22.10)	0.00 158.00

SG, Street-block group; PAC, primary adjacency community; CB, circular buffer; SA, service area buffer.

to the SG level (3.77). CB_800m indicated the lowest building density (1.85) which was only half of the counterpart using the SA buffer. Judged by the diversity measures, the destination mixture was the greatest at the SG level (0.48), followed by SA_400m (0.42), PAC (0.36), SA_800m (0.36) and CB_400m (0.34). CB_800m (0.28) had the smallest diversity in mixture of the destinations/services.

Judged by the design measures, the median block lengths were not consistent with the average block lengths. For example, the median length was 80.2 m compared to a mean of 118.0 m at the SG level. SA_800m had the smallest median length (51.0 m) among all spatial scales, while SG had the longest block length both with respect to the median and average measures. SA buffers had greater density of street intersections than the CB counterparts (*e.g.*, 0.00145 for SA_400m versus 0.00038 for CB_400m). Intriguingly, SG having the lowest connectivity measured using median bock length, that is having the longest block length (80.20), is reversed to have the highest connectivity measured using link-node ratio (0.85).

Judged by the destination accessibility measures, SG had the smallest quantity of destinations in most of the destination categories, while CB_800m held the largest quantity of destinations and showed striking differences between scales in categories of small business (5.62 versus 209.00), retails (21.70 versus 579.00), companies (10.60 versus 1210.00), and restaurants (19.10 versus 451.00). The quantities of destinations in SA_400m was less than half the quantity of destinations in CB_400m counterparts (*e.g.*, educational (16.80 versus 43.00), entertainments (28.70 versus 70.80), and restaurants (68.10 versus 162.00)). The differences in destination quantities were offset or even reversed compared to the destination density measures. For example, retail density between SG and CB_800m was reversed compared to the absolute measure: quantity was 21.70 versus 579.00, while the density was 0.00053 per m^2 versus 0.00029 per m^2. Generally, SG had the largest density of destinations of all the categories (except for the company category).

Judged by the distance to transit measures, SG and SA_400m had the largest density of transit (0.00006), while CB_800m had the smallest (0.00003). The quantity measures preserve the density ranking across spatial scales, with CB_800m having the largest amount of transit, 68.4 stops being within accessible distance on average compared to 4.5 at the SG level.

Mapping built environment measurement uncertainty

We used a set of maps to show the diversity of destination mix contra density and quantity of retail as examples of variability in measures across spatial scales when measuring the high-density BE of Hong Kong (Figure 3). Destination mixture was evenly distributed across the territory using SG. There was no clear difference, on this measure, between new towns in the New Territories and the city centre on Hong Kong Island. On the contrary, the distribution of service mix was much more uneven using SA_400m. The areas with relative low service mix were in the northern part of Hong Kong Island (from Sheung Wan to Causeway Bay) and the linear area from Tsim Sha Tsui to Mong Kok (around Nathan Road) in Kowloon. These were both among the most densely populated areas in Hong Kong.

Quantity measures of the retail service were quite different comparing SG and SA_400m. Most of the places which had less than 20 retail stores in the block measure had more than 100 in the 400m network buffer measure. The densest places measured in the retails quantity were in similar areas that had the relative lower destination mix in the northern part of Hong Kong island and around Nathan Road. The variations in retail density between the two spatial scales were much less than with the quantity measure, except for a few places such as the eastern part of Hong Kong island and the linear area from Hung Ham to To Kwa Wan in Kowloon. Similar degrees and patterns of uncertainty over spatial scale were found in most of the other destination categories referred in Tables 4-6.

Statistical analyses of variability/uncertainty

Spearman's rank correlations for BE measures across scales are shown in Table 7. Judged by the density measures, block-level building density correlated weakly with PAC, CB_400m, and SA_800m ($\rho>0.30$ and $\rho<=0.50$). It did not correlate with CB_800m ($\rho=0.27$). PAC had a weak correlation with SA_400m, a moderate correlation with SA_800m ($\rho=0.55$) and a strong correlation with CB_400m and CB_800m ($\rho>0.70$). CB_400m had a strong correlation with CB_800m, SA_400m, and SB800 ($\rho>0.70$). CB_800m had a weak correlation with SA_400m and a moderate correlation with SA_800m ($\rho=0.61$). A strong correlation was found with SA_400m and SA_800m ($\rho=0.83$).

Judged by the diversity measures, the mix of services had a weak correlation with SG and SA_400m, SG and SA_800m, PAC and CB_800m, CB_800m and SA_400m ($\rho=0.32\sim0.48$). There was no correlation between SG and CB_800m ($\rho=0.17$). A well-preserved correlation was shown between SA_400m and CB_800m, CB_400m and CB_800m, and CB_400m and SA_800m ($\rho=0.72\sim0.80$).

Judged by the design measures, median block length was less consistent across spatial scales than average block length except when comparing SG and PAC ($\rho=0.45$ versus 0.40), and SA_400m and SA_800m ($\rho=0.86$ versus 0.84). The average block length exhibits weak to moderate correlations among the six spatial scales ($\rho=0.34\sim0.67$), with the exception of a non-correlated relationship between SG and CB_800m ($\rho=0.23$) and a high correlation between SA_400m and SA_800m ($\rho=0.84$). Link-node ratio showed extreme variability across scales. Most rankings were not preserved ($\rho=-0.09\sim0.25$), except weak correlations between CB_400m and SA_800m ($\rho=0.32$) and SA_400m and SA_800m ($\rho=0.48$) and a moderate correlation between SG and PAC ($\rho=0.57$).

Judged by the destination accessibility measures, rank correlations of service destination density measures were preserved better than service destination quantity measures in general. For example, density measures of accessible entertainments shown moderate to high correlation between scales ($\rho=0.43\sim0.85$), while quantity measures in SG were not correlated with CB_400m ($\rho=0.11$), CB_800m ($\rho=-0.03$), SA_400m (0.18), or SA_800m (0.11).

Judged by the distance to transit measures, we observed weak correlations for density measures of accessible transit comparing SG and the other scales ($\rho=0.25\sim0.37$). However, the SG measures of accessible transit counts were not preserved with the other scales ($\rho= (-0.14) \sim (-0.02)$) except with PAC ($\rho=0.72$). Similarly, PAC measures of quantity were not correlated with CB_400m, CB_800m, SA_400m, and SA_800m ($\rho=-0.06\sim0.07$).

Discussion

This paper deals with our understanding of uncertainty, a long-

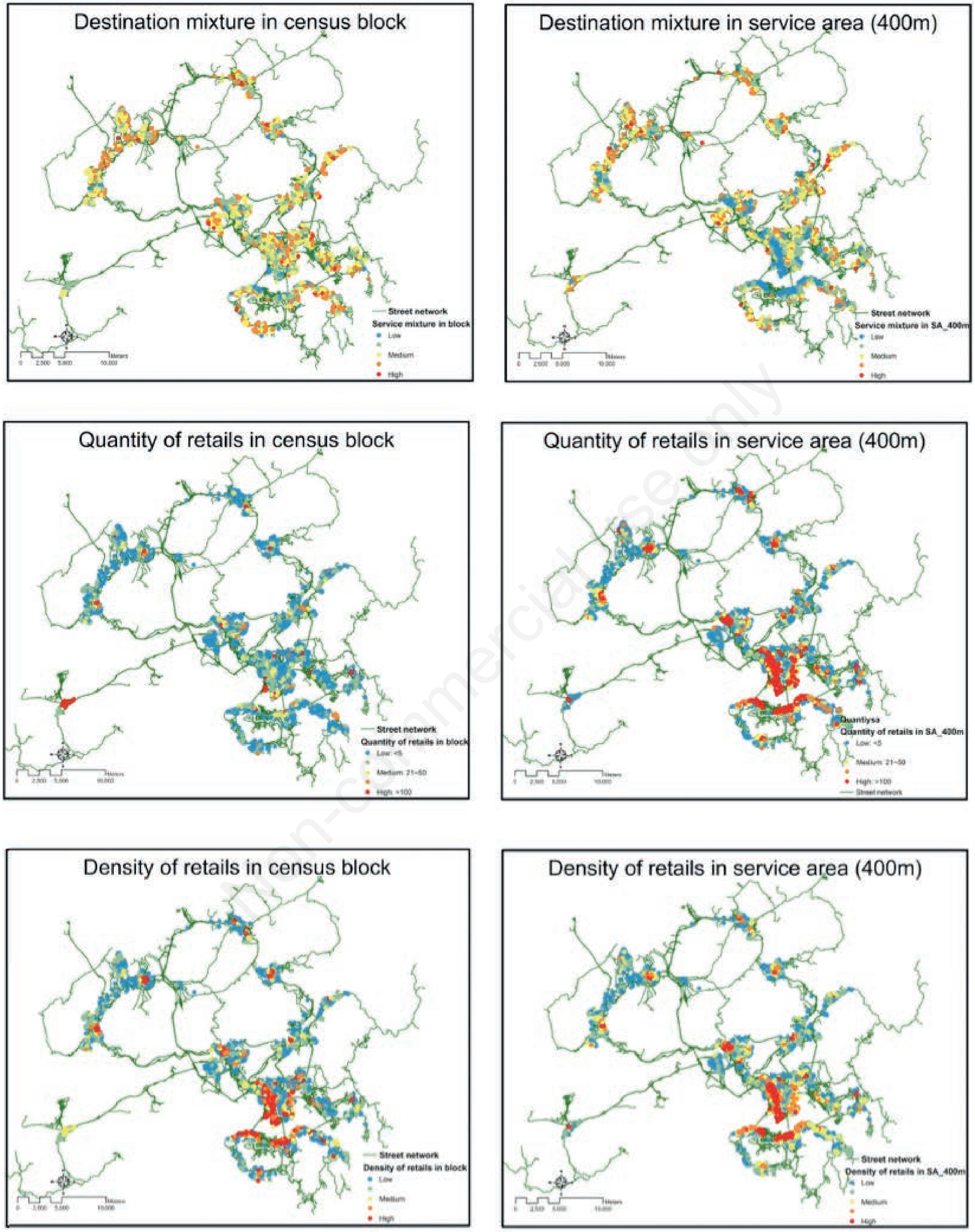

Figure 3. Examples for the uncertainty of construction methods and spatial scales in measuring the high density built environment of Hong Kong.

Table 7. Spearman's correlations among built environment characteristics in scales.

		SG	PAC	CB_400m	CB_800m	SA_400m	SA_800m
Density: building density	SG	1.00					
	PAC	0.38	1.00				
	CB_400m	0.47	0.72	1.00			
	CB_800m	0.27	0.70	0.80	1.00		
	SA_400m	0.54	0.49	0.70	0.46	1.00	
	SA_800m	0.50	0.55	0.77	0.61	0.83	1.00
Diversity: destination mixture	SG	1.00					
	PAC	0.38	1.00				
	CB_400m	0.28	0.66	1.00			
	CB_800m	0.16	0.47	0.72	1.00		
	SA_400m	0.35	0.55	0.65	0.45	1.00	
	SA_800m	0.28	0.57	0.74	0.61	0.76	1.00
Design							
Average block length	SG	1.00					
	PAC	0.40	1.00				
	CB_400m	0.40	0.67	1.00			
	CB_800m	0.23	0.66	0.64	1.00		
	SA_400m	0.35	0.48	0.59	0.39	1.00	
	SA_800m	0.34	0.49	0.63	0.48	0.84	1.00
Median block length	SG	1.00					
	PAC	0.45	1.00				
	CB_400m	0.40	0.61	1.00			
	CB_800m	0.28	0.55	0.60	1.00		
	SA_400m	0.07	0.17	0.26	0.15	1.00	
	SA_800m	0.06	0.17	0.27	0.16	0.86	1.00
Density of intersections	SG	1.00					
	PAC	0.51	1.00				
	CB_400m	0.53	0.80	1.00			
	CB_800m	0.42	0.78	0.82	1.00		
	SA_400m	0.05	0.02	0.12	-0.04	1.00	
	SA_800m	0.05	0.07	0.16	0.00	0.88	1.00
Link-node ratio	SG	1.00					
	PAC	0.57	1.00				
	CB_400m	-0.09	0.04	1.00			
	CB_800m	-0.05	-0.01	0.25	1.00		
	SA_400m	-0.02	-0.06	0.19	0.17	1.00	
	SA_800m	-0.04	-0.08	0.32	0.22	0.49	1.00
Destination accessibility: Density (Quantity) of destination i, i=1,2,…, 11)							
Small business	SG	1.00					
	PAC	0.62 (0.49)	1.00				
	CB_400m	0.59 (0.29)	0.82 (0.66)	1.00			
	CB_800m	0.45 (0.14)	0.77 (0.53)	0.83 (0.83)	1.00		
	SA_400m	0.63 (0.35)	0.73 (0.57)	0.79 (0.77)	0.65 (0.62)	1.00	
	SA_800m	0.58 (0.29)	0.76 (0.60)	0.87 (0.82)	0.77 (0.72)	0.84 (0.85)	1.00
Groceries, and supermarkets	SG	1.00					
	PAC	0.45 (0.41)	1.00				
	CB_400m	0.40 (-0.13)	0.75 (0.23)	1.00			
	CB_800m	0.30 (-0.24)	0.70 (0.05)	0.74 (0.74)	1.00		
	SA_400m	0.44 (-0.02)	0.61 (0.17)	0.70 (0.66)	0.52 (0.50)	1.00	
	SA_800m	0.38 (-0.12)	0.65 (0.16)	0.79 (0.75)	0.66 (0.64)	0.79 (0.82)	1.00
Entertainments	SG	1.00					
	PAC	0.60 (0.54)	1.00				
	CB_400m	0.57 (0.11)	0.84 (0.38)	1.00			
	CB_800m	0.43 (-0.03)	0.80 (0.28)	0.83 (0.83)	1.00		
	SA_400m	0.61 (0.18)	0.74 (0.34)	0.81 (0.75)	0.64 (0.60)	1.00	
	SA_800m	0.56 (0.11)	0.80 (0.34)	0.87 (0.78)	0.76 (0.69)	0.85 (0.87)	1.00

To be continued on the next page.

standing but less studied issue in urban health, with a particular focus in high-density and heterogonous urban situations. We examined the uncertainty in measuring high-density BE, as typified by Hong Kong, with a view to understand the variability of BE measures across different design methods and spatial units. Our results reveal how variability affects the sensitivity of BE measures in health studies.

We constructed 30 BE indicators of land use patterns, transport

Table 7. Continued from previous page.

		SG	PAC	CB_400m	CB_800m	SA_400m	SA_800m
Government and institutions	SG	1.00					
	PAC	0.36(0.52)	1.00				
	CB_400m	0.41(0.12)	0.75(0.44)	1.00			
	CB_800m	0.26(-0.06)	0.73(0.29)	0.79(0.79)	1.00		
	SA_400m	0.46(0.16)	0.63(0.37)	0.75(0.72)	0.59(0.57)	1.00	
	SA_800m	0.40(0.04)	0.69(0.33)	0.84(0.77)	0.72(0.68)	0.82(0.81)	1.00
Educational	SG	1.00					
	PAC	0.25(0.52)	1.00				
	CB_400m	0.26(-0.16)	0.75(0.21)	1.00			
	CB_800m	0.13(-0.32)	0.74(0.08)	0.78(0.78)	1.00		
	SA_400m	0.35(-0.05)	0.60(0.17)	0.70(0.64)	0.53(0.51)	1.00	
	SA_800m	0.25(-0.18)	0.65(0.12)	0.80(0.71)	0.68(0.64)	0.79(0.83)	1.00
Hotels	SG	1.00					
	PAC	0.51(0.54)	1.00				
	CB_400m	0.40(0.38)	0.73(0.70)	1.00			
	CB_800m	0.29(0.28)	0.59(0.56)	0.77(0.77)	1.00		
	SA_400m	0.46(0.44)	0.71(0.67)	0.79(0.79)	0.64(0.64)	1.00	
	SA_800m	0.38(0.36)	0.69(0.64)	0.85(0.84)	0.74(0.74)	0.83(0.83)	1.00
Retails	SG	1.00					
	PAC	0.61(0.50)	1.00				
	CB_400m	0.56(0.32)	0.77(0.61)	1.00			
	CB_800m	0.43(0.18)	0.67(0.44)	0.72(0.72)	1.00		
	SA_400m	0.60(0.35)	0.68(0.48)	0.73(0.71)	0.54(0.53)	1.00	
	SA_800m	0.55(0.30)	0.74(0.55)	0.82(0.79)	0.67(0.66)	0.82(0.84)	1.00
Companies	SG	1.00					
	PAC	0.51(0.47)	1.00				
	CB_400m	0.44(0.33)	0.77(0.67)	1.00			
	CB_800m	0.29(0.16)	0.68(0.53)	0.80(0.80)	1.00		
	SA_400m	0.54(0.42)	0.69(0.56)	0.72(0.70)	0.57(0.55)	1.00	
	SA_800m	0.47(0.35)	0.72(0.59)	0.81(0.78)	0.70(0.67)	0.82(0.83)	1.00
Health care services	SG	1.00					
	PAC	0.59(0.54)	1.00				
	CB_400m	0.49(0.10)	0.78(0.42)	1.00			
	CB_800m	0.37(-0.04)	0.71(0.27)	0.77(0.77)	1.00		
	SA_400m	0.55(0.17)	0.68(0.34)	0.74(0.70)	0.57(0.55)	1.00	
	SA_800m	0.49(0.10)	0.72(0.37)	0.84(0.78)	0.70(0.67)	0.81(0.84)	1.00
Financial services	SG	1.00					
	PAC	0.40(0.46)	1.00				
	CB_400m	0.28(0.15)	0.70(0.52)	1.00			
	CB_800m	0.16(-0.01)	0.64(0.33)	0.72(0.72)	1.00		
	SA_400m	0.37(0.23)	0.64(0.46)	0.71(0.70)	0.52(0.52)	1.00	
	SA_800m	0.29(0.14)	0.66(0.45)	0.81(0.79)	0.66(0.66)	0.78(0.80)	1.00
Restaurants	SG	1.00					
	PAC	0.60(0.46)	1.00				
	CB_400m	0.58(0.16)	0.79(0.51)	1.00			
	CB_800m	0.47(0.03)	0.74(0.36)	0.78(0.78)	1.00		
	SA_400m	0.63(0.23)	0.72(0.43)	0.78(0.75)	0.61(0.59)	1.00	
	SA_800m	0.58(0.16)	0.74(0.46)	0.84(0.80)	0.72(0.70)	0.84(0.86)	1.00
Distance to transit: density (quantity) of transit services	SG	1.00					
	PAC	0.37(0.72)	1.00				
	CB_400m	0.35(-0.03)	0.75(0.07)	1.00			
	CB_800m	0.25(-0.14)	0.75(0.00)	0.81(0.81)	1.00		
	SA_400m	0.35(-0.02)	0.58(0.02)	0.70(0.61)	0.55(0.48)	1.00	
	SA_800m	0.31(-0.13)	0.65(-0.06)	0.81(0.67)	0.72(0.62)	0.76(0.82)	1.00

SG, Street-block group; PAC, Primary adjacency community; CB_400m, Circular buffer in 400m; CB_800m, Circular buffer in 800m; SA_400m, Network area buffer in 400m; SA_800m, Network area buffer in 800m.

and urban design around 5,732 geocoded residential addresses of Hong Kong FAMILY Cohort members. Each indicator was calculated at six spatial scales, commonly applied in health-related behavioural studies, adopting the 5-D BE framework to increase comparability with international studies. These urban morphology metrics were constructed based on a complete database; specifically, we measured destination/service diversity from a complete suite of points of interest in detailed categories. It is different from pervious diversity measures using mixture indices constructed at the parcel level (*e.g.* residential, commercial, or industrial levels) with abstract land use categories (Frank *et al.*, 2005). The abstract land use at the parcel level is unable to capture the variations in high-density environments with intense mixed-use development, which may lead to invalid findings regarding the linkages of BE-health outcomes (Lu *et al.*, 2016). We posed a detailed taxonomy of the classification of services for destination accessibility measures, which can serve as a protocol for future studies.

We found a high variability in construction methods of BE indicators. For example, significant differences in the urban design dimension appear between block length (median and average) and street connectivity (density of intersections and link-node ratios), and between quantity measures of destination accessibility and their counterparts in density measures. Median block length and link-node ratio showed less preserved correlations in ranking than other measures of the design dimension, the median being more sensitive than the average for measuring variability of the block size. Measurement rankings can even be reversed in different design methods of indicators. For example, the lowest connectivity measured by the median bock length at the SG level was shown to have the highest connectivity in link-node ratio on the contrary, which may lead to extreme inconsistence when applying them separately in regression models. Quantity measures of service destination accessibility were found to be more sensitive than the service density measures. These uncertainties are somewhat in line with the findings in low-density cities (Mitra and Buliung, 2012; Clark and Scott, 2014; Strominger *et al.*, 2016), but the uncertainty level is more pronounced in the high-density environment.

We found considerable uncertainties in measuring a high-density BE across spatial scales. Most of measures using the smallest census tract of Hong Kong, the SG scale, were quite inconsistent with other scales, indicating minimal correlation. The census tract scale may therefore be inappropriate for capturing variability of urban morphology in high-density building areas, although it has the advantage of correlating BE measures with census variables. This calls attention to health research using census tracts in similar high-density contexts. Likewise, we found none or weak correlations when comparing indicator rankings at the CB_800m levels with other scales. The poorly preserved correlations between CB and others may partially originate from the constraint layout of the urban area in Hong Kong, where developed land is squeezed between mountains and the sea. CB used in this morphological context is likely to include a large proportion of uninhabited areas of mountains or water body. Similarly, larger zonal PAC measures perform poorly because they tend to involve inaccessible spaces due to ownership or institutional, configurational, slope and other reasons. Models of BE-health associations using these scales could, therefore, fail to infer valid linkages between BE and health impact. On the contrary, a network buffer, which is less contaminated by inaccessible spaces, becomes a more appropriate unit for analysis.

Implications

The uncertainty demands reflection with regard to design methods and spatial scales when constructing BE indicators for health studies. Qualitative interviews of subjects would be required to gain a better understanding of activity space, thus informing selection of BE metrics to better reflect a subject's geographic context. Taking the quantity and density of accessible destinations as an example, destination counts are better at reflecting a location's vitality than destination density. However, subjects may perceive no difference in utility between neighbourhood environments with 10~20 restaurants and another with 20~30. It therefore matters that the two types of measures have significantly different rankings when measured at different scales and with different shapes. Density measures will be biased as an indicator of place viability, due to intrinsic lack of correlation with the more important destination count morphology.

Researchers need to use a scale that is appropriate to the behaviours investigated. When constructing a BE measure, subjects may be asked, for example, to actively draw what they consider their behavioural space to be, or passively reveal the ideal spatial scales for some particular choice set (*e.g.*, active trajectories by GPS) (Tribby *et al.*, 2017). An extension of our study would be to repeat the systematic comparison of BE measures across scales within the context of a BE-health associational study. In this way, the impact of using certain measures rather than others could be assessed in terms of correlation coefficients, not just in terms of the descriptive performance of the measures compared against each other.

Limitation and strengths

This study has several limitations, *e.g.*, we did not consider the weights of different destinations/services in measuring the diversity of land use. Weighting would be needed when linking these indicators to health outcomes. For example, retail destinations may be more important for walking studies than small businesses, which need to be differentiated from companies. We used a street network rather than a pedestrian network for the urban design measures and there may be behavioural differences between those two networks (Sun *et al.*, 2015). The study was conducted in a high-density urban environment, so generalization of the finding should be done with caution. However, the methodology can be reliably adapted to other high-density cities and elsewhere, with additional considerations. Finally, we only discussed static BE exposure measures based on residential addresses, while dynamic measures of exposure may be required to connect 'activity spaces' with exposures in different environments. Understanding the spatial and temporal variations of exposure is critical when dynamic exposures are required (Kwan, 2013; Burgoine *et al.*, 2014; Tenailleau *et al.*, 2015).

To the best of our knowledge, this is the first study to systematically profile variability of BE measures across scale and shape of measurement buffers in a high-density city. This is a notable strength as this approach is fundamental for research and practice for promoting healthy high-density cities. We can further explore the linkage of BE and health behaviours and disentangle the impact of BE on health through rigorous and solid measures, which represents evidence of the need for effective BE intervention in high- density cities for urban planners, policy makers and public health practitioners. We are working on building an open data web platform to support scholars who are interested in studies of BE-health associations in Hong Kong. The methodologies, including data collection protocols, measures, and modelling provide a benchmark for high density BE-health studies in Hong Kong and other high-density cities around the world.

Conclusions

We measured and classified attributes of the high-density BE based on a comprehensive urban dataset which is essential for testing health-related research hypotheses. Our findings suggest complete data, appropriate design methods and suitable spatial scales of measures are crucial in high density BE related health studies. Some indictors were found to be more robust than others. When high-density urban space is linearly constrained by uninhabited areas, as in Hong Kong, network buffers likely to retain more meaningful activity space than circular buffers while circular buffers and block-based geography, with the latter's attraction of linked census data, may be more acceptable surrogates in homogenous lower density cities. This is the first study to systematically examine BE in a high-density city, which can be framework of measuring BE for healthy studies in other similar contexts.

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