



Anatomy of density: measurable factors that constitute urban density

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ABSTRACT

Serious concerns about global warming have been translated into urgent calls for increasing urban densities, as higher densities are associated with lower carbon emissions from both vehicles and buildings. However, attempts at effective densification have generally failed and urban densities continue to decline in cities across the world. Calls for densification without making room for it have resulted in serious housing supply bottlenecks in many cities and have rendered their housing unaffordable. If affordable densification is to be successful, it is necessary to understand the factors that constitute urban density. A novel way is presented for factoring the average density of cities into constituent factors—three or seven factors—that when multiplied together reconstitute urban density. This factoring methodology is presented together with the preliminary measurement of these factors in 10 cities in 10 world regions. This approach allows, for the first time, a clear understanding of how different cities acquire their density: Hong Kong gets its density from building height; Kinshasa from crowding; and Dhaka and Bogotá from residential coverage. This anatomy of density offers a new outline for a comprehensive strategy for city densification: one that addresses each and every one of the factors that constitute urban density.

PRACTICE RELEVANCE

Urban density is usually defined as the ratio of the total population of a city and its total area. This is the most appropriate single metric for measuring progress in densification in cities and is now a central objective of the global climate change agenda. However, this metric is rather crude and often hides more than it reveals. The anatomy of density offers a new, simple method for factoring urban density into its constituent factors that when multiplied together reconstitute urban density. This approach offers city leaders and urban planners a new way to consider and develop comprehensive policy options and strategies for city densification that addresses each and every one of the factors that constitute urban density and the tradeoffs between them.

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1.1 A KEY SUSTAINABILITY METRIC

Urban density or, more precisely, urban population density is simply understood as the ratio of the total number of inhabitants living within a well-defined footprint of a city and the total area of this footprint. Increasing urban density, or densification, has been correctly identified as a worthwhile sustainability objective. First, because urban density translates population into land consumption: a city with a given population will occupy a smaller geographical footprint—and will therefore need to convert less of the surrounding countryside to urban use when its urban density is higher. Second, because the inhabitants of a more compact city with a higher urban density will be closer to each other. Other things being equal (*i.e.* disregarding variations in the overall shape of its footprint, in internal spatial variations in density or in internal arrangements of land use), everything in a more compact city will be closer, making movement from place to place more efficient. In terms of both land consumption and transportation, a more compact city will be a more sustainable city.

Because of these substantial benefits, densification is now ‘enshrined in land use planning policy in many countries’ (Burton 2001: 219) as well as in Goal 11 (Indicator 11.3.1) of the United Nations’ Sustainable Development Goals (Opoku 2016). Most developed and many less-developed countries now pursue policies that promote compact urban form (OECD 2012), and studies have indeed revealed a range of secondary benefits from compactness: more productivity; lower cost public services; enhanced social and economic mobility as well as diversity; increased public transit use; lower energy use and emissions; and improved health and wellbeing (for a comprehensive review, see Boyko & Cooper 2011). This is also seen in pandemics such as Covid-19, which thrive in larger cities, not denser ones:

Larger cities have more than their share of cases and deaths in part because the larger the city, the larger the number of possible interactions among its inhabitants. And it is this larger number, rather than the overall average proximity of people to each other—expressed by the average density in the city—that accounts for that larger share. In fact, when it pertains to Covid-19 cases and deaths, denser metropolitan areas appear to be better able to contain their numbers than more spread out ones.

(Angel & Blei 2020: 28)

1.2 MEASURING DENSITY IN CITIES

There are many ways to measure density (for a comprehensive review, see Churchman 1999) and a large number of academic articles have been devoted (1) to measuring it in cities and metropolitan areas, in neighborhoods, and in individual building projects in different ways; (2) to arguing the merits and demerits of particular measures; and (3) to discussing the difficulties of measurement given the limitations of available data. The main density metrics found in the literature are shown in [Table 1](#).¹

Several authors (*e.g.* Banai & DePriest 2014) focus on data issues in measuring urban population densities. Population data are typically obtained from censuses. Since census data are collected and assigned to homes, the population in a given census tract is its ‘residential’, or its night-time, population. The entire population of a city is thus assigned to its residential areas, since by definition no population inhabits non-residential areas. Still, Banai & DePriest (2014: 3) (quoting Bourne 2001) point out that:

lower-density commercial and industrial uses contribute to sprawl more than higher-density residential uses

suggesting that urban density refers to the entire urban footprint rather than be restricted to residential areas within that footprint. As for the urban footprint of cities, Banai & DePriest (2014) point out that recent advances in remote sensing and Geographical Information Systems (GIS) have made it possible to identify the contiguous built-up areas of cities, as well as the urbanized open spaces encompassed by these built-up areas and metropolitan areas. This is done with the

DENSITY CATEGORY	RATIO	REFERENCE
Indoor density		
Persons per dwelling unit	$\frac{\text{Total population}}{\text{Total number of dwelling units}}$	US Census Bureau (1950); Grebler (1951)
Persons per habitable room	$\frac{\text{Total population}}{\text{Total number of rooms}}$	Blake <i>et al.</i> (2007)
Floor area per person	$\frac{\text{Total area of dwelling units}}{\text{Total population}}$	UN-Habitat (1996); Blake <i>et al.</i> (2007)
Occupied floor area per person	$\frac{\text{Total occupied floor area}}{\text{Total population}}$	WHO (2009)
Parcel density		
Floor area ratio	$\frac{\text{Gross residential floor area}}{\text{Residential plot area}}$	ASPO (1958); Kogo <i>et al.</i> (2010)
Dwelling unit per hectare (ha)	$\frac{\text{Total number of dwelling units}}{\text{Residential plot area}}$	ASPO (1958); Forsyth (2003)
Residential neighborhood density		
People per residential neighborhood area	$\frac{\text{Total population}}{\text{Residential neighborhood area}}$	Eldridge (1984)
Dwelling units per residential neighborhood area	$\frac{\text{Total number of dwelling units}}{\text{Residential neighborhood area}}$	ASPO (1958); Alexander (1993); Forsyth (2003)
Dwelling units per 'developable land' area	$\frac{\text{Total number of dwelling units}}{\text{Total 'developable land' area}}$	Galster <i>et al.</i> (2001)
Citywide density		
Citywide floor area ratio	$\frac{\text{Total floor area}}{\text{Area of urban footprint}}$	McDonald and McMillen (2010); Krehl <i>et al.</i> (2016)
Citywide floor area per person	$\frac{\text{Total residential floor area}}{\text{Total population}}$	Krehl <i>et al.</i> (2016)
Citywide people per total residential area	$\frac{\text{Total population}}{\text{Total residential area}}$	Frenkel and Ashkenazi (2008)
Urban density	$\frac{\text{Total population}}{\text{Urban Footprint}}$	James (1967: 55); Angel <i>et al.</i> (2016); OECD (2018)
Built-up area density	$\frac{\text{Total population}}{\text{Built-up area in urban footprint}}$	Angel <i>et al.</i> (2016)

Table 1 Main measures of urban density in the literature and selected sources that mention them.

aim of producing comparable global results. As cities and metropolitan areas typically form single, integrated labor markets, we contend that these urban footprints are also the proper areas of analysis for exploring the issues of sustainability described in the previous section.

Dovey & Pafka (2016) call for 'greater density literacy,' pointing out the distinctions between indoor densities (people per m² of occupied floor area) and outdoor densities, between net residential densities (confined to residential blocks) and gross (urban) densities, between daytime and night-time densities, between person-based densities and dwelling-unit densities, between low- and high-rise densities, and between area density and street density or 'intensity.' While it is true that most of these densities (**Table 1**) are 'factors' of the overall urban density of cities, data limitations restrict our analysis (and those of most practitioners) to night-time densities and make it impossible to explore the 'intensity' of cities in general or the density of individual urban neighborhoods in particular.

To the best of the authors' knowledge, few publications discuss the arithmetic relationships between different density metrics. Different densities are usually treated as discrete quantities, with authors pointing out, for example, that 'net residential density' is higher than 'gross residential density' because the area in the denominator of the latter is larger than that of the former, but without specifying exactly what their ratio is or what it denotes.

1.3 URBAN DENSITY AS A SINGLE METRIC

Despite the proliferation of density measures, the authors believe it is vital to preserve urban density as the single key metric for measuring densification. Many measures of density describe important urban phenomena, but a mission-oriented public policy that measures its success by pursuing a single goal with a single measure for the city at large is likely to be easier to formulate, garner support, and implement than a policy that seeks to attain disparate goals requiring disparate measures.

The use of urban density in this way is problematic, however, because it may hide more than it reveals, something easily illustrated with five brief examples:

- *Overcrowding*: High density is achieved by packing large households into small dwelling units.
- *High plot coverage*: High density is achieved by residential blocks with 'handshake' buildings that almost touch each other.
- *Ghost cities*: Conversely, low-density status may be achieved despite high 'floor area ratios' or high levels of 'dwelling units density' because most buildings are vacant. (The densification of such a city does not require additional construction; it simply requires people to inhabit it.)
- *Towers with low plot coverage and large apartments*: Luxury residential towers may exhibit a low urban density because these towers house very few people in large apartments and/or occupy only a small fraction of their plot areas. In such a city, displacing dense, low-rise neighborhoods with high-rise 'towers in the park' may lower, rather than increase, 'urban density.'
- *Small residential share*: High-density residential neighborhoods may contribute little to lowering overall urban density because a large share of a city's urban footprint is devoted to industrial use.

These examples point to the core insight of this paper: the same urban density can be the result of very different phenomena, and any serious densification policy must attend to all these different phenomena if it is to be effective. This is unlikely to occur as long as these different phenomena are hidden under the mantle of a single density measure.

The key research questions posed here are:

- What are the measurable factors that interact to create the overall urban density of cities?
- How can understanding the 'anatomy of density' be used to overcome the limitations of urban density as a single metric?

The answers offer policy-actionable insights into cities and preserve urban density as a single metric for measuring densification at the scale of the urban footprint.

2. THE THEORY: FACTORING URBAN DENSITY

Urban density can be factored into its constituent parts in different ways that expose its anatomy. Factoring is simply defined as breaking down a quantity into its constituents in such a way that multiplying them by each other yields that quantity (e.g. $12 = 3 \times 4$ or $12 = 2 \times 2 \times 3$). Exposing the components of urban density in a city makes it possible to treat them individually while considering their effect on urban density as a whole, much in the way that understanding the human body's anatomy makes it possible to treat its organs singly, while still considering their effect on the body as a whole. What is more, factoring urban density exposes the relationships among individual density metrics, thus giving both order and structure to the discussion of urban density and highlighting the tradeoffs inherent in different urban policies that impact density.

To realize these benefits, the factors of urban density must be measured at a scale that will create results that are comparable among cities and have meaning for the sustainability goals stated in the introduction. This means measuring the anatomy of density using averages for each density factor for the urban footprint, meaning the city or metropolitan area as a whole.²

There is more than one way to factor urban density. In total, 10 discrete factors have been identified. These factors can be meaningfully grouped into sets of two, three, four and seven. Each set of factors retains the key characteristic that lends utility to the approach, namely, the product of each set of factors is equal to urban density. This means that any desired change in urban density must come from a change in one of those factors, and that any change in one factor will, all else being held equal, result in a change in urban density. In a decision-making context, this new understanding will assist in framing tradeoffs among different policy options. The more detailed the factoring, the more comprehensive the resulting snapshot of urban density.

To illustrate this, the subsequent two sections will provide definitions of numerous factors of urban density. Section 2.1 will initially focus on three factors and section 2.2 on the most comprehensive set of seven factors. Both sections will incorporate some discussion of how increases in each of these factors will, all else being equal, lead to an increase in urban density. For reference, these factors—with additional factoring of urban density into two and four factors as well—are shown in *Figure 1*.

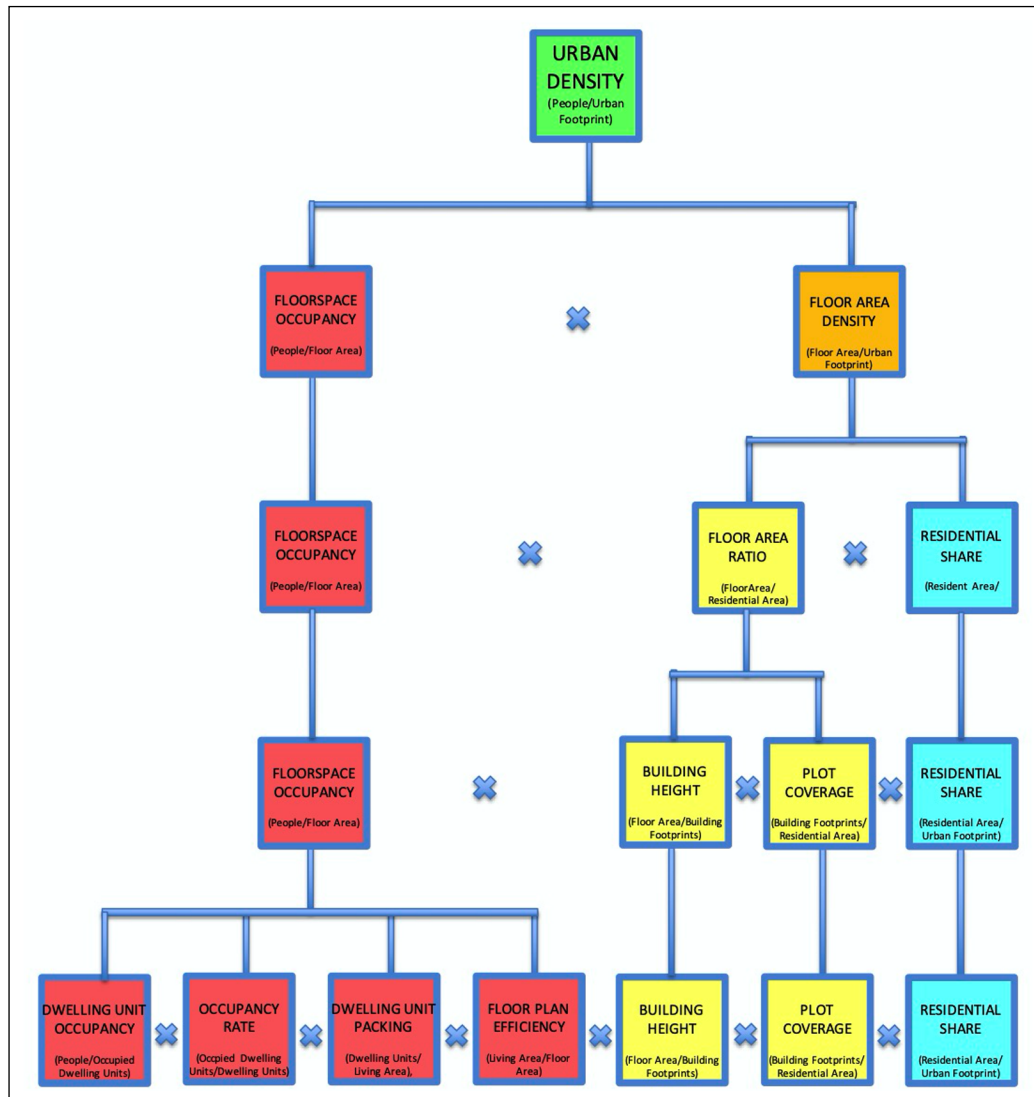


Figure 1: The two, three, four and seven factors that, when multiplied together, constitute urban density.

2.1 URBAN DENSITY AS A PRODUCT OF THREE FACTORS

'Urban density' is defined as the ratio of the 'total population' residing in a given 'urban footprint' and the total area of the urban footprint (top row of *Figure 1*):³

$$\text{Urban density} = \frac{\text{Total population}}{\text{Area of urban footprint}} \quad (1)$$

We can decompose urban density into three factors that when multiplied together yield urban density: 'floorspace occupancy,' 'floor area ratio' and 'residential share' (third row of *Figure 1*).

The first factor, floorspace occupancy, is the ratio of the total population of a city and its total residential floor area, the gross residential floor area, including wall thicknesses and common areas:⁴

$$\text{Floorspace occupancy} = \frac{\text{Total population}}{\text{Total residential floor area}} \quad (2)$$

Floorspace occupancy is simply the reciprocal of a more familiar metric: the average residential 'floor area per person' in the city (UN-Habitat 1996; Blake *et al.* 2007):

$$\text{Floor area per person} = \frac{\text{Total residential floor area}}{\text{Total population}} \quad (3)$$

Floorspace occupancy is used as a factor of urban density instead of using floor area per person because urban density increases proportionally when it increases. In contrast, urban density decreases proportionally when floor area per person increases.

The second factor is the average residential 'floor area ratio', a metric used to regulate the allowable building volume on a given plot (*e.g.* ASPO 1958; Kogo *et al.* 2010), restricted to the 'total area of residential plots':

$$\text{Floor area ratio} = \frac{\text{Total residential floor area}}{\text{Total area of residential plots}} \quad (4)$$

The total area of residential plots is defined net of streets, public spaces or civic facilities.⁵

The third factor is 'residential share,' the share of the total area of the city's urban footprint taken up by residential plots, a common metric used in quantifying urban land-use plans (*e.g.* Perez *et al.* 2004; Keys *et al.* 2007):

$$\text{Residential share} = \frac{\text{Total area of residential plots}}{\text{Total area of the urban footprint}} \quad (5)$$

All else being equal, a city with a higher share of its land in residential use will be able to host a greater number of people and will have a higher urban density.

It can now be ascertained that when floorspace occupancy, floor area ratio and residential share are multiplied together, everything cancels out and their product equals urban density:

$$\text{Floorspace occupancy} \times \text{floor area ratio} \times \text{residential share} = \text{urban density} \quad (6)$$

2.2 URBAN DENSITY AS A PRODUCT OF SEVEN FACTORS

We can also decompose urban density into seven factors (bottom row of *Figure 1*). This is accomplished by factoring floorspace occupancy into four factors, factoring floor area ratio into two factors and leaving residential share as before.

The first factor in a seven-factor decomposition of urban density is ‘dwelling unit occupancy.’ Dwelling unit occupancy is a measure of the average number of people occupying a single dwelling unit, typically one household, large or small, and sometimes doubled-up households. It is a more refined measure of overcrowding than floorspace occupancy because it measures occupancy in the net floor area of ‘occupied dwelling units,’ disregarding vacant ones (WHO 2009):

$$\text{Dwelling unit occupancy} = \frac{\text{Total population}}{\text{Total number of occupied dwelling units}} \quad (7)$$

The denominator of this factor focuses on the total number of occupied dwelling units in the city, a subset of the total number of dwelling units. All else being equal, if a larger total population lives within the occupied dwelling units of the city, the city will have a higher urban density. A low dwelling unit occupancy, due to decreased household size or increased income, lowers urban density.

The second factor is the ‘occupancy rate,’ a measure used in the real estate sector to assess the utilization of the available housing stock:

$$\text{Occupancy rate} = \frac{\text{Total number of occupied dwelling units}}{\text{Total number of dwelling units}} \quad (8)$$

The denominator of this factor focuses on the total number of dwelling units in the city, units, which make up the total living area of dwelling units. All else being equal, if more dwelling units in a city are occupied (not vacant), a greater number of households will be able to fit in the city and the city will have a higher urban density.

The third factor is ‘dwelling unit packing,’ a measure of the number of dwelling units that can be fitted in a hectare (ha) of salable or rentable floorspace net of common areas such as corridors, lobbies, staircases or elevator shafts. Dwelling unit packing is used as a factor of urban density instead of ‘dwelling unit size’ (equation 9a) because, other things being equal, when it increases, urban density increases proportionally. In contrast, other things being equal, urban density decreases proportionally when the average dwelling unit size increases:⁶

$$\text{Dwelling unit packing} = \frac{1}{\text{Dwelling unit size}} = \frac{\text{Total number of dwelling units}}{\text{Total living area of dwelling units}} \quad (9)$$

$$\text{Dwelling unit size} = \frac{\text{Total living area of dwelling units}}{\text{Total number of dwelling units}} \quad (9a)$$

The denominator of dwelling unit packing focuses on the total living area of all the dwelling units in the city, a subset of the total residential floor area. All else being equal, if this living area is larger, more households will be able to fit in the city and the city will have a higher urban density.

The fourth factor is ‘floor plan efficiency,’ a measure commonly used by developers to calculate the salable floor space of their buildings, excluding wall thicknesses, common corridors and staircases, elevator and utility shafts, lobbies, common public areas and common open floors, storage areas, and areas dedicated to off-street parking (e.g. Barton 2014):

$$\text{Floor plan efficiency} = \frac{\text{Total living area of dwelling units}}{\text{Total residential floor area}} \quad (10)$$

The denominator of this factor focuses on the floor area of residential buildings in the city. All else being equal, if residential buildings have on average more of their total floor area available for the living area of dwelling units (through more efficient designs, for example), more people will be able to live in each building and the city will have a higher urban density.

The fifth factor is ‘building height,’ measured as the average number of residential floors—exclusive of commercial floors in mixed-use buildings—in the city as a whole (e.g. ASPO 1958; Bertaud & Brueckner 2005):

$$\text{Building height} = \frac{\text{Total residential floor area}}{\text{Total area of residential building footprints}} \quad (11)$$

The denominator of this factor focuses on the area of residential building footprints, a part of the total residential area of the city. All else being equal, if the residential building footprints within the city contain more residential floor area (an outcome that can only be achieved by building up or digging down), more people will be able to live within each building footprint and the city will have a higher urban density.

The sixth factor is ‘plot coverage,’ measured as the average share of residential plots occupied by residential building footprints:

$$\text{Plot coverage} = \frac{\text{Total area of residential building footprints}}{\text{Total area of residential plots}} \quad (12)$$

The denominator of this factor focuses on just the residential area of the city, a part of the urban footprint. All else being equal, a city with a greater share of its residential area occupied by residential buildings can host a greater number of people within its residential area and will have a higher urban density.

The seventh factor is ‘residential share,’ the share of the total area of the city’s urban footprint taken up by residential plots:

$$\text{Residential share} = \frac{\text{Total area of residential plots}}{\text{Total area of the urban footprint}} \quad (13)$$

Each of these seven factors is a ratio of two averages for the city as a whole. When multiplying these ratios together, most of these averages cancel. This is illustrated in the bottom row of **Figure 1**. Starting from the far left, the denominator of each factor cancels out the numerator of the factor to the right of it: first occupied dwelling units cancels, followed by dwelling units, followed by living area, followed by floor area, then building footprints and finally residential area. Population is the only remaining numerator and urban area is the only remaining denominator. The ratio of these two variables was previously defined in equation (1) as urban density:

$$\begin{aligned} & \text{Dwelling unit occupancy} \times \text{occupancy rate} \times \text{dwelling unit packing} \times \text{floor plan efficiency} \\ & \times \text{building height} \times \text{plot coverage} \times \text{residential share} = \text{urban density.} \end{aligned}$$

For the factors that constitute urban density to be useful, they must also be measurable. This paper demonstrates this by calculating average citywide values for each factor. The results of these measurements are preliminary and quite possibly subject to substantial errors, but they are useful in illustrating for the first time that there are important variations in the anatomy of density among cities: different cities get their urban density from different combinations of factors.

3. METHODOLOGY FOR OBTAINING EMPIRICAL RESULTS

3.1 TEN REPRESENTATIVE CITIES

To measure the factors that constitute urban density, 10 representative cities were selected from the global sample of 200 cities in the *Atlas of Urban Expansion—2016 Edition* (Angel *et al.* 2016). The selected cities are listed in **Table 2**, which also shows that urban density in this group of cities was not highly correlated with city gross domestic product (GDP) or with city population. The cities were selected to maximize diversity in size, location, and economic development in order to test the methodology for obtaining the empirical results in a range of contexts.

CITY	COUNTRY	REGION	CITY GDP PER CAPITA, 2012	SATELLITE IMAGE DATE	URBAN FOOTPRINT AT THE DATE (HA)	POPULATION IN THE URBAN FOOTPRINT ('000s)	URBAN DENSITY (PERSONS/HA)
Dhaka	Bangladesh	South and Central Asia	US\$4,979	1 March 2014	36,541	13,609	372
Hong Kong	Hong Kong (SAR), China	East Asia and the Pacific	US\$50,746	1 October 2013	12,278	4,322	352
Kinshasa	Congo Democratic Republic	Sub-Saharan Africa	US\$1,849	1 July 2013	45,681	10,226	224
Bogotá	Colombia	Latin America and the Caribbean	US\$15,933	1 January 2010	39,723	7,802	196
Cairo	Egypt	North Africa	US\$12,067	1 May 2013	136,396	15,735	115
Baku	Azerbaijan	Western Asia	US\$13,536	1 August 2014	25,662	1,672	65
Madrid	Spain	Europe	US\$38,069	1 May 2010	84,407	5,256	62
Bangkok	Thailand	Southeast Asia	US\$23,309	1 January 2015	294,462	14,011	48
Wuhan	China	East Asia and the Pacific	US\$17,783	1 September 2013	183,723	8,174	44
Minneapolis	United States	North America	US\$59,082	1 October 2014	251,256	2,627	10

3.2 MEASURABLE METRICS

The measurable metrics that give an insight into the factors of urban density in each city are defined in [Table 3](#).

Table 2 Basic data on the 10 representative cities, arranged by their urban density, from the highest (Dhaka) to the lowest (Minneapolis).

METRIC	DEFINITION
Urban footprint	Total contiguous built-up area of the city and its urbanized open space
Total population	Total population residing within the urban footprint
Residential share	Share of the urban footprint occupied by residential buildings/plots
Plot coverage	Share of the total area of residential plots occupied by residential buildings
Building height	Average number of residential floors on a unit area of a residential building footprint
Floor plan efficiency	Average share of the gross residential floor area allocated to living areas in dwelling units
Occupancy rate	Share of the total number of dwelling units that are occupied
Persons per dwelling unit	Average number of persons per dwelling unit in the city

Table 3 Eight metrics that need to be obtained in a city to calculate urban density and all its factors and their definitions.

In this section we provide short summaries that explain how the values for each of these eight metrics were obtained. Detailed explanations are provided in the Appendix in the supplemental data online.

The urban footprint and total population were drawn from previous work of the authors. Several authors (e.g. Banai & DePriest 2014) have noted that the administrative boundary of the city is not an appropriate denominator for measuring its density because it may be too large or too small in comparison with its contiguous built-up area and may change arbitrarily from one year to another. This study uses urban footprints for the 10 cities that were previously created (Angel *et al.* 2016) by classifying recent Landsat imagery in study areas containing these cities.⁷ As part of the same exercise, the total population living within the urban footprints of these 10 cities was estimated using a methodology described by Angel *et al.* (2016) to address the modifiable areal unit problem.⁸

Residential share, plot coverage and building height estimates were obtained from Google Earth and Bing satellite imagery using an intra-urban spatial sampling methodology that identified a set of quasi-random points within the urban extent at a desired point density based on a Halton sequence (Halton 1964). This technique, developed for the *Atlas of Urban Expansion* (Angel *et al.* 2016) facilitates the collection of samples within a geographic area, permitting statistical analysis of the results. Trained image analysts assessed each point sample and conducted digitization work using the satellite imagery, based on techniques akin to aerial image analysis. The specific digitization rules used in this research are novel and offer a new and low-cost way to gather data in cities. For each of the sampled measurements, a running average was calculated after the fact to check that sufficient samples had been collected to stabilize the average.

Residential share was measured by determining for each point in the Halton sequence whether the land use at that point was ‘residential’ or ‘non-residential’ and calculating the residential share.⁹ More than 2000 points were sampled in each city.

Building height was estimated by counting residential floors in the nearest residential building to a Halton point identified as ‘residential’ earlier. Each building was placed in a typology: (1) single family; (2) non-core multi-family; and (3) core multi-family, where core buildings were defined as having centralized elevator shafts and stairwells. Analysts then counted the stories of that building, excluding floors that were identifiable non-residential uses (such as stores or parking).¹⁰ Building heights were gathered for an average of 1500 buildings in each of the 10 pilot cities.

Plot coverage was estimated by digitizing the boundaries of the blocks surrounding the first few hundred sampled points identified as ‘residential.’ These boundaries could be streets surrounding residential city blocks or intra-block boundaries between ‘residential’ and ‘non-residential’ land uses. The footprints of all residential buildings within a bounded area defined as ‘residential’ were digitized and their total area was calculated. An average of 460 residential blocks was digitized in each of the 10 pilot cities.

Occupancy rate, floorplan efficiency and persons per dwelling unit were collected from secondary sources.

The occupancy rate of residential units was estimated using three methods, reflecting different levels of data availability. (1) For Cairo, Madrid and Minneapolis national census data provided the occupancy rate directly. (2) For Bangkok, Bogotá, Dhaka, and Hong Kong the census provided ‘households sharing the same housing unit’ and ‘total number of domestic households’ for the city. The former was subtracted from the latter, yielding the number of occupied units (with the assumption that every household occupied a single unit). (3) For Baku, Kinshasa, and Wuhan the same arithmetic was used as in (2), but the total number of dwelling units was calculated by dividing the total square meters of residential floor space in the city by the average dwelling unit size, estimated by multiplying floor area per person and average household size.

Estimating floor plan efficiency required examining architectural drawings of buildings of varying sizes and heights, grouped by the building typology identified earlier.¹¹ Data gathering for this metric was preliminary and consisted of collecting and digitizing approximately 50 floor plans to estimate the share of the gross floor area of residential buildings devoted to dwelling units, net of wall thicknesses, lobbies, elevator shafts, stairwells, and mechanical spaces.

Persons per dwelling unit was typically calculated from national census data using the total population and total number of dwelling units. In some countries it was only available inferentially. In Azerbaijan, for example, the census provided the total residential floorspace in Baku, average square meters per person, and average household size, from which the total number of dwelling units was estimated. The urban extent of the cities used by the respective censuses to collect this information did not usually correspond exactly to the urban footprint of the city. We adopted the empirical value for persons per dwelling unit calculated from census data for the urban footprint as a whole, assuming that it did not vary appreciably from this empirical value.

4. EMPIRICAL FINDINGS IN 10 REPRESENTATIVE CITIES

4.1 DATA-GATHERING AND FINDINGS

Data-gathering in the 10 cities showed the viability of measuring the factors of density in a range of different contexts. The empirical findings are shown in **Tables 4–6**. The primary and secondary metrics obtained from the collection exercise are shown in **Table 4**. The six intermediary values shown in **Table 5** are necessary for computing the factors and were calculated from the values shown in **Table 4**. The urban densities and all their factors were calculated from **Tables 4** and **5**. **Table 6** displays estimates for urban density, 10 of its factors and three familiar complementary metrics that are commonly encountered in discussions of urban density.

Table 4 Estimated values for eight metrics obtained from primary and secondary data for the 10 representative cities.

Note: Cities are arranged from left to right in order of decreasing urban density.

METRICS OBTAINED FROM PRIMARY AND SECONDARY DATA	DHAKA	HONG KONG	KINSHASA	BOGOTÁ	CAIRO	BAKU	MADRID	BANGKOK	WUHAN	MINNEAPOLIS
a Population ('000s)	13,609	4,322	10,226	7,802	15,735	1,672	5,256	14,011	8,174	2,627
b Urban footprint (ha)	36,541	12,278	45,681	39,723	136,396	25,662	84,407	294,462	183,723	251,256
c Building height (stories)	2.5	20.5	1.1	2.8	4.4	2.6	3.4	1.9	5.8	1.4
d Plot coverage (%)	53%	22%	20%	52%	43%	35%	26%	44%	32%	11%
e Residential share (%)	37%	16%	46%	31%	26%	35%	19%	20%	14%	36%
f Persons per dwelling unit	4.2	2.8	5.1	3.6	2.1	3.8	2.3	3.0	2.2	2.4
g Occupancy rate (%)	97%	96%	99%	96%	66%	88%	88%	96%	77%	96%
h Floorplan efficiency (%)	85%	75%	95%	87%	79%	67%	83%	89%	75%	90%

INTERMEDIARY METRICS (CALCULATED)	CALCULATION	DHAKA	HONG KONG	KINSHASA	BOGOTÁ	CAIRO	BAKU	MADRID	BANGKOK	WUHAN	MINNEAPOLIS
i Gross residential floor area (ha)	$b \times c \times d \times e$	17,805	8,643	4,481	17,737	66,310	8,117	13,927	50,264	47,286	13,789
j Residential area (ha)	$b \times e$	13,536	1,955	20,812	12,170	35,335	9,102	15,846	59,786	24,911	90,671
k Residential building footprints (ha)	$b \times d \times e$	7,110	422	4,182	6,314	15,213	3,141	4,112	26,076	8,095	10,179
l Dwelling units ('000s)	a/f	3,215	1,527	2,009	2,154	7,405	441	2,321	4,687	3,689	1,077
m Occupied dwelling units ('000s)	$l \times g$	3,128	1,467	1,989	2,064	4,920	389	2,045	4,481	2,822	1,029
n Area of dwelling units (ha)	$i \times h$	15,140	6,495	4,256	15,378	52,127	5,439	11,519	44,639	35,465	12,377

Table 5 Estimated values for six intermediary metrics calculated for the 10 representative cities from metrics obtained from primary and secondary data.

URBAN DENSITY AND ITS FACTORS	CALCULATION	DHAKA	HONG KONG	KINSHASA	BOGOTÁ	CAIRO	BAKU	MADRID	BANGKOK	WUHAN	MINNEAPOLIS
o Urban density (persons/ha)	a/b	372	352	224	196	115	65	62	48	44	10
p Floorspace occupancy (persons/ha)	a/i	764	500	2,282	440	237	206	377	279	173	191
q Floor area density	i/b	0.5	0.7	0.1	0.4	0.5	0.3	0.2	0.2	0.3	0.1
r Floor area ratio	i/j	1.3	4.4	0.2	1.5	1.9	0.9	0.9	0.8	1.9	0.2
e Residential share (%)	e	37%	16%	46%	31%	26%	35%	19%	20%	14%	36%
c Building height (stories)	c	2.5	20.5	1.1	2.8	4.4	2.6	3.4	1.9	5.8	1.4
d Plot coverage (%)	d	53%	22%	20%	52%	43%	35%	26%	44%	32%	11%
s Dwelling unit occupancy (persons/occupied dwelling unit)	a/m	4.4	2.9	5.1	3.8	3.2	4.3	2.6	3.1	2.9	2.6
g Occupancy rate (%)	g	97%	96%	99%	96%	66%	88%	88%	96%	77%	96%
t Dwelling unit packing (dwelling unit/ha)	l/n	212	235	472	140	142	81	201	105	104	87
h Floorplan efficiency (%)	h	85%	75%	95%	87%	79%	67%	83%	89%	75%	90%
COMPLEMENTARY METRICS											
u * Floor area per person (m ²) [reciprocal of p]	1/p	13	20	4	23	42	49	26	36	58	52
v * Dwelling unit size (m ²) [reciprocal of t]	1/t	47	43	21	71	70	123	50	95	96	115
w * Occupied floor area per person (m ²)	v/s	11	14	4	19	22	29	19	30	33	45

4.2 IMPLICATIONS OF FINDINGS

The empirical results for the set of representative cities presented here are purely descriptive and cannot be extrapolated to the universe of cities. However, the results are internally valid and reveal large variations in the metrics that are not necessarily correlated with overall urban density. At a minimum, these findings show the value of decomposing density into its constituent factors by confirming the assertion that comparisons of urban density as a composite indicator may hide more than they reveal. They also show that different cities obtain their density from quite different combinations of factors.

The former point is illustrated by graphs showing the variations in urban density, floorspace occupancy, floor area density and floor area per person (the reciprocal of floorspace occupancy) in the 10 representative cities (*Figure 2*). The cities in *Table 6* and in *Figures 2* and *3* are arranged in order of declining urban density: from Dhaka, with an urban density of 372 persons/ha, to Minneapolis, with 10 persons/ha.

Table 6 Estimated urban densities and their factors calculated for the 10 representative cities from metrics obtained from data presented in *Tables 4* and *5*.

Note: The column labeled ‘Calculation’ indicates how the values were computed from the values given in *Tables 4* and *5*.

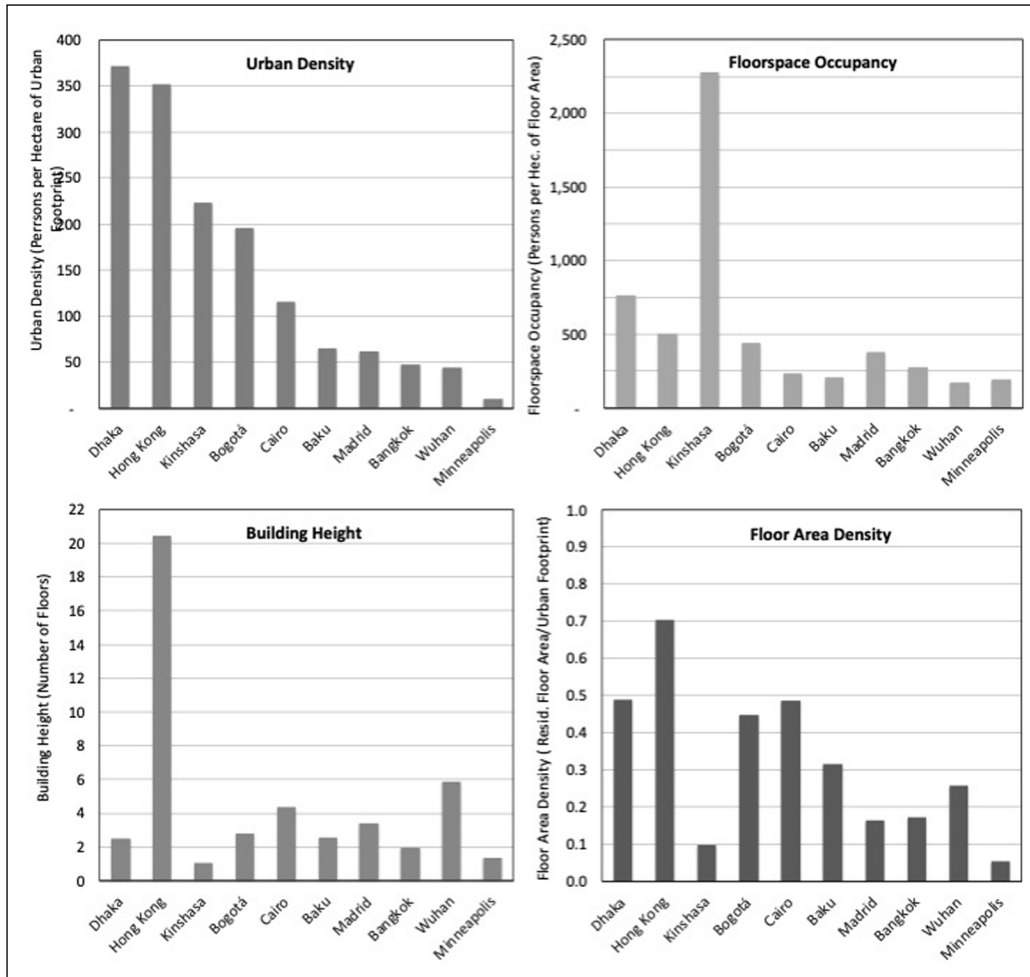


Figure 2: Observed variations in urban density, floorspace occupancy, floor area density and floor area per person in the 10 representative cities.

Figure 2 shows very weak correlations between urban density and its factors: as expected, urban density tended to be higher in cities with higher floor area density and floorspace occupancy and lower in cities with higher floor area per person. But exceptions abound: floor area density was higher in Hong Kong than in Dhaka, even though its overall urban density is lower; Cairo’s floor area density was equal to that of Dhaka, even though its urban density was only the fifth highest in the group; and Kinshasa’s floor area density was the second lowest in the group, even though its urban density was the third highest, and floorspace occupancy was highest in Kinshasa even though its urban density was only the third highest in the group.

The latter point—that different cities obtain their density from combinations of different factors—is illustrated in the subsequent section.

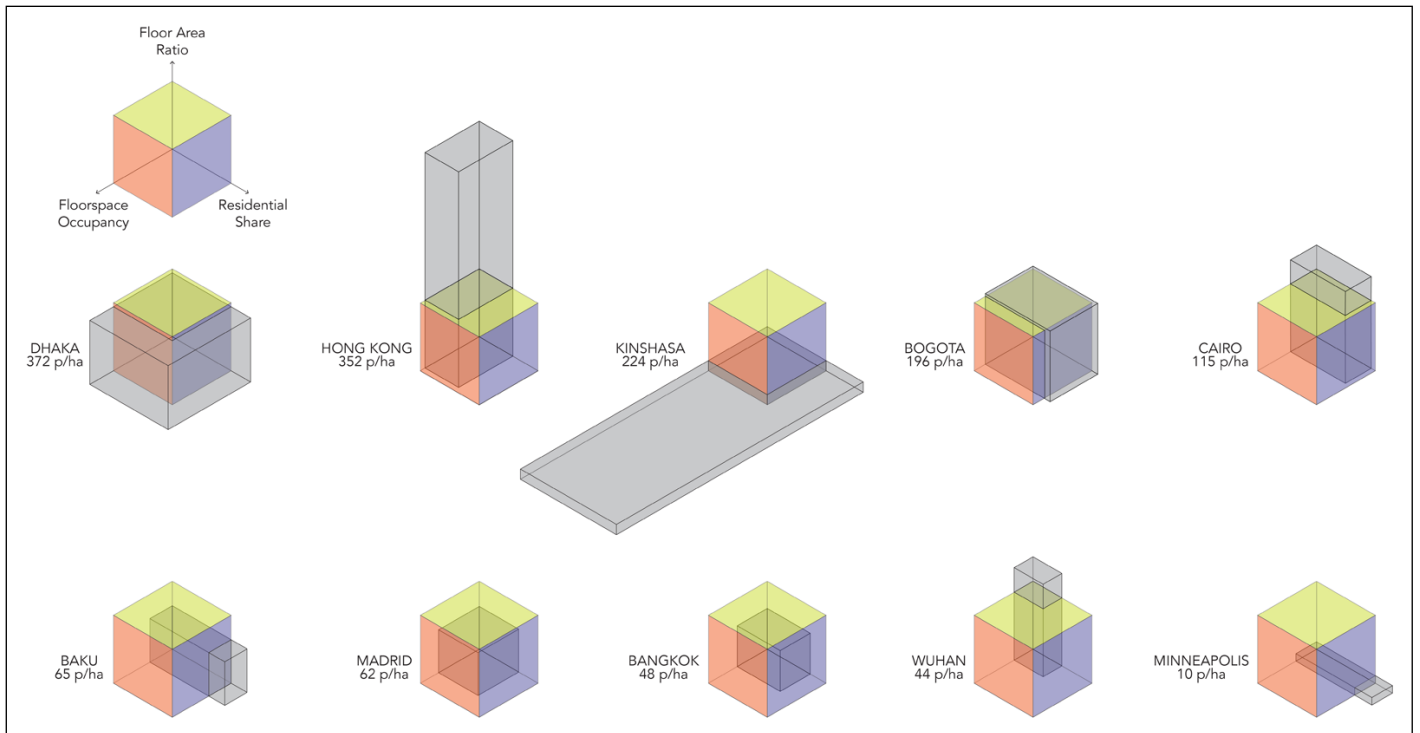
4.4 REPRESENTING URBAN DENSITY IN THREE DIMENSIONS

Section 2.2 focused on urban density as a product of seven factors, an approach that—while yielding a great deal of useful data—is not intuitive or easy to visualize. A simpler way to understand urban density as a product of factors is to focus on the three factors introduced in section 2.1:

$$\text{Floorspace occupancy} \times \text{floor area ratio} \times \text{residential share} = \text{urban density} \quad (6)$$

Perceiving urban density as a product of three factors as shown above makes it possible to represent it as a box in three-dimensional space. As before, a given urban density offers no hints as to which factor is responsible for it being high or low; but representing urban density as a box for each of the 10 cities begins to reveal its basic anatomy (Figure 3). Floorspace occupancy is measured on the x-axis; residential share is measured on the y-axis; and floor area ratio is measured on the

z-axis. Because urban density is a product of these three factors, it can only increase if one or more of these factors increases. The colored cube on the top left of **Figure 3** represents the 10-city averages, and the dimensions of each box are simply multiples of these averages.



The visual representation of urban density as a volume makes the relative contributions of different factors more apparent than the reliance on a single number. For example, Dhaka obtained its high density from its above-average floorspace occupancy and its above-average residential coverage, despite its floor area ratio being below average. Hong Kong, which had an urban density similar to that of Dhaka, obtained its high density from its above-average floor area ratio, while its floorspace occupancy was somewhat below average and its residential share was far below average. Kinshasa obtained its high density from its very high floorspace occupancy—more than three times that of Dhaka—while its floor area ratio was far below average. And Bogotá obtained its high density from its above-average floor area ratio and its above-average residential share. At the other end of the spectrum, Wuhan had a relatively low urban density despite its above-average floor area ratio, largely because of its very low residential share and its below-average floorspace occupancy. Finally, Minneapolis had the lowest urban density in the group because of its very low values for two of the three factors. In all, **Figure 3** demonstrates that the fact that a city has a relatively high urban density does not necessarily imply that its factors all have above-average values, and that a city with a relatively low urban density does not necessarily imply that its factors all have below-average values.

Figure 3: Urban densities of 10 cities represented as volumes of boxes (in grey) in decreasing order from right to left and from top to bottom. The colored cube represents the 10-city averages for each of the three factors that make up urban density.

5. CONCLUSIONS: TOWARDS A COMPREHENSIVE STRATEGY FOR CITY DENSIFICATION

This article has laid out a new theory for decomposing urban density into measurable factors, and a rigorous and replicable methodology for calculating these factors.¹² This has made it possible to both understand densification more clearly and envision a comprehensive strategy for the public sector to use one or more of these factors in facilitating densification, while monitoring the others to ensure that increases in some factors are not compromised by decreases in others.

This also lays the groundwork for a global study of the factors of urban density. All the factors of density, as well as urban density itself, are ratios rather than totals. These ratios are all ‘normalized’, *i.e.* independent of city totals of one kind or another, and are therefore comparable from one city to another. The data-generating process used in this paper is not only viable, it is also scalable, and

we believe it would be possible to obtain rigorous and externally valid results for the universe of all 4,231 cities and metropolitan areas with populations over 100,000 in 2010.

Such results would advance the study of urban density by providing statistically valid data and internationally comparable data that could be used for hypothesis testing. This work will require an investment of resources, but recent developments in machine learning and the increased availability of large geospatial data sets both promise to reduce projected costs appreciably.

The results of such an exercise would also support planning practice by establishing the distribution of values for different factors, helping to calibrate the expectations of cities seeking to densify through one technique or another.

The true value of the methodology will come with further study of the relationships between the factors. Section 2 established the mathematical relationship between the different factors of urban density, with implications for practice that become evident with the data in hand: policies that seek to increase urban density by focusing on one of the factors, such as floor area density, must also be assessed in terms of their relationship with all of the other factors in order to be effective. For instance, a policy to increase dwelling unit packing without maintaining the occupancy rate and dwelling unit occupancy (which would only be possible with an increase in the population and number of households) would produce a neutral result at great cost.

Such an approach could plausibly be applied in a decision-making context to reduce or eliminate these sorts of errors. This fresh look at the anatomy of density affords an opportunity to reconsider plans for cities—and, where appropriate, higher levels of government as well—to establish attainable and measurable densification goals for each factor. This is indeed a challenge, and an effective densification strategy could gain support by joining with existing agendas that seek to minimize greenhouse gas emissions, preserve the countryside, address inequality and promote affordable housing.

Urban planners are experts in understanding the practical difficulties of densification: the cultural and political barriers, the difficulties in revising the regulatory framework, and the budget available for implementation. These are unique to every city and cannot be determined in advance. This paper and the theory of the anatomy of density that it introduces helps urban planners and city leaders retain urban density as the key metric for measuring densification by providing the necessary framework to expose the vital information that urban density contains. The simplicity and transparency of this approach helps distinguish between effective and ineffective policies for densification, providing a way for cities to take rapid and meaningful action on this critical issue in the years to come.

NOTES

- 1 Bourne (2001) notes that a single focus on residential densities, as do all but the last four metrics in Table 1, may fail to account for the effect of low-density commercial and industrial uses on the overall compactness of cities, particularly where sustainability issues are concerned. Indeed, since population data are collected at people's homes, urban density as defined here is a night-time density, *i.e.* a residential density rather than an employment density. But as we shall show, overall urban density can increase if the residential share of land use in the city increases at the expense of commercial and industrial uses, *i.e.* when overall employment density increases. Urban density thus includes employment density.
- 2 We note at the outset that an 'average' ratio of two quantities can have two distinct meanings (The Math Forum 2003). For example, the 'average building height' in a city, measured in floors, could be the ratio of the total floor area in the city and the total area of building footprints in the city. Alternatively, it could be the 'average (or mean) height of individual buildings in the city, which would be the sum of the heights of individual buildings (which are the ratios of their floor areas and building footprints) divided by the total number of buildings. In this paper, all the averages of the factors that constitute urban density are defined as the ratio of sums and not as means of individual observations.

- 3 For a detailed definition of the urban footprint and the method of mapping and calculating urban footprints using Landsat satellite imagery, see Angel *et al.* (2016: 21–30).
- 4 For example, stairwells, corridors and elevator shafts.
- 5 The product of floorspace occupancy and floor area ratio yields the familiar ‘net residential density,’ a common measure of the average number of people in a hectare of net residential area in the city.
- 6 An important measure of residential overcrowding (e.g. Gove *et al.* 1983; Blake *et al.* 2007; Dol & Haffner 2010: 51, tab. 2.1), ‘occupied floor area per person’ is simply the ratio of dwelling unit size and dwelling unit occupancy, but only if we assume that the size of occupied and unoccupied dwelling units is the same:

$$\text{Occupied floor area per person} = \text{dwelling unit size} / \text{dwelling unit occupancy} = (\text{total living area in occupied dwelling units} / \text{total number of occupied dwelling units}) / (\text{total population} / \text{total number of occupied dwelling units}) = \text{total living area in occupied dwelling units} / \text{total population.} \quad (13)$$


If, as we suspect, the average size of unoccupied dwelling units is larger than the average size of occupied dwelling units, then a correct estimate of occupied floor area per person may be smaller than that estimated here.


- 7 We classified the Landsat imagery into built-up and non-built-up pixels. We then classified the built-up pixels into urban, suburban or rural ones, based on the shares of built-up pixels within a 1 km² walking distance circle around them: Those with <25% were classified as rural; those with 25–50% were classified as suburban; and those with ≥50% were classified as urban. We created urban clusters by grouping contiguous urban and suburban pixels. We included fringe open spaces that were within 100 m of them, and captured open spaces that were fully enclosed by urban and suburban pixels and fringe open spaces, and were <200 ha in area in urban clusters. Urban clusters that shared buffers surrounding them equal to one-quarter of their area were then combined to form the city’s urban footprint (Figure 3).
- 8 Each census enumeration district contains built-up pixels and the population within each enumeration district is assumed to be living within those built-up pixels. It is further assumed that the population is equally divided among those built-up pixels. Only the portion of the population living in pixels that fall within the urban footprint, as defined above, is counted in the population of the city.
- 9 This classification was based on a taxonomy developed for Angel *et al.* (2016). A point that fell on a plot or a building with mixed land use, including residential use, was considered to be ‘residential.’ Residential share was estimated as the share of ‘residential’ points in the total number of points sampled.
- 10 In the majority of cases, it was possible to count the number of floors in high-resolution satellite imagery or Google Street View based on window openings and balconies. Occasionally, the number of floors in a building in our sample was estimated by comparing it with an adjacent building of similar height with visible windows, or by comparing the length its shadow with that of buildings with visible windows.
- 11 For each architectural floor plan, analysts distinguish living and non-living areas, with areas that are exclusively within a private dwelling unit categorized as ‘living areas.’ The average ratio of living area to total floor area was calculated for each building type, and then a weighted average ratio was calculated for each city based on the mix of building types identified in the building height measurement.
- 12 The simplicity and rigor of the proposed methodology has made it easy to replicate. For a recent report on the replication of this methodology for factoring urban density in 10 Japanese cities, see Narro *et al.* (2020).

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COMPETING INTERESTS

The authors have no competing interests to declare.

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