Article Type: Research article

Title: Built-environment stocks in the context of rapid urbanization: A case study of Chandigarh, India

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Conflict of Interest Statement: The authors declare no conflict of interest

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords: Built environment, material flow analysis, industrial ecology, urban planning, resource efficiency

Abstract: Construction materials accumulate in the built environment forming material stocks of buildings and infrastructure, providing various services to society that result in a nexus of human development and environmental impact. The Global South is experiencing unprecedented levels of urbanization increasing demand for resources and threatening sustainable development. India, in particular, is set to lead urbanization rates globally. Meanwhile no study has yet explored material stocks and their spatial distribution within cities in India or within cities rapidly constructed with high living standards in mind. The present study begins to fill these gaps and aims to investigate patterns of built-environment material stock accumulation in Chandigarh, an exceptionally quickly developed city master planned to ensure universally high standards of living through a unique urban form. We adopt a bottom-up approach to quantify the residential building and road material stock at the city and sub-city scale. We find 28 Mt (50 t/cap and 391 kt/km^2) and 63 Mt (66 t/cap and 638 kt/km^2) of material stocked in residential buildings and roads respectively. The relative accumulation of road to building stock is significantly larger than in other cities and is driven by the gridiron urban form. This is shown to be environmentally detrimental as future urban development is limited and promotes demolition of existing stocks, whose composition severely limits their potential as secondary resources. This study therefore provides empirical evidence to support the integration of material stock assessments into urban planning and development.

1 INTRODUCTION

Construction materials are among the most widely used materials globally, the manufacture of which accounts for 11% of process-related carbon dioxide emissions (IEA, 2019). These materials accumulate within cities in the form of built-environment material stocks (MS) which shape future material and energy use (Krausmann et al., 2017) and play important roles in society through the provision of residence, transportation and various other services (Tanikawa, Fishman, Okuoka, & Sugimoto, 2015). Built-environment stocks therefore result in the nexus of anthropogenic carbon emissions and human development (B. Müller, 2006; Haberl, Wiedenhofer, Erb, Görg, & Krausmann, 2017; Müller et al., 2013; Tanikawa et al., 2015; Wiedenhofer, Steinberger, Eisenmenger, & Haas, 2015), the decoupling of which is seen as critical for achieving levels of development that are considered ‘sustainable’. However, unprecedented urbanization in the Global South (UN, 2018) is putting significant strain on the primary resources required for built-environment material stocks and may threaten the achievement of sustainable development globally. More than two-thirds of the world's population will live in cities by 2050 (UN, 2018)

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with around 60% of the cities required to accommodate this urbanization yet to be built (UNEP, 2013). Further, deficits in living standards (UN-Habitat, 2020; UNDP, 2019) mean nations in the Global South must increase net resource consumption to build, maintain and upgrade the built-environment in an effort to improve living standards (Krausmann et al., 2017) whilst simultaneously reducing environmental impact (UNEP, 2015). Built-environment stocks have therefore become of increasing focus in assessments of sustainable development and resource management strategies. Urban mining perspectives view this stock as a repository of secondary resources, which can be recirculated into the economy to minimize future demand for natural resources (Lanau & Liu, 2020). Additionally, the organization of the built-environment, or rather the urban form, impacts resource efficiency (Fleischmann, Romice, & Porta, 2021) and sustainable development, for example by influencing how people access and use services such as transport and water. Thus, a detailed understanding of built-environment stock composition and accumulation within and across cities may shed new light on outcomes of urban planning in terms of resource use as well as pathways towards low carbon and more equitable development futures.

1.1 Quantifying material stocks

Much of the research quantifying built-environment MS accumulation focusses at national levels (see Lanau et al., (2019)) quantifying the MS of residential (Bergsdal, Brattebø, Bohne, & Müller, 2007; Ortlepp, Gruhler, & Schiller, 2018; Wiedenhofer et al., 2015) and non-residential (Ortlepp, Gruhler, & Schiller, 2015) buildings as well as transport infrastructure (Miatto, Schandl, Wiedenhofer, Krausmann, & Tanikawa, 2017; Tanikawa et al., 2015; Wiedenhofer et al., 2015). Several methodologies can be used to quantify stock accumulation and assess the locations and quality of material which influences waste management strategies. However, bottom-up material stock analysis (MSA) is generally favoured over other MSA methods at city and sub-city scales

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due to the lack of high-resolution stocks data nationally and regionally and where quantification and location of object and component level MS is required (Lanau et al., 2019). The bottom-up approach has therefore been adopted to quantify the stock of residential buildings (García-Torres, Kahhat, & Santa-Cruz, 2017; Z. Guo, Hu, Zhang, Huang, & Xiao, 2014; Mesta, Kahhat, & Santa-Cruz, 2019), non-residential buildings (Huang, Han, & Chen, 2017; Mao, Bao, Huang, Liu, & Liu, 2020; Tanikawa & Hashimoto, 2009), and roads (Z. Guo et al., 2014; Huang et al., 2017; Mao et al., 2020), as well as shedding light on urban development (Mao et al., 2020) and potential resource efficiency strategies (Arora, Raspall, Cheah, & Silva, 2019; Lanau & Liu, 2020) within cities. While city-level assessments in the Global South are limited and often concentrated in China due to the availability of data (J. Guo et al., 2020; Z. Guo et al., 2014; Hu et al., 2010; Huang et al., 2017; Mao et al., 2020), studies are emerging in other countries such as Peru (García-Torres et al., 2017; Mesta et al., 2019), Indonesia (Surahman, Higashi, & Kubota, 2017) and Brazil (Condeixa, Haddad, & Boer, 2017). This is largely due to the flexibility of the bottom-up approach in making use of available case-specific data. Bottom-up MSA begins with the inventory of items, e.g., m^2 of residential buildings, which are multiplied by a material intensity coefficient (MIC), often in kg/m^2, thus extrapolating a sample of product-level MICs over the population of corresponding product types within an area. The approach also lends itself to assessments of stock density and per capita stock accumulation that often feature in debates about the intensification of physical development of the built form globally, offering comparability between studies (e.g. (Arora et al., 2019), (Lanau & Liu, 2020)).

Bottom-up MSA therefore offers a flexible approach to quantify and locate built-environment MS as well as to evaluate potential resource efficiency strategies at the component and material-level within cities. This is important in rapidly urbanizing areas where demand for housing and

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services is projected to increase. This is particularly important in India, a country set to lead urbanization rates globally, adding over 400 million urban dwellers by 2050 (UN, 2018) and with a significant demand for new buildings expected to 2030 (Ram & Kalidindi, 2017). Further, it is estimated that 70-80% of the urban infrastructure expected to exist in India by 2050 is yet to be built (IRP, 2018). Thus an understanding of existing stock accumulation and potential resource efficiency strategies may be crucial to understand future resource use and pathways towards sustainable urban development. However, to-date there remains limited studies quantifying city-level built-environment MS in India.

1.2 Material stock accounting in India

Built-environment stock research in India has, to date, largely focused on material and embodied energy (EE) intensities of individual residential buildings (Bansal & Nandy, 2010; Bansal, Singh, & Sawhney, 2014; Debnath, Singh, & Singh, 1995; Vengala, Ramesh, Dharek, Krishna, & Kumar, 2021). The EE relates to the total energy required to produce and transport materials as well as the energy required to construct the product, e.g., building, road etc., (Praseeda, Reddy, & Mani, 2016) and is often reported in studies focused on built-environment material use in India. Studies have evaluated the potential for energy efficiency in buildings, focusing on construction material use (Bansal et al., 2014; Mastrucci & Rao, 2019) and operational energy demand (Mastrucci & Rao, 2019). Bottom-up approaches have been used to estimate the resource requirements needed to provide minimum standards of living nationally (Mastrucci & Rao, 2019; Rao, Min, & Mastrucci, 2019). This has been combined with district-level statistics to estimate the material implications of closing deficits in living standards through the assessment of city-wide cement material demand for Delhi and Chandigarh (Nagpure, Reiner, & Ramaswami, 2018). The bottom-up approach has also been applied nationally to estimate the energy requirements needed

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to meet basic standards of living through the provision of adequate infrastructure (Rao et al., 2019) and to meet housing demands (Mastrucci & Rao, 2019). However, national estimates fall short of offering insight into material efficiency strategies at the material- and product-level, as well as an understanding of the intensity of the built-form within cities. City-level studies in India are therefore limited to city-wide material flows (Nagpure et al., 2018) and estimations of construction and demolition waste (Ram & Kalidindi, 2017). However, there remains a lack of knowledge of the current composition and spatial distribution of MS within cities. Further, given data gaps it is currently difficult to draw robust conclusions regarding the impact of different urban forms on the accumulation of built-environment MS. It is therefore important to begin to address these research gaps given rapid urbanization and the consequent demand for built-environment MS.

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1.3 Aims and objectives

In this paper, we investigate the patterns of built-environment MS accumulation in a young but rapidly developed city, which was master planned to deliver high standards of living to inhabitants via adequate access to services. The novel contribution of this paper is found in the quantification of residential buildings and road MS at the city and sub-city scale in India. In doing so, we ensure comparability to other studies at the product-level in line with current recommendations within literature (Schiller et al., 2018) and those assessing material and EE intensities within India. Through the quantification of built-environment MS we also offer insight into urban form and stock accumulation and thus future implications for urban planning. Thus, the present study provides the first steps towards an improved understanding of built-environment MS accumulation within India and explores the impact of urban form on the stock-flow-service nexus through the use of the city of Chandigarh as a case study.

2 METHODS

2.1 Case study area and scope

Chandigarh is a Union Territory and the capital city of the two northern states of Punjab and Haryana. The district of Chandigarh has a total population of 1,055,450 and covers 114km^2, with 97% of the population living in urban areas covering approximately 110 km^2 (Directorate of Census Operations, 2011). The Municipal Corporation of Chandigarh comprises the majority of the urban areas of Chandigarh and contains a population of 961,587, spread across 26 electoral wards (Census of India, 2011) and covering an area of approximately 99km^2 (Census of India, 2011; sandeepgadhwal & devdattaT, 2018). According to the 2011 Census, the population density of the urban area of Chandigarh is approximately 9408 persons/ km^2 (Census of India, 2011). The district is primarily constructed on alluvium (Directorate of Census Operations, 2011; Kandpal, John, & Joshi, 2009) and is located in seismic zone IV which, in accordance with Indian design codes (BIS, 1984), controls aspects of building construction to ensure structural safety in the event of earthquakes.

Chandigarh was conceived in the mid-1900s and is one of the first planned cities in India (Gupta & Kavita, 2020). Chandigarh is constructed on a site originally containing 59 villages and is the result of the detailed master planning of Le Corbusier (Chandigarh Administration, 2018; Rodríguez-Lora, Rosado, Navas-Carrillo, & Le, 2021). The general motivation for the post-war 'Garden City' was to provide high quality living standards for inhabitants, where high-rise buildings were excluded and access to amenities and assets including green space were prioritized (Chandigarh Administration, 2022b). Construction began in the early 1950's and was completed in two key phases. The first phase contains 30 low density housing sectors, typically 1-2 stories, with the second phase containing 17 higher density housing sectors, typically 3-4 stories, to accommodate significant increases in urban residential populations (Chandigarh Administration, 2018, 2022b). The city is organized on the basis of regularly repeating neighbourhood units that

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are designed to be self-sufficient, with access to various amenities and assets within reasonable walking distance (Chandigarh Administration, 2018). These neighbourhood units, or *sectors,* are combined to form wards, the lowest administrative division within urban areas (Census of India, 2011) (see Figure 1). Sectors are typically 800x1200m (Chandigarh Administration, 2022b) and are separated by a hierarchical road network, which results in a gridiron urban form. The road network offers connections between the periphery of the city and the sectors, serving commercial, leisure and residential areas. The road network is a key element of the masterplan and is designed to be integrated within and across sectors, aiming for efficient traffic circulation and that noise and traffic pollution is minimized within neighbourhoods. Stringent architectural controls have dictated the composition of housing resulting in a residential building stock that is homogenous in its construction type.

Given the degree of urban planning, Chandigarh is an insightful case study in which to assess stock accumulation and investigate the linkages between urban planning and built environment resource use. Furthermore, it is a useful comparative to other stock studies to understand how rapid development has impacted on the distribution of stock accumulation. Against this backdrop, we quantify the residential building MS in Chandigarh using architectural control drawings and layout plans provided by the Chandigarh Administration (Chandigarh Administration, 2022b) and georeferenced boundary data sourced from (sandeepgadhwal & devdattaT, 2018). While data pertaining to road construction is limited in India, we note the importance of estimating road MS in this context and turn to various data sources to fill data gaps, outlined in section 2.4. We include all 26 wards in the assessment of road MS, omitting a total of 9 wards from the residential building study area due to insufficient data, enabling the calculation of inventories of buildings and their respective MICs. This corresponds to a final study area for

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residential building MS of 71km^2 accommodating 553,954 urban inhabitants and accounting for approximately 72% and 58% of the study area and population of the Municipal Corporation of Chandigarh respectively, when compared to the road MS study area (Table 1).

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[Placeholder for Figure 1]

Table 1: Ward-level data for residential buildings and roads.
Population data is retrieved from the Census of India (Census of India, 2011) with areas provided within georeferenced data available in GitHub (sandeepgadhwal & devdattaT, 2018). The number of sectors refers to the number of sectors for which residential building MS can be computed due to data availability, with actual total number of sectors shown in brackets. The number of plots is estimated using the sector-wise layout plans as described in section 2.3 and Figure 2. The total road length is calculated using OpenStreetMap data as outlined in section 2.4.

Ward No.	**Population**	**Area (km²)**	**No. of Sectors**	**Estimated No. of Plots**	**Total road length (km)**
1	24,686	14.9	11 (11)	3,564	178
2	32,047	7.9	3 (3)	1,644	99
3	21,058	3.5	3 (3)	826	90
4	25,441	3.2	3 (3)	3,689	73
5	39,075	4.2	N/A (2)	N/A	4
6	27,654	1.7	N/A (No sectors)	N/A	19
7	28,972	3.8	N/A (No sectors)	N/A	20
8	39,585	3.3	3 (3)	2,895	86
9	27,567	2.5	2 (2)	2,937	62
10	38,088	2.2	2 (2)	2,056	52
11	47,491	2.7	N/A	N/A	36
12	47,367	2.6	2 (2)	1,067	69
13	56,671	3.6	N/A (3)	N/A	81
14	51,859	1.1	1 (1)	1,211	29
15	30,957	3.3	3 (3)	3,531	92
16	26,593	2.2	2 (2)	3,202	59
17	25,215	3.2	3 (3)	3,039	81
18	30,964	3.3	3 (3)	3,798	79
19	33,859	4.6	1 (2)	453	78
20	39,389	7.0	1 (1)	2,522	117
21	29,654	2.1	2 (2)	2,173	55
22	29,625	4.5	3 (3)	2,433	113
23	74,187	3.1	N/A (No sectors)	N/A	54
24	52,070	3.5	N/A (No sectors)	N/A	50
25	45,216	2.3	N/A (No sectors)	N/A	64
26	36,297	3.0	N/A (No sectors)	N/A	45
Total	**961,587**	**99.0**	**48**	**41.040**	**1,923**

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2.2 Bottom-up material stock characterization for residential buildings and roads

We quantify the MS in roads and residential buildings for the reference year 2011. We argue in section 2.4 that the number of housing plots has remained unchanged per sector since the completion of the masterplan, thus we are able to provide a comparison of the stock accumulation to population and area statistics available within the Census of India (Census of India, 2011) and georeferenced data (sandeepgadhwal & devdattaT, 2018). We adopt a bottom-up approach to MS characterization that is comparable with approaches employed Tanikawa et al., (2015) and Lanau et al., (2019), where the total mass of in-use stocks is estimated by multiplying the MIC by the total inventory of items in the reference area and year. The item types are a result of the archetype approach which homogenizes items, i.e., residential buildings and roads, by a set of characteristics, for example building age and construction type. As result an MIC is calculated for each archetype. The general approach is shown formally below:

$$MS_{m,t} = \sum_{i} MS_{m,\,i,\,t} = \sum INV_{i,t} \, x \, MIC_{m,i,t} \qquad [1]$$

Where MS corresponds to the total mass of material or component, m, of type, i, in the reference year, t. The inventory of items of type, i, in a dimensional unit such as local administrative boundaries, as in (Kloostra, Makarchuk, & Saxe, 2022), for the reference year, t, is then multiplied by the MIC, often in mass per dimensional unit such as gross floor area, to calculate the total mass of each material in each item type which is summed over the spatial unit considered. However, bottom-up approaches generally deviate to match the units of the inventory of items with the MICs. For example, studies have overcome the lack of detailed floor area data by simplifying building inventory data to match MIC calculations (García-Torres et al., 2017) as well as using a combination of data sources and indirect calculations to fill data gaps (Condeixa et al., 2017). As a result, we adjust the method for both residential buildings, see Figure 2, and roads to suit the availability of data as outlined in sections 2.3 and 2.4 respectively.

Due to the diversity of bottom-up MSA applications and data availability in different contexts, MICs are often inconsistent making them difficult to compare (Schiller et al., 2018). Our starting point is to address the calculation of MICs and EE intensities (EEI) for residential buildings, the latter of which is undertaken to ensure greater comparability to existing studies within India. We therefore adopt EE values used by Mastrucci & Rao, (2019) to calculate

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residential building EE in India in an attempt to reflect the prevailing material production and construction practices of India. From here we use the same building samples to create building archetypes specific to Chandigarh with which to further improve the accuracy of MS estimations. We use the Municipal Corporation and its respective administrative wards to define the city and sub-city scales respectively, as in Kloostra, Makarchuk, & Saxe, (2022). At these scales we calculate the total MS and MS coefficients, e.g., MS per capita and MS per km^2, for each stock type based on the study area considered. Key assumptions are presented in sections 1.5 and 2.3 of the SI for residential buildings and roads respectively.

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2.3 Residential building material stock calculation

Architectural control drawings hosted by the Chandigarh Administration are used to calculate product-level MICs and EEIs (see section 1 of the SI). All drawing samples contain a single three-story multi-family residential building (MFH-3F) for sectors of both the first and second phase of construction. We begin the calculation of residential building MS by calculating MICs in terms of kg/m^2 and MJ/m^2 of gross floor area to ensure comparability between bottom-up studies and those addressing material use within residential buildings in India. The MIC is calculated as the total mass of material or component type for all building samples is summed to arrive at a total kg of material or component. From here the total gross floor area (GFA), as defined in (Schiller et al., 2018), is calculated for each building and summed to result in the total floor area of the building archetype. Finally, the MIC is calculated by dividing the total MS by the GFA. The EEI is calculated by multiplying the mass of material, *kg,* by the EE coefficient, *MJ/kg*, using India specific EE values (Mastrucci & Rao, 2019).

In order to calculate city- and sub-city scale MS accumulation the MICs must be matched to the available inventory data. Architectural control drawings show that each building is located on a plot type characterized by either: 1) one of the standardized plot sizes, m^2, or 2) the plot scheme, e.g., high-income group housing. The size of the plot is defined as the total footprint of the building and any outside areas such as gardens or courtyards which is standardized through the architectural control. The government housing scheme generally refers to the income band that the housing construction is reserved for, e.g., low-income groups. Sector-wise layout plans locate plot types within sectors and can be used to extrapolate building sample calculations to the population of plot types (see section 1 of the SI). The building located on each plot is shown to be standardized through the architectural control drawings which note various standard specifications for the structural framing such as maximum building height, internal and external wall thickness, roof terrace coverage, as well as standardization of roof and floor finishes. In total, seven plot archetypes are created, three of which relate to the government housing scheme, i.e., low-income group (LIG), middle-income group (MIG), and high-income group (HIG), with the remaining four relating to the standardized plot size (see SI Tables 2-5). We omit wards where sufficient data is not available to describe the quantity or composition of inventory items limiting the extrapolation of MICs (see Table 1). The plot types are then related to plots shown on the sector-wise layout plans as per the master plan. A total of 48 of 56 sector layout plans are available, 13 of which provided a schedule of the number of plots for each category with a manual count required for each archetype in the remaining sectors. We use an average MS where archetypes contain more than one drawing sample and calculate maximum and minimum errors using the maximum and minimum MS per archetype. Where building samples for plot types are unavailable, we classify the plot by the closest available plot size for the available building samples. Where plot types within sectors are unknown, we calculate a construction-phase-specific archetype, e.g., buildings constructed in phase 1 or phase 2, to homogenize buildings where plot type data is unavailable, see Figure 2. While we use masterplan documents dating from 1957 to 2005, records demonstrate

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that the masterplan of Chandigarh has been implemented over multiple decades (Chandigarh Administration, 2022a), with no changes to the boundaries of the district and with continued urban growth experienced to the periphery of the city (Directorate of Census Operations, 2011). Given that sectors are of fixed size and bound by the road network, with little room for densification as per the layout plans, we assume that the total number of plots has remained unchanged since completion.

The residential building stock is then calculated within each sector by relating the total MS per plot type, or construction phase, to the total number of plots, by plot type and/or scheme or construction phase, within each sector. The sector-wise MS is then aggregated into their respective wards as per the ward map shown in Figure 1 (Census of India, 2011). The method is shown more formally in Figure 2 and explained in greater detail in section 1 of the SI.

[Placeholder for Figure 2]

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2.4 Road material stock calculation

The MS of roads within the Municipal Corporation of Chandigarh and its respective wards is estimated using OpenStreetMap data to obtain the total length of different road types. We dissect road data among wards using available georeferenced ward boundary data (sandeepgadhwal & devdattaT, 2018). The study data covers all road types, excluding pedestrian and cycle paths, due to incomplete data, and therefore covers roads intended for vehicular use. We include approximately 93% of the total available raw data, equal to approximately 1,923km. We archetype roads using the classifications for standard road widths provided by the Indian Road Congress (IRC) (IRC, 1983) and categorise these to ensure comparability to road stocks studies in other cities, such as Beijing (Z. Guo et al., 2014) and Toronto (Kloostra et al., 2022). We therefore evaluate the MS for urban expressways, arterial and sub-arterial roads, collector streets and local streets. Standard specifications for cross-sectional composition of roads are not provided within the Indian design standard publications provided by the Ministry of Urban Transport, Ministry of Road Transport and Highways, and the IRC, which generally provide information relating to road safety and quality control. We therefore turn to the assumptions made in a similar context to enable a comparison of stock accumulation between the two sectors and the city-wide composition to other cities. Studies quantifying the MS of roads in developing countries are very limited, however MIC values from a recent study in Vietnam may offer a reasonable estimation of road MS. We adopt the MIC values estimated for roads in Vietnam to calculate road MS relating to two key road compositions of varying widths (Nguyen, Fishman, Miatto, & Tanikawa, 2019). We estimate road widths for each archetype using areal imagery from Google Earth and combine these with MIC values from Nguyen et al., (2019) to create archetype-specific MICs, kg/m. We assume the composition of roads based on road width in relation to Nguyen et al., (2019) and the visual

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appearance from areal images which we verify with pot hole samples within Chandigarh (Kanoungo, Sharma, Goyal, Kanoungo, & Singh, 2021). The method follows the formal expression of the stock calculation as outlined in equation 1, where the total MS of each material, m, for road archetype, i, in ward, w, is estimated by summing the product of the total length of each road archetype, INV_i , in ward, w, by the MIC, *kg/m*, of each material, m, for road archetype, i.

3 RESULTS

We firstly present results for the MIC and EEI for the city-level archetype of residential buildings which are calculated to provide comparability with other product-level and bottom-up studies. Residential buildings in Chandigarh pertain to a single archetype containing the same structural framing, number of stories and material specifications and vary only in the GFA provided. The MIC and EEI for MFH-3F in Chandigarh is found to be 2,550 kg/m^2 and 4,190 MJ/m^2. Material- (Figure 3) and component-wise (SI Tables 4-5) results show that there is little variation in MIC and EEI across buildings samples. Thus, we find that the architectural control of Chandigarh has resulted in a population of residential buildings that require broadly similar quantities of material and EE per GFA, with variations largely captured by differences in brick and concrete consumption (see SI Tables 2-5).

The EEI found is within the range of 3,000-5,000MJ/m^2 for residential building in India (Debnath et al., 1995), however we find differences among other studies considering a similar archetype classification of residential building in India. Praseeda et al., (2016) find values ranging between 3,790-4,250MJ/m^2 across a large range of built-up building areas (m^2) with Bansal et al., (2014) finding values of 3,536MJ/m^2 and 3,382MJ/m^2 for three- and four-story residential buildings within the same climatic and seismic zones. Vengala et al., (2021) find a value for four-

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story residential buildings in Vijayawada, a city in the south-east of India in different climatic and seismic zones to Chandigarh, of approximately 3,100MJ/m^2 (see SI Table 7 for a comparison of studies based on climatic and seismic zone as well as archetype and location). While we are able to provide a brief comparison of EEI values in India here, the lack of transparency in material calculations and standardized units of EE limit the comparability of studies and should be considered in future work comparing product-level material and energy consumption.

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3.2 Material stocks of residential buildings and roads in Chandigarh and its wards

Here we present the estimated MS for residential buildings at the city and sub-city scale. We discuss these results further in terms of resulting urban form and opportunities for secondary resource use in sections 4.1 and 4.2 respectively.

To estimate the MS of residential buildings within Chandigarh and its wards we further archetype building samples by plot category or by development phase depending on the availability of inventory data, as outlined in section 2.3 and figure 2. We estimate the total residential building MS for the year 2011 and find a total of 41,040 plots across the 17 wards for which data is available. We estimate circa 27.8 Mt of MS in residential buildings in Chandigarh, ranging in distribution from 0.3 to 2.9 Mt across different wards. Brick and concrete comprise the majority of the total MS of residential buildings and are used for the primary structural framing, accounting for 51% and 41% of the total MS respectively. Steel reinforcement in foundations, floors and roofs, accounts for just over 1% of the total MS with clay and bitumen used for finishes to floors and roofs accounting for the remaining 7%. The residential building stock is therefore largely comprised of materials for walls (37%), floors (32%) and foundations (23%) with roof materials accounting for the remaining 9% of the total MS. The total per capita MS at the city-level is found to be 50 tons/cap ranging from 9 to 110 tons/cap between wards. The total MS density is found to be 391 kt/km^2 ranging from 68 to 1,120 kt/km^2. Figure 4 shows the variation in stock accumulation between the wards of the Municipal Corporation of Chandigarh.

We estimate a total of circa 63.1Mt of MS in roads across the Municipal Corporation of Chandigarh ranging from 0.6 to 5.7 Mt between wards. Roads therefore account for over twice the total residential building MS. The total per capita MS is found to be 66 tons/cap ranging from 18 to 229 tons/cap, see Figure 5. The total MS density is found to be 638 kt/km^2 ranging from 168 to 981 kt/km^2. The results highlight that the distribution of road MS is relatively uniform across the

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city, more so than residential building MS. In total, sand, stone, and asphalt account for 52%, 45% and 3% of the total MS of roads with approximately half of the combined MS for roads and residential buildings used for sand in base layer construction of asphalt and concrete paved roads, i.e., urban expressways, arterial and sub-arterial roads. Larger roads leading from the periphery of Chandigarh towards residential sectors account for approximately 21% of the total road length and 39% of the total MS. Roads within sectors account for the remaining 79% of the total road length and 61% of the total MS. Thus, the results indicate that the resource requirements for roads are largely driven by the need for mobility within rather than between sectors.

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4 DISCUSSION

4.1 Composition and distribution of built-environment stocks in cities

Figure 6 shows the MS per capita and MS density for a selection of city-level studies from different countries, see section 3 of SI for data used. The findings in comparison to other cities suggest that the unique urban form has driven an unusual accumulation of MS across the city. This has been necessitated by the need to connect people with places and services distributed within and across residential sectors. The results show that the total MS varies among wards, but that relative composition of wards generally remains uniform. This can be largely explained by urban form and architectural control as well as variations in the amount of non-residential floor space and the combination of sectors into wards. For example, ward 1 contains a large amount of non-residential floor space compared to others, including a cricket stadium and University, and is comprised of 11 sectors. On the other hand, ward 14 contains only one sector with half of the area dedicated to residential floor space and the other half to a village burial site. This variation in the available residential floor space and the uniformity of road provision among wards through a gridiron urban form of residential sectors means that the distribution of MS does not seem to be located within a central 'core' as found in other cities, such as Chiclayo (Mesta et al., 2019). The result is that the MS of roads is significantly larger per capita and km^2 compared to other rapidly urbanizing cities such as Beijing and developed cities such as Manchester and Wakayama (see Figure 6). To explain this further, and despite limited studies to draw comparison to, we compare the road-to-building MS ratio with other cities. We calculate this as the ratio of the total MS of roads to the total MS of residential buildings at the city-level. We find this ratio to be 2.27 which is considerably larger than other studies such as the city centre (0.32) and outskirts of Odense (0.86) (Lanau & Liu, 2020), Salford (0.29) (Tanikawa & Hashimoto, 2009) or Wakayama city centre (0.13) (Tanikawa & Hashimoto, 2009). This ratio suggests that Chandigarh's built-

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environment MS is distributed in a manner more akin to the outskirts of cities where we often find a sparser distribution of buildings with an increased length of road to connect inhabitants to services, as discussed as by (Lanau & Liu, 2020). This finding corresponds with Chandigarh's restriction on high-rise buildings (discussed in section 2.1), which will inherently limit the density of urban development as floor space becomes limited and lead to a stock distribution which is more sprawled. It should also be noted that the ratio of road-to-building MS is impacted by the difference in study area for road and residential building MS accounting, and that here we account for only residential buildings. As such, the actual value of this ratio is expected to be lower than calculated here.

We also find that the per capita and km^2 accumulation of residential building MS is comparable to other rapidly urbanizing cities such as Bandung and is much lower than some developed cities such as Esch-sur-Alzette. Differences in residential building MS accumulation may be explained by the differences in building typology. For example, the studies in Chiclayo (Mesta et al., 2019) and Bandung (Surahman et al., 2017) consider relatively low-rise housing compared to Rio de Janeiro (Condeixa et al., 2017) and are similar typologies to those found in Chandigarh. The higher-rise profile of residential buildings in Rio de Janeiro may therefore contribute to lower per capita stocks despite a broader pallet of materials being considered and a lower population density compared to the present study. These results highlight that even though we find similarities in residential building MS accumulation, the gridiron urban form and planned low-rise 'horizontal' development seems to have driven a much higher accumulation of road MS and relative accumulation of road MS to building MS than in other cities.

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[Placeholder for Figure 6]

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4.2 Secondary resource use and implications for resource efficiency

While road MS dominates overall MS accumulation, we find that this stock offers limited potential for secondary use beyond standard construction practice. Base layer construction of roads accounts for approximately 86% of the total MS of urban roads and 60% of the total city-wide MS. Sand and stone are the primary resources for base layer construction and are limited in their recoverability. However, their reuse is generally implicit in the recarpeting of roads, and as such resources used for road construction offer limited additional opportunities for secondary use. The stock of materials in residential buildings is largely comprised of brick for walls and foundations and reinforced concrete for floors, foundations, and roofs. These materials account for only 16% and 13% of the total city-wide MS respectively, however they may offer a greater opportunity for resource efficiency strategies. Steel reinforcing generally limits the recoverability of components as materials are difficult to separate, as a result the reuse of foundations from demolished buildings may present the most appropriate strategy for secondary resource use. Given that building designs in terms of typology and material use are largely standardized, future buildings may be able to reuse foundations due to similar loading criteria. However, the lack of structurally code compliant design in Chandigarh (Chandigarh Administration, 2022a) may impact the quality and reusability of materials and components. The masterplan for Chandigarh to 2031 (Chandigarh Administration, 2022a) proposes identifying opportunities for densification of first phase sectors due to the lack of land availability in the city, and the provision of housing for the urban poor. One option for densification could be through the vertical extension of existing buildings. Additional materials would likely be required to reinforce the existing structures to facilitate this, and expansion will still be limited. Alternatively, poor quality housing may become a useful secondary resource, which may have the potential for deconstruction, particularly for non-reinforced components such as brick walls and finishes to floors and roofs, and to be recirculated into future housing schemes.

The urban form has resulted in a considerable ‘lock-in’ effect which significantly restricts opportunities for urban development within the existing urban structure. As a result, it is reasonable to assume that future development will be accommodated by either vertical extension (where structurally feasible) or, more likely, demolition of existing buildings. These results highlight the importance of understanding MS to predict future demolition waste, and to uncover the potential for secondary resource use within any redevelopment of the city.

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4.3 Conclusions and limitations

The major contribution of this study is the quantification of built-environment MS at the city and sub-city scale in India for the first time with the aim to investigate patterns of MS accumulation in a unique and rapidly developed city. Although we have provided first steps in this direction, there remains limitations to understanding built-environment MS accumulation within India. While we find that the per capita accumulation of residential building MS varies among wards, the Census of India shows that the distribution of household sizes remains similar (Census of India, 2011) despite uniform housing construction. As such, plot number estimations across wards may limit the accuracy of per capita stock assessments. Such building-level and floor area information is lacking across cities within India and future work should seek to collect primary data, for example through site surveys and remote sensing, enabling the verification of the bottom-up stock estimates here and completion of bottom-up stock estimates in other cities. This is of particular importance for an understanding of the material intensity of roads within India which is currently significantly lacking.

To conclude, we show here that the rapid development of Chandigarh as a city centred around universally high living standards has driven a significantly larger ratio of road-to-building MS than the centre and outskirts of other developed cities. While residential building MS is comparable to other cities in the Global South, road MS has accumulated to a much greater extent than some rapidly urbanizing and developed cities. Considerations to connectivity and living standards have resulted in an urban form which presents ‘lock-ins’ limiting future urban development without demolition of existing stock. However, the existing stock was not considered for use as a secondary resource, and it is now important to understand demolition waste flows and their potential for recirculation into the economy. This is particularly important due to the

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significant amount of waste expected to be generated in India from the construction sector due to rapid urbanization (Ram & Kalidindi, 2017) and the planned redevelopment of Chandigarh to 2031 (Chandigarh Administration, 2022a). We therefore provide empirical evidence pointing towards the need to integrate material stock thinking into urban planning and development, with a particular focus on transport infrastructure and connectivity. Future integration of this within assessments of living standards will become useful to provide an empirical understanding of the relationship between built-environment MS and the development of cities.

ACKNOWLEDGMENTS

The authors would like to thank EPSRC for providing the doctoral funding for this research project (Project Reference: 2280244)

FUNDING INFORMATION

EPSRC doctoral funding (Project Reference: 2280244)

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SUPPORTING INFORMATION

Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information provides additional details of the data sources used and assumption made in the main text. Section 1 outlines and presents examples of data used to calculate residential building material stocks and a detailed disaggregation of results. Section 2 outlines the data used and assumptions made to calculate the material stocks of roads. Section 3 outlines the data used and numerical results of material stock coefficients from other city-level studies in comparison with the results presented in the main text. Finally, section 4 provides a detailed map of Chandigarh.

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Figure Legends

Figure 1: Map of the Municipal Corporation of Chandigarh as per the available georeferenced boundary data (sandeepgadhwal & devdattaT, 2018) showing a) the administrative wards, b) the road network, and c) an example ward illustrating its composition of a number of sectors. Table 1 indicates the total study area and population for both stock types based on the data available. See SI Figure 4 for a detailed map of the administrative divisions of Chandigarh as per the Census of India (Census of India, 2011).

Figure 2: Bottom-up methodology for city and sub-city level MS estimation of residential buildings (authors own). We also highlight the MIC calculation for the city-archetype to facilitate a comparison to broader studies in India. The total MS of each material or component, m, for residential building archetype, i, in sector, s, is estimated by summing the product of the total number of plots per plot type, INV_i, in each sector, s, by the MIC of each material or component, m, for plot type, i. The MIC refers to the total kg of material or components for each plot, with the plot defined by the plot type and/or scheme or the development phase, resulting in units of *kg/plot* or *kg/phase*, depending on the available inventory data.

Figure 3: MIC disaggregated by building components and materials (top) and embodied energy intensity of components and materials (bottom) for MFH-3F housing of brick walls and reinforced concrete floors and roofs. Material properties are shown in SI Table 1, with MIC and EEI results presented in greater detailed in SI Tables 2-5. The underlying data from comparative studies is presented in SI Table 7. We use twelve building samples corresponding to various plot sizes, m^2, and government housing schemes which includes high-, middle- and low-income group housing. To match the available MIC data to the inventory data we also calculate MICs based on the construction phase of the sector in which the building plots are located. Note: marla and kanal are units of land area used as part of the masterplan. One marla is equivalent to approximately 272 ft^2 or 25m^2, with one kanal equal to twenty marla.

Figure 4: Material stock of residential buildings by material type across the wards of the Municipal Corporation of Chandigarh. (Top) Total stock accumulation, (middle) total per capita stocks, (bottom) material stock density. See SI Figure 3 for a summary of results by component and SI Table 6 for data underlying the results.

Figure 5: Material stock of roads by material across the wards of the Municipal Corporation of Chandigarh. (Top) Total stock accumulation, (middle) total per capita stocks. (bottom) material stock density See SI Table 8 for a summary of road archetypes and MICs as well as SI Table 6 for data underlying ward- and city-level MS.

Figure 6: (Top) Material stock per capita and (bottom) material stock density comparison to other city-level studies. See SI tables 9-10 for data used to calculate MS coefficients and a comparison of the material stock coefficients respectively.

Table 1: Ward-level data for residential buildings and roads. Population data is is retrieved from the Census of India (Census of India, 2011) with areas provided within georeferenced data

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available in GitHub (sandeepgadhwal & devdattaT, 2018). The number of sectors refers to the number of sectors for which residential building MS can be computed due to data availability, with actual total number of sectors shown in brackets. The number of plots is estimated using the sector-wise layout plans as described in section 2.3 and highlighted in Figure 2. The total road length is calculated using OpenStreetMap data as outlined in section 2.4.

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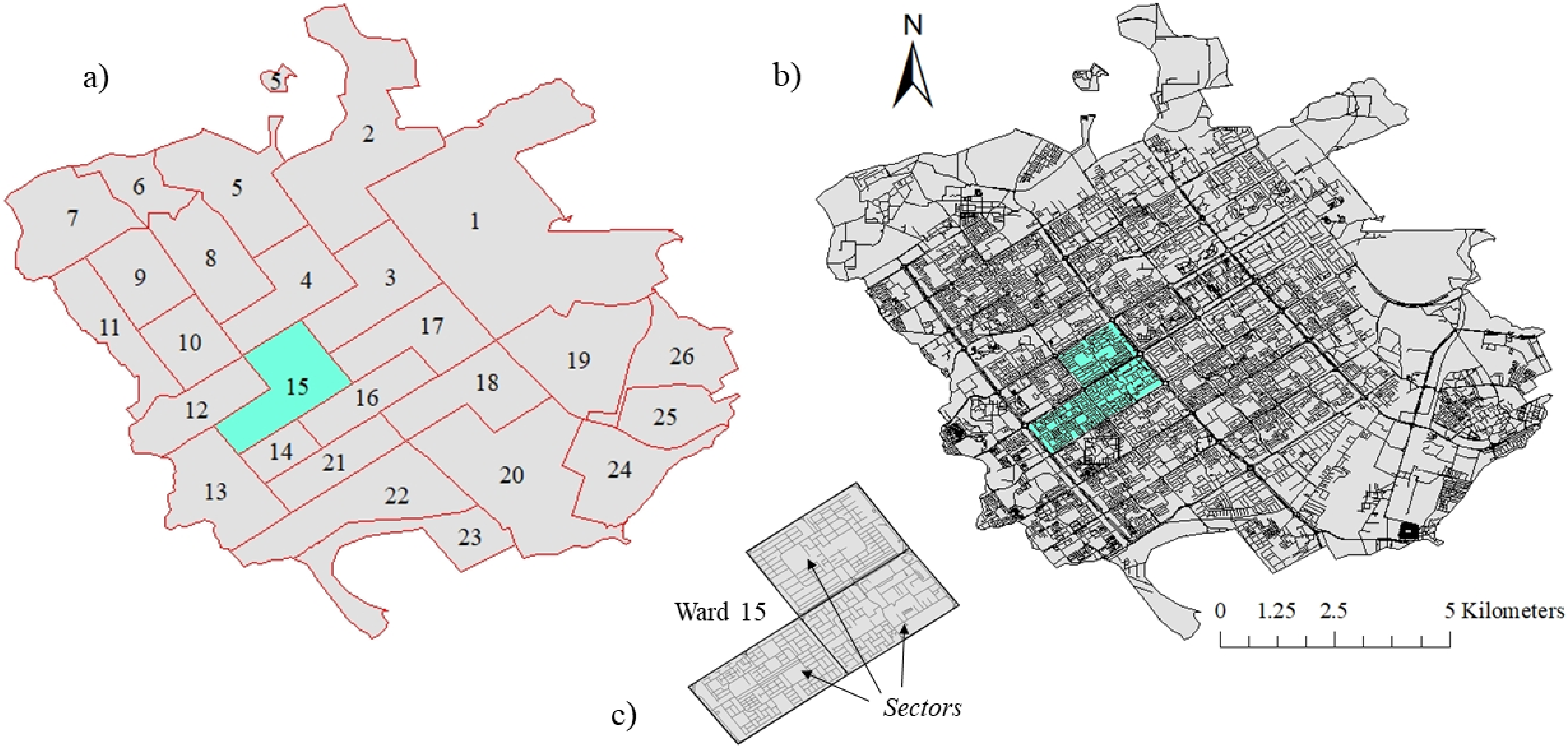
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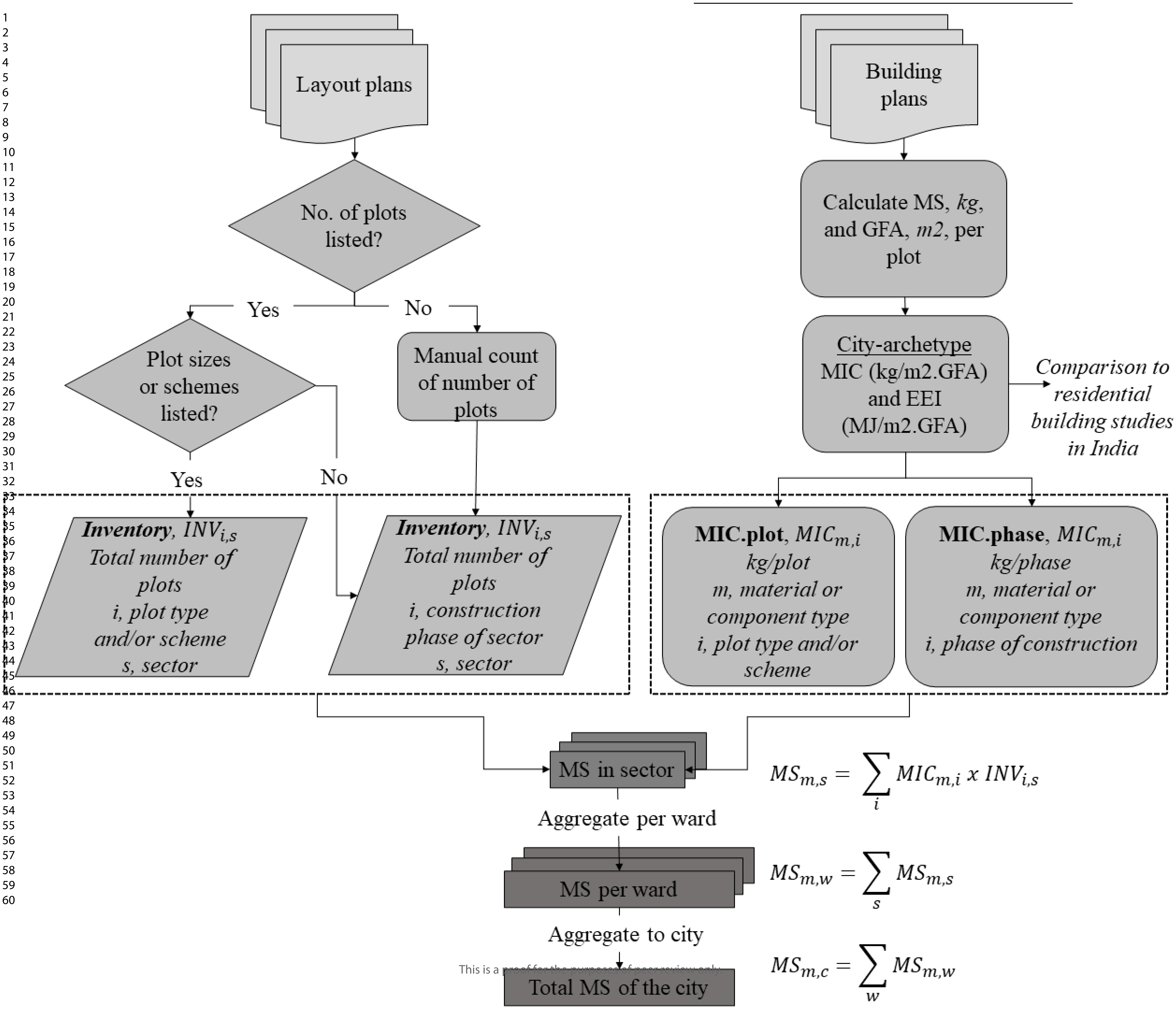

$$MS_{m,s} = \sum_{i} MIC_{m,i} \; x \; INV_{i,s}$$

$$MS_{m,w} = \sum_{s} MS_{m,s}$$

$$MS_{m,c} = \sum_{w} MS_{m,w}$$

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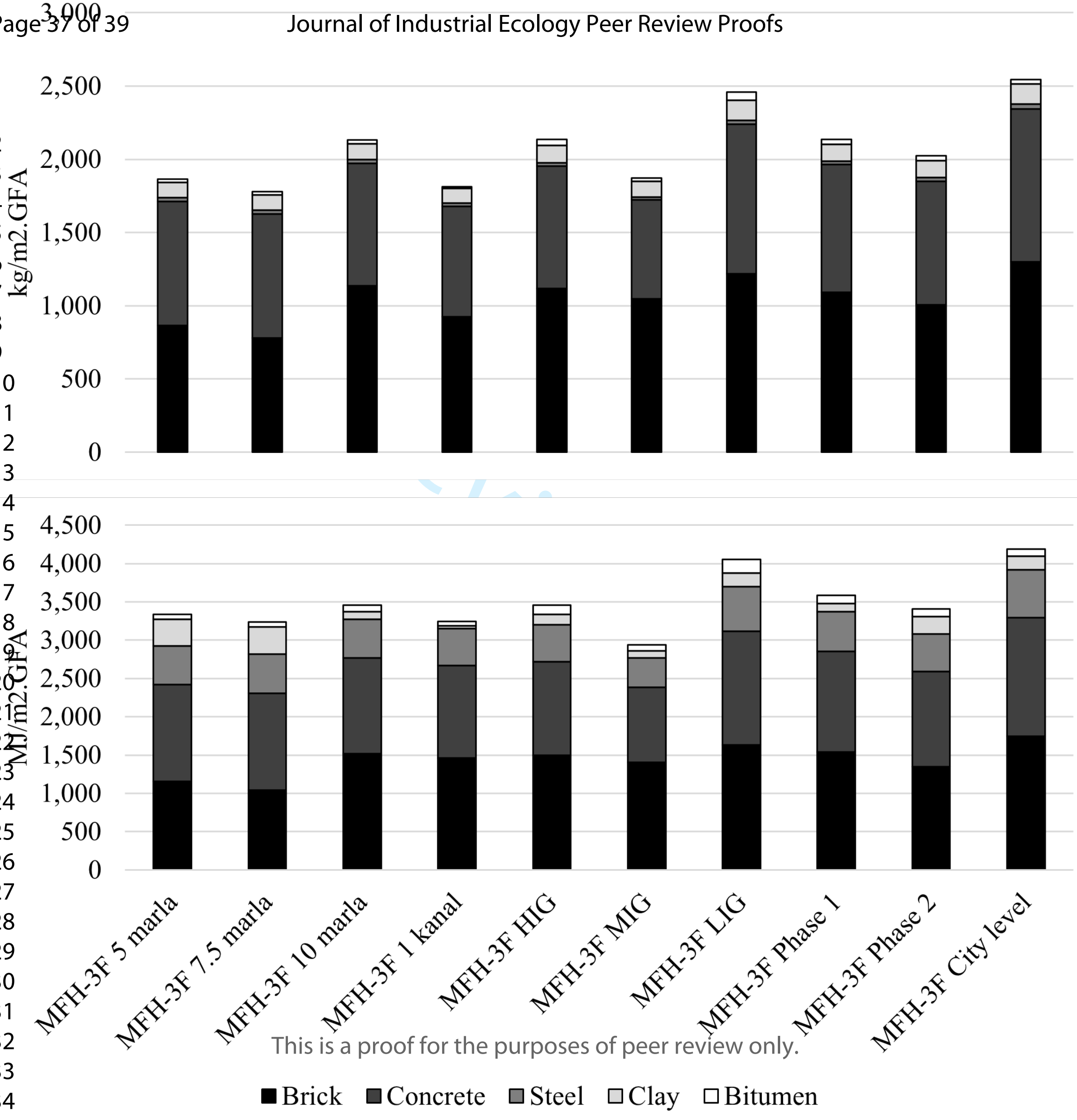
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1,000
500
0
MJ/m2.GFA
MFH-3F 5 marla
MFH-3F 7.5 marla
MFH-3F 10 marla
MFH-3F 1 kanal
MFH-3F HIG
MFH-3F MIG
MFH-3F LIG
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MFH-3F City level
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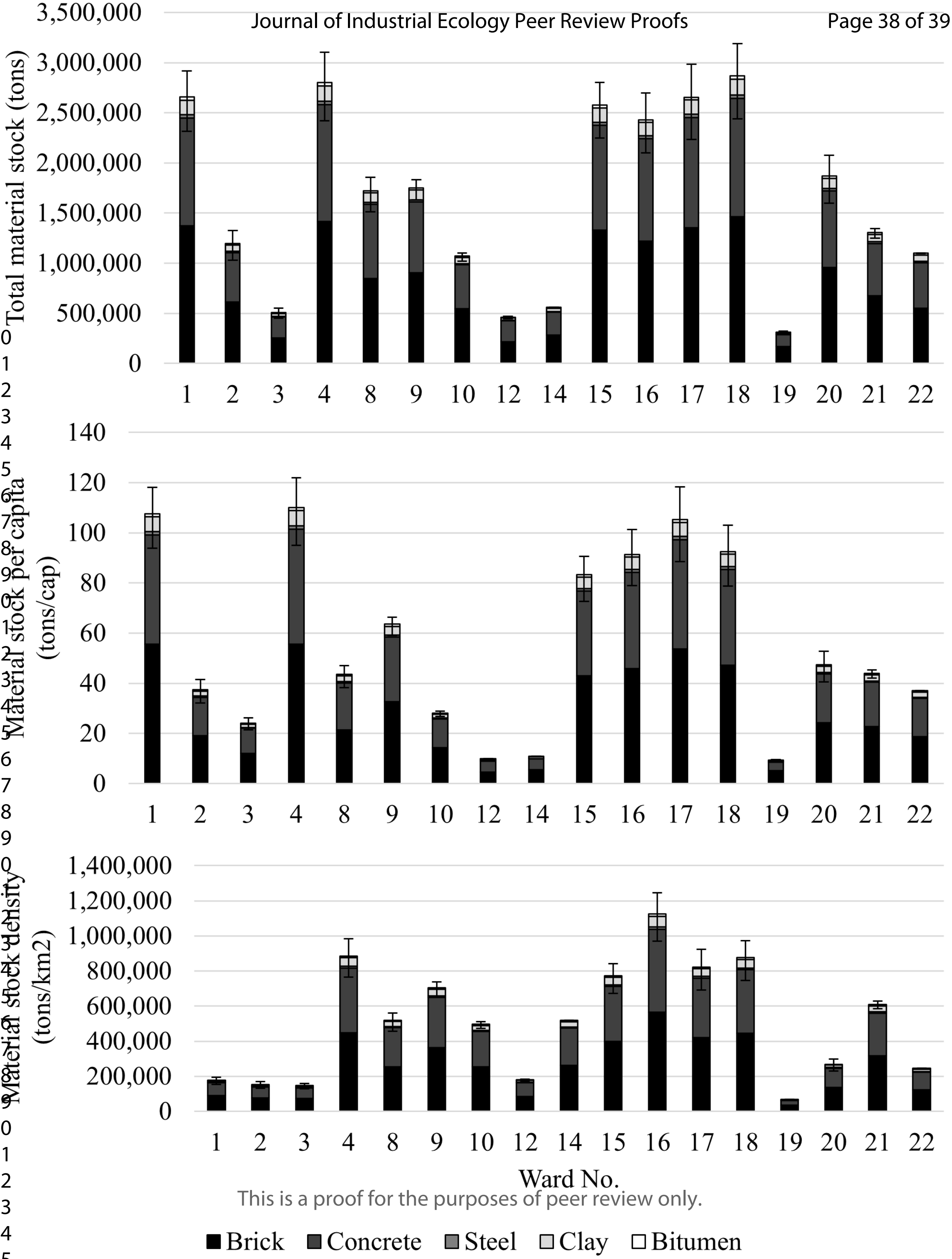
■ Concrete
■ Steel
□ Clay
□ Bitumen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Total material stock (tons)
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4
8
9
10
12
14
15
16
17
18
19
20
21
22
140
120
100
80
60
40
20
0
Material stock per capita (tons/cap)
1
2
3
4
8
9
10
12
14
15
16
17
18
19
20
21
22
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
Material stock density (tons/km2)
1
2
3
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8
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Ward No.
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■ Concrete
■ Steel
■ Clay
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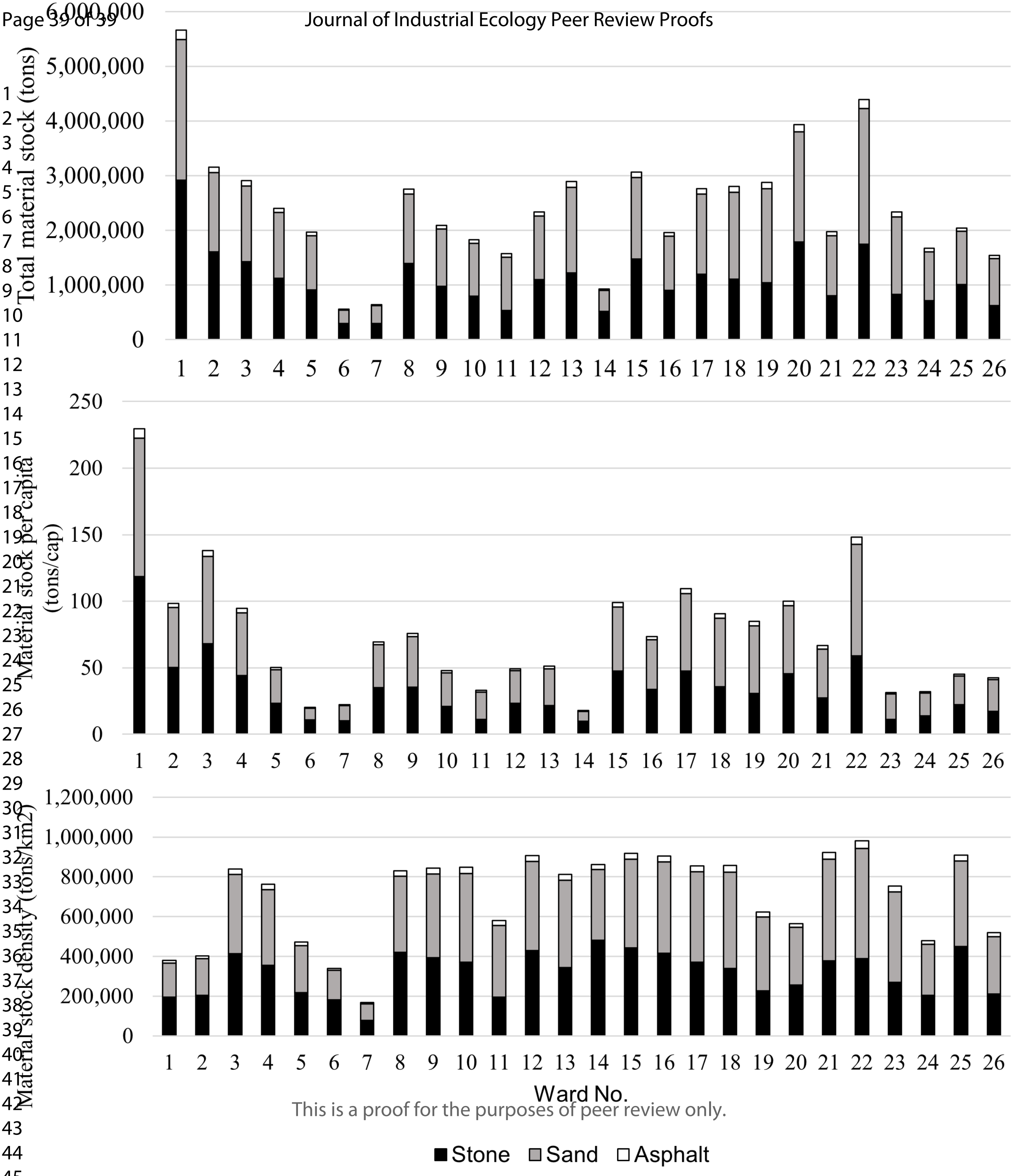
Total material stock (tons)
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Material stock per capita (tons/cap)
250
200
150
100
50
0
Material stock density (tons/km2)
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
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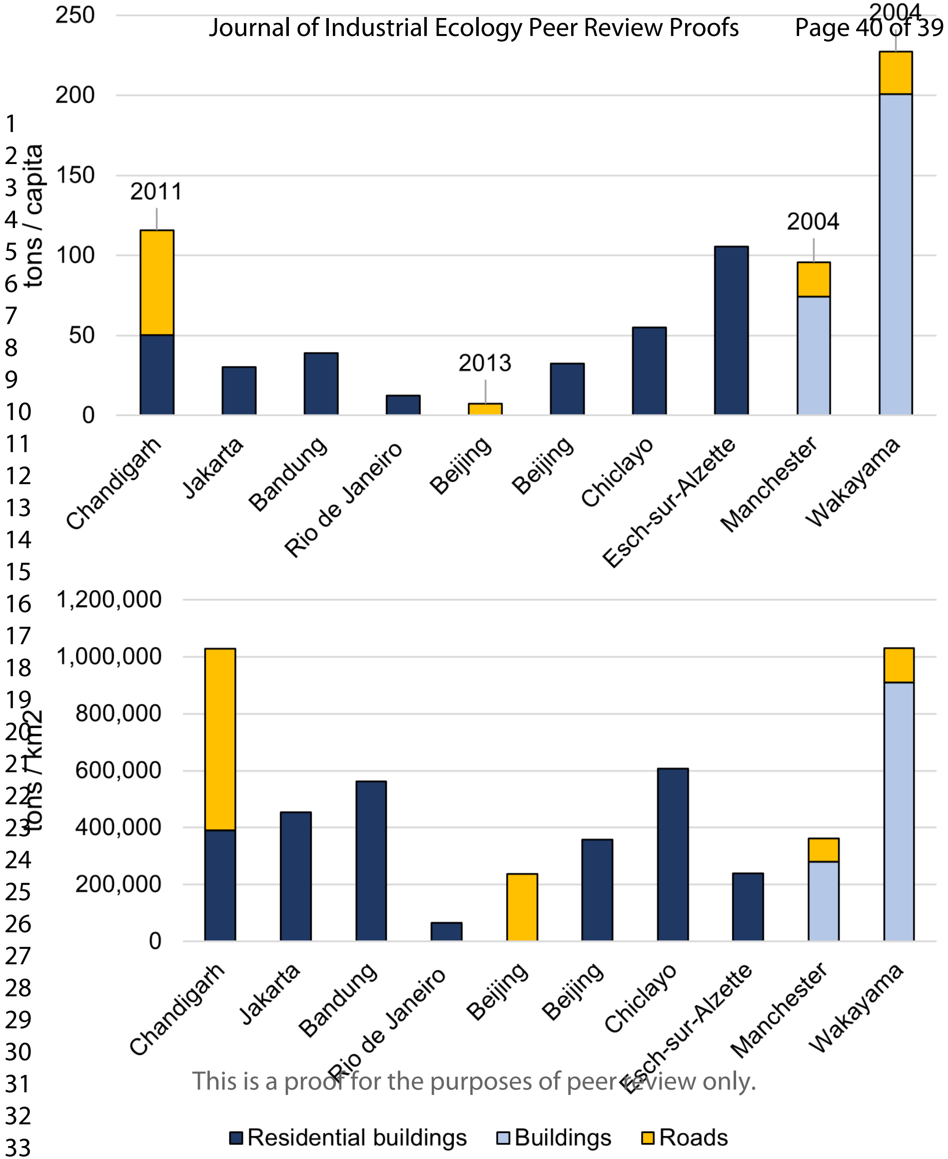
Ward No.
■ Stone ▨ Sand □ Asphalt


tons / capita
250
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150
100
50
0
2011
2013
2004
2004
Chandigarh
Jakarta
Bandung
Rio de Janeiro
Beijing
Beijing
Chiclayo
Esch-sur-Alzette
Manchester
Wakayama
tons / km2
1,200,000
1,000,000
800,000
600,000
400,000
200,000
0
Chandigarh
Jakarta
Bandung
Rio de Janeiro
Beijing
Beijing
Chiclayo
Esch-sur-Alzette
Manchester
Wakayama
Residential buildings
Buildings
Roads