Understanding the relationship between resource consumption & development levels

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Declaration

All work presented within this thesis is the author's own work except where specific reference has been made to the work of others.

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Date: 15th February 2023

Statement of conjoint work

The candidate confirms that the work submitted is their own, except where work that has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. The body of work contained within the thesis has resulted in the following work which is either published or under review:

1. **Chapter 3 -** Mihkelson, W., Arbabi, H., Hincks, S., Densley Tingley, D. (2023). An exploration of minimum living standards and the built environment materials to provide them. *Urban Sustainability* – Submitted September 2023.
2. **Chapter 4** - Mihkelson, W., Arbabi, H., Hincks, S., Densley Tingley, D. (2023). An exploration of minimum living standards and the built environment materials to provide them. *Urban Sustainability* – Submitted September 2023.
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Abstract

Developing an empirical understanding of the relationship between built environment material stocks and minimum standards of living is essential to understanding challenges and opportunities for sustainable development. This is particularly important in the Global South given the existing deficits in living standards and the unprecedented rates of urbanization expected in the coming decades. The following body of work seeks to provide an improved understanding of this relationship through an empirical analysis of India which is used as a topical testbed to address this research aim. Multiscale observations reveal widespread challenges to minimum standards of living and resource consumption and thus the achievement of interconnected SDGs. The empirical quantification of the coupling of MS and basic needs outcomes across scales reveals existing national trends, where minimum standards of living have grown with the provision of carbon intensive materials within the built environment. The results also reveal that significant deficits in overall basic needs still exist and that a substantial amount of residential building MS are required to fill deficits for minimal improvements to overall basic needs if current trends are to continue. Through a city- and sub-city scale assessment of built environment MS accumulation within India for the first time, improved insight into the provision of MS in the context of high basic needs outcomes is developed. This is of crucial importance for future policy making given that the observed national trends are likely a result of policy choices in how urban infrastructure and housing are provided within India. The results therefore point to the need to integrate MS thinking and SDG monitoring within future urban planning and to develop empirical understandings of this relationship in other nations of the Global South such that nations identify appropriate strategies to decouple from global trends.

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List of Abbreviations

DLS	Decent living standards
DLSI	Decent living standards index
EC	Embodied carbon
EE	Embodied energy
EEI	Embodied energy intensity
GIS	Geographic information System
GoI	Government of India
HDI	Human Development Index
MAUP	Modifiable areal unit problem
MIC	Material intensity coefficient
MFA	Material flow analysis
MS	Material stocks
MSA	Material stock analysis
MPI	Multidimensional Poverty Index
NSS	National Sample Survey
NTL	Night-time light
OLS	Ordinary least squares
OSM	OpenStreetMap
SDG	Sustainable Development Goal
SDI	Sustainable development index
SEM	Socioeconomic metabolism
SPI	Social Progress Index
UN	United Nations
UNDP	United Nations Development Programme
WLC	Whole Life Carbon
WLS	Weighted least squares

1 Introduction

1.1 Background and motivation

The 2030 Agenda for Sustainable Development saw 193 Governments committing to achieving 17 Sustainable Development Goals (SDGs) and pledging to the global ambition of leaving no one behind. The SDGs cover various social, economic, and environmental targets marking a significant step towards transforming global socioeconomic development and have now become universally accepted reference points for member states to track and monitor progress towards sustainable levels of development (1). While they are often monitored at global and national scales, there is now an increasing focus on cities to ensure sustainable levels of development and it is now widely accepted that significant monitoring and implementation efforts must be made in these areas (2,3).

Cities are expected to be key to achieving multiple SDGs, particularly those aiming to ensure a universal minimum standard of living relating to the provision of basic infrastructure such as water, sanitation, and housing (4). More than two-thirds of the world's population will live in cities by 2050 with around 90% of this urbanization expected in the Global South (5). It is also estimated that around 60% of the future cities required to accommodate this urbanization are yet to be built. However, rapid urbanization has already resulted in significant disparities in minimum living standards in these regions (6–8), with two-billion urban dwellers estimated to live without access to adequate housing by 2030 (9). A significant demand for construction materials is therefore anticipated in the coming decades.

Construction materials accumulate within the built environment in the form of buildings and infrastructure, forming the biophysical spatial structure of societies by transforming material and energy flows into services essential to a minimum standard of living (10,11). These material stocks (MS) account for a substantial proportion of all primary materials used globally (10), with the manufacture of construction materials accounting for 11% of energy and process-related carbon dioxide emissions (12). Built environment MS therefore result in the nexus of anthropogenic carbon emissions and human wellbeing (11,13–16) the decoupling of which is seen as essential to achieve levels of development considered ‘sustainable’. As such, 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 (10) whilst simultaneously reducing environmental impacts (17). However, there remains significantly limited empirical evidence as to the extent to which living standards are coupled with built environment MS and thus the extent to which this challenge threatens sustainable development. This is further underlined when considering the simultaneous achievement of the multiple SDGs associated with this challenge, given that increases to basic infrastructure provision, i.e., SDGs 1, 6, 7, and 11, will likely result in significant increases to resource consumption, i.e., SDG 12. The provision of built environment services to improve living standards may therefore create tensions to achieving key SDGs within the Global South.

Recent progress in systems thinking has conceptualized this problem and identified the need for improved empirical evidence to effectively inform urban policymaking (13,18,19). Despite this, much of the focus of research investigating such relationships has been on the coupling of economic growth with built environment MS which has played a central role in discussions surrounding sustainable development globally (10,20,21). While studies have revealed the coupling of in-use built environment MS and economic growth sub-nationally, there remains limited insight into the coupling of such MS and minimum standards of living. Scholars now agree on the need for integrated assessments of living standards which go beyond measures of income and consumption by measuring social benefits associated with the provision of built environment MS (4,6,19,22). This may enable improved policy implications to ensure effective allocation of resources conducive to equitable and resource efficient development. Elaborating an understanding of the relationship between built environment MS accumulation and basic needs outcomes within urban areas is therefore imperative for sustainable development and will be crucial to the simultaneous achievement of interconnected SDGs. However, while this relationship may be known intuitively, there is a clear gap in the current empirical understanding of such a relationship.

1.2 Scope, aim and objectives

To date, in this area of research there remain two key challenges to developing this understanding: 1) the quantification of built environment MS at sub-national scales, particularly in the Global South, and 2) the quantification of living standards relating to built environment MS, which remains a key shortcoming within socioeconomic metabolism research. The overarching aim of this thesis is to ***understand the relationship between the provision of built environment MS and minimum standards of living***.

The body of work contained in this thesis links empirical measures of basic needs outcomes with characteristics of built environment MS across scales of analysis, capturing the variation in perceived outcomes and offering insight into the implications for urban planning to simultaneously achieve interconnected SDGs. In doing so, it provides an approach to quantify standards of living relating to built environment MS and expands the current understanding of built environment MS accumulation in the context of high living standards within cities of the Global South.

Assessments of built environment MS and standards of living must be tackled in-place to address the aforementioned research gap. As such, the nation of India is adopted as an important testbed due to its current position in the global context. India is set to become the most populous country by 2023 (23) and is expected to lead urbanization rates to 2050 by adding over 400 million urban dwellers (5). As such, it is estimated that 70-80% of the urban infrastructure expected to exist in India by 2050 is yet to be built (24) with a significant demand for new buildings expected to 2030 (25). The Government of India also provide comprehensive information relating to socioeconomic factors as well as categorical data relating to the material consumption for housing enabling adequate consolidation of living standards and material use.

We address the previously stated research aim by asking the following research questions and work to answer these by completing the respective research objectives:

1) To what extent do households experience deficits in basic needs relating to non-mobile built-environment material stocks?
    - Identify dimensions of basic needs relating to non-mobile built-environment material stocks
    - Measure the extent to which households experience deprivation in access to non-mobile built-environment material stocks, using complementary metrics across scales to capture variations in perceived outcomes.

2) To what extent is the composition of built environment MS coupled with basic needs outcomes?
    - Quantify the relationship between basic needs outcomes and the material composition of residential buildings across scales of analysis.

3) What is the built environment material stock accumulation within a city with high basic needs outcomes in India?
    - For a city with near universal achievement of basic needs, quantify the material stocks of residential buildings and roads at the city- and sub-city-scale.
    - Examine how the accumulation of material stocks in residential buildings and roads has facilitated high basic needs outcomes.

4) What are the material stock requirements and consequent impacts on basic needs resulting from the upgrade of inadequate housing nationally?
    - Quantify the material stocks required per household based on current adequate housing provision.
    - Relate the magnitude of material stocks required to upgrade inadequate housing to the changes in overall basic needs outcomes and associated inequality across scales of analysis.

While "minimum living standards" may refer to a variety of dimensions which differ between contexts, here we refer to minimum living standards in the context of basic needs. Moving forward, we refer to basic needs outcomes as the levels of achievement of minimum living standards within areas resulting from adequate access to basic services. As we will discuss, such services are associated with key non-mobile built environment MS. It is important to note that we do not explicitly address poverty, as the study does not aim to assess the affordability of key services. As such, low development, i.e., deprivation, indicates a lack of basic needs outcomes and therefore low access to basic services, with high development levels referring to high basic needs outcomes and therefore high access to basic services.

1.3 Structure and outline

We begin with a review of the current state-of-the-art and relevant literature in Chapter 2. We overview the research highlighting the scale of challenges associated with urbanization and place the research problem within this context. From here we review literature aiming to further our understanding of built environment MS accumulation, its relationship to development levels, as well as key studies and recommendations relating to the monitoring of basic needs outcomes. We introduce socioeconomic metabolism research and examine its evolution from flow-centred studies towards integrated assessments of stocks and services resulting from recent conceptual frameworks. We then expand on current conceptual challenges within SEM research by reviewing key literature assessing basic needs outcomes before providing a summary of the key research gaps which parallel the above research questions. Following the literature review we seek to answer the four posited research questions across Chapters 3 to 6 respectively, with each chapter building on the previous by addressing key research gaps as the study develops.

In **Chapter 3**, we present an empirical analysis of the provision of built environment MS and reveal the extent to which basic needs are met in relation to built environment MS. We firstly address the intuitive relationship between non-mobile built environment MS and basic needs and identify the associated dimensions to quantify such outcomes. We then formulate complementary metrics across scales to address key statistical implications and highlight current progress and key challenges towards achieving basic needs as well as the resulting policy implications. The proposed approach to measure average basic needs outcomes is then adopted throughout the remaining chapters. As we will see, the multiscale observations reveal that deficits in basic needs are widespread and most challenging at regional scales with the provision of key urban infrastructure remaining a significant challenge to sustainable development. A key area for further work identified here is a quantified understanding of the relationship between the measured basic needs outcomes and the composition of built environment MS.

In **Chapter 4**, we then extend the analysis of average basic needs outcomes by investigating whether they are statistically related to the composition of built environment MS across scales. We develop a statistical model to relate the composition of residential buildings with basic needs outcomes, revealing that concrete and brick stocks have grown in conjunction with basic needs outcomes within the urban areas of India. This provides the basis for city selection to investigate built environment MS accumulation in relation to high basic needs outcomes in Chapter 5. A key area for further work identified here is a quantification of the extent to which built environment MS have accumulated, and its relationship to the measured basic needs outcomes.

In **Chapter 5,** we quantify the MS of residential buildings and roads at the city- and sub-city scale in Chandigarh, a rapidly developed city master planned to achieve universally high basic needs outcomes and accommodate rapid urbanization. We outline the available data and implications for utilizing it in bottom-up MS accounting to quantify and map MS. The study begins by comparing the residential building material intensities to other studies in India to shed light on the relative intensity of material use and improve comparability within socioeconomic metabolism research. We then quantify city- and sub-city MS within India for the first time and provide a comparison to cities in other international contexts. As we will see, the results reveal key urban planning implications for resource efficient urban development relating to the achievement of basic needs. A key area for further work identified here is a quantified understanding of the MS requirements to upgrade inadequate built environment services across India.

We then investigate the material requirements for providing improved housing access nationally and its impact on basic needs in **Chapter 6**. We begin by overviewing the methodological approach which integrates the results of the previous chapters within the methodological framework in Chapter 3. We quantify the material requirements for residential building MS and relate this to changes in overall basic needs outcomes and resulting inequality across scales. The results reveal the magnitude of challenges resulting from the coupling of built environment MS and basic needs outcomes and the implications for decoupling to ensure sustainable levels of future urban development.

Finally, we present key concluding remarks and recommendations for further work in **Chapter 7**. Key discussion points and limitations specific to each study are presented in the respective chapters. However, we also provide a brief discussion of the wider implications of the findings in relation to the new urban planning reforms within India.

An overview of how these chapters form an overall narrative is presented in Figure 1.1.

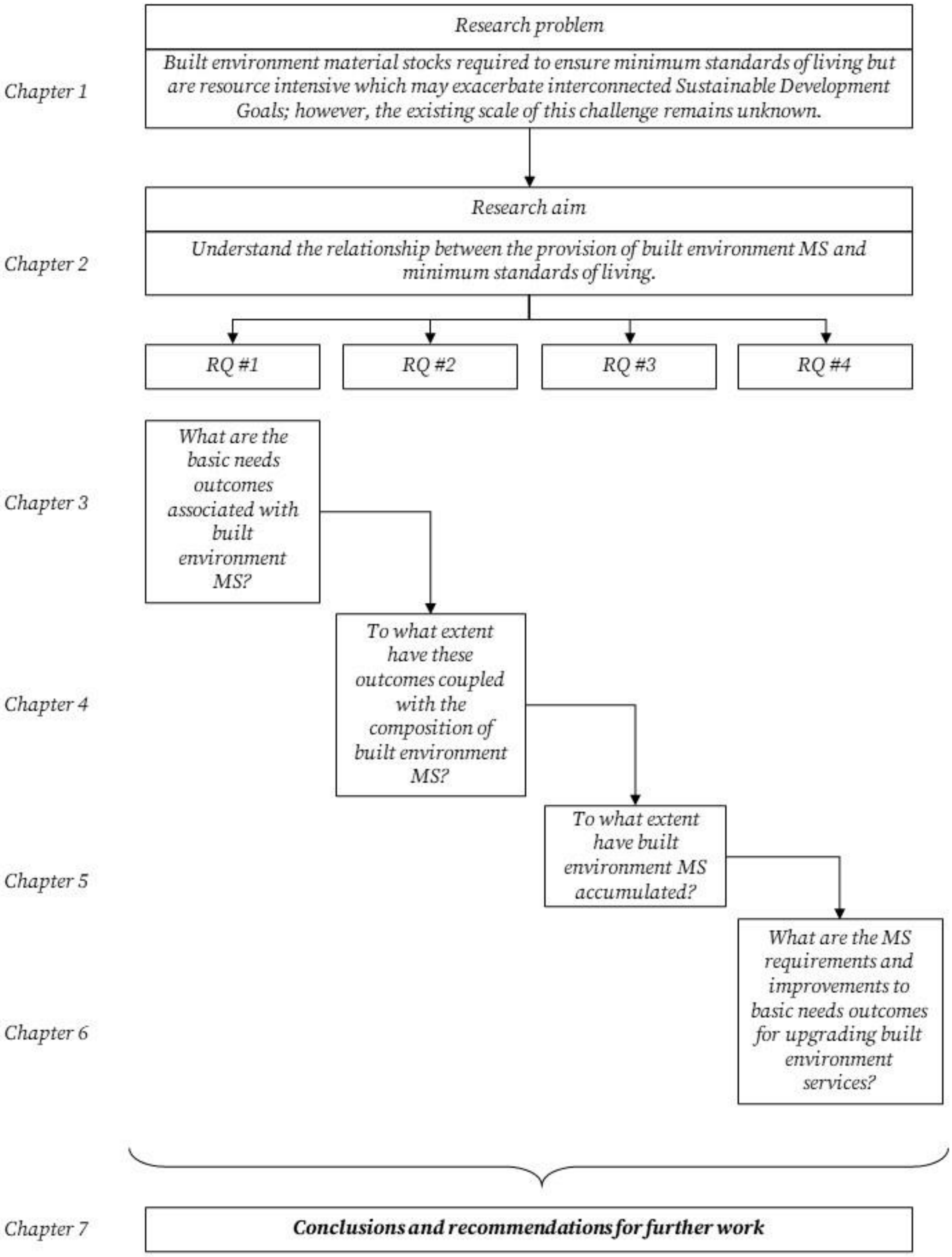

Figure 1.1: Outline of the thesis structure mapping research questions to their associated chapters. The research questions are rephrased to highlight how the thesis narrative is formed across these chapters, with each chapter building on the key further work requirements from previous chapters.

2 Literature review

To begin to elaborate an understanding of the relationship between society and the built environment MS on which it relies it is important to firstly introduce key characteristics of city growth. This provides scientific evidence to support placing the living standards versus material use debate within cities. In section 2.1, we therefore briefly turn to the literature forming a scientific understanding of cities to highlight their role in achieving sustainable levels of development. The rest of this chapter aims to review the current state-of-the-art of research fields quantifying built environment MS, section 2.2, and understanding its relationship to standards of living, section 2.3. As we will see, there is a clear need to improve assessments of living standards within such studies. Therefore, section 2.3.2 aims to integrate key approaches to measuring development outcomes to enhance assessments of MS accumulation and levels of development. The chapter concludes with a brief summary of the key research needs and their relationship to the research questions and objectives presented in Chapter 1.

2.1 A brief introduction to the science of city growth

Cities concentrate socioeconomic actives and are therefore vastly important for human societies. As such, urbanization is now seen as a primary development strategy in many nations (26), and is generally motivated by economic growth and human behaviour patterns (27). Cities take various forms over significantly varying scales, from small urban areas to large metropolitan areas, however studies are now revealing the seemingly persistent distribution of characteristics pertaining to human populations (28–34), with empirical evidence showing that the properties of cities, in terms of urban infrastructure and socioeconomic activity, depend on the size of the city. There are now abundant observations of the scaling of urban properties relating to resource consumption and development. This is owed to two general phenomena which characterize cities: agglomerations effects and inequality. Agglomeration effects manifests two key relations: 1) sub-linear scaling, or economies of scale, e.g., of material infrastructure through more dense urban forms (27,31,34,35), and 2) super-linear scaling, or increasing returns, e.g., of socioeconomic quantities such as access to basic services (27,30–35). As such, these relations mathematically describe infrastructure systems and the social maturity of cities respectively (27). For example, sub-linear scaling is shown for key services such as roads (34,35) highlighting increased material efficiency of infrastructure as cities grow due to a greater intensity of use based on the population size. This implies that a doubling of the population would require only an approximate 85% increase in urban infrastructure and thus a 15% saving resulting from efficiencies in material use associated with densification (29). On the other hand, super-linear scaling of socioeconomic quantities, such as Gross-Domestic Product (GDP) (36) and access to basic services such as water and sanitation (34), has been shown highlighting opportunities for development in larger cities. However, scaling may also lead to disproportionate outcomes within cities. For example, income and housing costs are shown to scale similarly and thus larger cities agglomerate higher earners whilst exhibiting low concentrations of low income inhabitants, with the opposite trend generally true (33). Additionally, slum populations characterized by a lack of access to basic services tend to grow faster than the total population (34). The growth of cities therefore tends to simultaneously drive resource consumption, economic growth (31,37) and more efficient use of urban infrastructure (28) as well as creating strong inequalities of outcomes among urban dwellers relating to urban infrastructure and housing (6,34,38).

These overarching observations highlight that city growth poses challenges and opportunities for urban infrastructure provision in terms of resource use and their associated human development outcomes. This underlines the motivation for focusing sustainability efforts within cities. Studies across urban scaling and urban morphology have therefore noted the critical importance of providing adequate basic services to all whilst focusing on resource efficiency strategies (6,37), such as effective design and planning of urban forms, to transition towards sustainable cities (37,39). There is now a clear need to integrate environmental impact assessments of key physical provisioning systems, such as buildings and water supplies, with the monitoring of human wellbeing which accounts for inequality of outcomes to ensure effective and equitable allocation of public resources (19). Despite this there remains little empirical research relating outcomes of human wellbeing associated with urban services to their resource requirements and environmental impacts. We now turn to the research field and concepts central to understanding characteristics of the built environment to begin to unpack the integrated nature of this problem.

2.2 Socioeconomic metabolism

Human societies are comprised of the biophysical, social, and natural environments which are often described as socio-ecological systems (40). The systems perspective of human societies has formed various fields of research and approaches to quantify characteristics of the socio-ecological system. Socioeconomic metabolism (SEM) is an important paradigm in this context which generally captures research exploring social, industrial and anthropogenic metabolisms (41) and which has “become the cornerstone of sustainability science” (13). SEM research has continually evolved and has facilitated the unification of related research fields (40) which generally encompass research relating social and ecological systems, such as industrial ecology (42,43) and urban metabolism (44) and which are central to developing sustainable cities and communities (45). It is therefore broadly defined as a systems perspective on resource use which studies society-nature interactions (46). Conceptually, it begins with a broad perspective on the socio-metabolic interactions of materials, energy, waste, and emissions (21) by considering human society akin to an organism in which the metabolism refers to the interaction of human society with the natural environment. SEM research therefore considers the biophysical flows of materials and energy within a system, e.g., between social systems and the natural environment, which form and support retained biophysical structures within these systems, e.g., buildings and infrastructure, referred to hereafter as material stocks (MS) (46). However, given the challenges to natural resource extraction and discharge in the form of waste and emissions, a significant amount of SEM research has focussed on the resource efficiency of material and energy flows (13).

2.2.1 Built environment material stocks

More recently, the importance of the built environment as the biophysical spatial structure of societies has become more apparent (10,11,47). The accumulation of various construction materials forms various structures such as buildings and infrastructure which enable the functioning of human societies. More than half of the annual global resource extraction is used to build up and maintain MS and an already significant portion of global primary materials have accumulated within the built environment (10). SEM research has highlighted the importance of built environment MS due to their various characteristics and roles within social and physical environments. Built environment MS have long lifespans which is important to ensure continued service provision, however this presents numerous challenges to resource efficiency and urban development. Firstly, the legacies of such MS present lock-ins to future resource use and settlement patterns (10,13,48,49). The impact of built environment MS therefore extends across their lifetime, dictating the flow of materials and energy for maintenance and demolition, as well as creating spatial structures which influence future urban development (10,13,47). Research has therefore highlighted the importance of urban densification and form, and thus the organization of built environment MS, on resource efficiency (37,39,50) broadly agreeing with the observations outlined in section 2.1. Secondly, built environment MS can be perceived as a reservoir of secondary materials which has led to concepts such as 'urban mining' extending into sustainable resource management discourse (51,52). Such MS may therefore present opportunities for future resource efficiency such as the circular economy, which aims to maintain the value of materials and keep them in circulation within the economy and is seen a key strategy to decouple growth from anthropogenic carbon emissions (53,54). The provision of built environment MS may therefore present key challenges and opportunities for sustainable development.

A key methodology to quantify the biophysical flows and stocks of material within SEM is material flow analysis (MFA), which is a tool used to enable the systematic evaluation of material or energy within a system defined in space and time (55). It links the flow of resources in and out of a system to measure the size and structure of the SEM and is a well-recognised method that has been widely used within research exploring sustainable resource consumption and management strategies (11,55–57). A diversity of MFA applications has demonstrated the capability of various approaches to assess material-based systems over a range of spatial and temporal scales. Studies within SEM have used MFA approaches to understand systems of chemical compounds within products (58,59), the accumulation of building and infrastructure material at the national (11,16,41,56,60–64) and sub-national scale (4,11,56,60,65–69) and to explore potential resource efficiency strategies within the built environment (41,69–72).

2.2.2 Material stock accounting

To simplify and organize the diversity of methodologies, MFA has been summarised into four overarching approaches: bottom-up, top-down, demand-driven and remote sensing (11). Methods are generally characterized by the type and use of data, with approaches proving beneficial at different spatial and temporal scales. They relate to static and dynamic models, with static models providing a snapshot of the system in time and dynamic models generally analysing the lifecycle of stocks and flows over time (11). We briefly outline these broad approaches below and refer to their applications in material stock accounting. We therefore refer to these as material stock accounting (MSA) approaches.

2.2.2.1 Top down

At the core of the top-down approach is the mass balance principle, with MS derived from the net flow of material within a system (73). Top-down approaches generally follow economy-wide material flow accounting frameworks which monitor the material flows through economies (46). Inflow statistics are often available at the national level, however outflow data is more difficult to monitor (52). Therefore, the top-down method generally uses economy-wide inflow and outflow statistics over a period of time supplemented by estimations of MS depreciation. It is therefore an effective approach for assessing stock dynamics at national levels over large temporal scales and has been used to understand material stocks in various sectors at the national level (64,74). As a result, it is a common methodological approach to quantify stocks in relation to socioeconomic factors measured at national scales. For example, it has been used to track national trends of aluminium stock accumulation and economic growth through time (64) and to understand the cross-sectional global trends of in-use stock accumulation and human wellbeing (75). Where adequately disaggregated data is available, the top down approach can also be used to estimate material flows at sub-national scales and has been adopted to calculate city-wide material flows (4). However, a key limitation of this approach is the spatial resolution and description of MS. Due to the data available for this approach, studies are often limited to larger spatial scales, lacking description at the product or aggregated product level and therefore the sectoral distribution of MS (52,56,76).

2.2.2.2 Bottom-up

The bottom-up approach estimates stocks directly by beginning at the inventory of end-use objects within a system. It is a coefficient-based approach in which material coefficients are extrapolated out over the population of object types. This usually follows an archetype approach which homogenises objects by a select set of characteristics, such as building age, use and construction type. A material intensity coefficient (MIC), e.g., mass per unit of gross-floor area, kg/m^2.GFA, is calculated for each archetype and extrapolated out over the total population of objects, e.g., total gross floor area. The bottom-up method is shown to be effective at understanding the distribution of stocks at the local- (65,66) and city-level (11) and to estimate the magnitude of national-level stocks for non-domestic (72) and domestic (16,77) buildings. Where available, national databases have been used to aid the estimation of MS. Detailed databases providing information of the inventory of items and associated MICs, often within Geographical Information Systems (GIS), can be used to assess the magnitude, and in some cases the distribution, of material stocks at the national level. Such a comprehensive study has been exemplified for Japan (11), however MIC and detailed GIS databases are not available for many countries. Due to the lack of such information more nuanced approaches are often required. These may combine various data sources to establish a spatiotemporal database which can be used to estimate the size and distribution of MS. Such datasets can be created using satellite imagery, georeferenced building footprints and datasets of building characteristics such as use and height. Further, multiple bottom-up accounts can be combined across different years to provide an understanding of the changes through time. For example, satellite imagery, historical maps, aerial photos and existing GIS datasets have been combined to digitise and georeferenced buildings across multiple years assessing the dynamics of urban development for a single Chinese district (65). The bottom-up approach therefore offers a relatively flexible approach to assess built environment MS accumulation, its distribution, and end-use, specifically at local spatial scales such as within cities. However, key challenges remain surrounding the availability of data and the coherence and transferability of methods.

2.2.2.3 Remote sensing

Remote sensing approaches generally utilize information gathered from satellite readings of surfaces. It is therefore a static approach which inherently describes the spatial distribution of stocks. Satellite imagery may be used to address areas of data scarcity as well as for high resolution studies requiring vast statistical data across large geographical scales to better describe the spatial distribution of stocks (60). Night-time light (NTL) data has extended the remote sensing methodology by using NTL as a proxy for in-use stock distribution within the built environment. Studies have suggested the strong correlation between NTL and in-use steel stocks (78,79), with recent technological advancements in NTL products enabling more accurate estimates of in-use stocks within the built environment (60). However, key limitations relate to the ability of remote sensing techniques to identify the end-use of MS as well as the composition of stocks (11). Remote sensing methods are therefore often combined with other approaches. For example, bottom-up and life-cycle analysis approaches have been combined with GIS data, the detail of which is improved through remote sensing, to assess the environmental impact of residential building MS within the city of Esch-sur-Alzette (Luxembourg) (71).

2.2.2.4 Demand-driven.

The demand-driven approach adopts socioeconomic factors to model the demand for stocks based on their associated service. It generally combines socioeconomic indicators, such as the population's demand for residence (61), with material requirement estimations for objects as with MICs in the bottom-up approach (11). Its introduction presented a pioneering first step to account for and forecast MS accumulation over large temporal and spatial scales, assessing and forecasting concrete consumption in Dutch residential buildings from the years 1900-2100 (15). The method assumes that the population and its lifestyle are driving forces central to stock accumulation and that these stocks of products and services are one of the drivers of material flows. The method has since been adopted and developed with varying statistical approaches for product lifetime estimation (61,70,80,81) and has inspired recent conceptual frameworks within SEM research discussed in section 2.3.1.

2.2.2.5 Discussion

While several MSA methodologies can be used to quantify stock accumulation, the choice of approach is largely driven by the need to capture desirable characteristics at different spatial and temporal scales. Life cycle analysis methods have been combined with both dynamic (69) and static (82) MSA approaches to quantify embodied energy[1] (83) and elaborate material efficiency strategies from end-of-life scenarios. Developing such insight is important for informed policy making regarding life cycle resource management and for implementing resource efficiency strategies such as the circular economy (52). However, despite attempts to ensure the accuracy of the above methods, there remains inherent uncertainty in the

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[1] Embodied energy relates to the total energy required to produce and transport materials as well as the energy required to construct biophysical structures such as buildings and roads etc., (191). Although operational energy is an important consideration in the life-cycle energy use of buildings and infrastructure, the embodied energy from construction material has become a key factor in many studies (86,118,190,191,197,219,225). This is largely owed to the focus on operational energy which has spurred innovations which, in combination with decarbonization of the electricity grid, has reduced operational energy demand. However, this trend has increased the relative contribution of embodied energy to whole-life carbon emissions and thus embodied energy is becoming of increasing importance.

analysis of MS which is a largely a consequence of the available data regarding stock characteristics, material composition and age distributions (16). For methods adopting cohorts of objects, lifetime and composition of objects remains uncertain which limits dynamic models (61). Studies have attempted to account for the uncertainty incurred from the variation in the quality and coverage of data by combining dynamic and static approaches (41,56,84). Literature has demonstrated the ability of a hybrid approach to describe the additions to stocks at the city-level with low data dependency (56). However, bottom-up approaches have proved effective at describing stock characteristics at the city-level to inform resource efficiency strategies and understand patterns of urban development. Dynamic approaches tend to adopt data aggregated to larger spatial scales, which limits insight into city-level and sector-specific MS composition and distribution. The bottom-up approach is therefore favoured over other MSA methods at city and sub-city scales 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 (52). Such descriptions are important to better understand the impacts of material stock compositions on social progress in terms of services, as these approaches consider the end-use of MS. However, there remains a lack of coherent structure in the construction and assignment of MICs which limits comparisons and understandings of MS across nations, regions, and end-use objects. For example, studies assessing the MIC of buildings have shown that the number of floors has a considerable effects on the final MIC (67,85,86), a characteristic not always included in building archetypes. Further, the ability of the MIC to accurately describe the population of objects is difficult to evaluate. Studies therefore recommend that expert estimations are required to reduce uncertainty when sample sizes are small (77) and that further MIC studies in new geographical areas and within a coherent framework are required to improve comparability between studies (85,87).

2.2.3 Built environment material stock accounting in the Global South

While studies quantifying built environment MS have increased in the past decade, much of this research is focussed at national levels and in developed countries (52), with studies, for example, quantifying the MS of residential (16,61,77) and non-residential (72) buildings as well as transport infrastructure (11,16,62). This is largely owed to the availability of adequately disaggregated spatiotemporal databases within developed countries which has led to comprehensive studies of MS accumulation and distribution across nations (11). There is now an increasing need to focus sustainability efforts within cities given the significant rates of urbanization and population increase, particularly in the Global South (5). In this context, studies in the Global South have begun to develop an understanding of the accumulation and composition of built environment MS. Much of this research is motivated by the need to understand patterns of MS accumulation to shed light on urban development in the context of rapid urbanization (48,65,76,88) as well as strategies for the efficient use of materials from construction and demolition waste (25,67) or through the reuse of existing stocks (48,89). While city-level assessments in the Global South are limited and often concentrated in China due to the availability of data (26,65,76,88,90–92), studies are emerging in other countries such as Peru (48,68,93), Indonesia (94) and Brazil (67).

Studies in the Global South have quantified the stock of residential buildings (68,91,93), non-residential buildings (66,88,90), and roads (88,90,91) and demonstrated an ability to map these results at high resolution and over large temporal scales. For example, a comprehensive study assessing over one-hundred years of MS accumulation has revealed the dynamics of development at the sub-urban scale and highlighted the need to account for environmental impacts and waste generation into future plans for urban redevelopment (65). The sectoral transformation of this area from industrial to predominantly residential highlights the implications of lock-in effects which limit future urban development and require extensive demolition activities to renew urban areas. It also further highlights the need to understand MS at the product-level to better inform resource efficiency strategies such as urban mining or building reuse to ensure that lock-in effects minimize waste. Others have highlighted such challenges in other contexts (48,49). For example, a recent study has suggested the existence of lock-in effects within the city of Lima, Peru, by combining the bottom-up approach with GIS modelling to quantify and map building stocks (48). The study sheds light on the potential maximum growth of MS in this city and its use as secondary resource and highlights the importance of assessing constraints relating to urban planning such as horizonal growth and the provision of basic services to better understand lock-ins.

At the forefront of this research has been the bottom-up approach, owed to its ability to quantify and map stocks at city- and sub-city scales, offering a high-resolution understanding as to the composition, quality and distribution of MS whilst making use of context-specific data. The approach also lends itself to assessments of stock density and per capita stock accumulation that feature in debates surrounding the intensification of physical development of the built form globally (53,89). There remains limited comparison between countries of the Global South and rapidly developing regions, however such comparisons may aid in understanding future development pathways in comparison to developed regions such as the potential saturation of stocks which are yet to be observed (52,95).

As we have briefly discussed in Section 2.1, economic growth as well as the population of households lacking access to basic services has been shown to scale super-linearly with city size. While studies have begun to develop an understanding of stock accumulation in relation to resource efficiency and urban development in the Global South, there remains a lack of understanding of the relationship between MS and the societal outcomes of its associated service provision. We now turn to the body of research which provides first steps in this direction.

2.3 Relating built environment material stocks to standards of living

Economic growth and population increase have been at the centre of contemporary discussion surrounding sustainable development and SEM research has now begun to relate such factors to in-use stocks. Studies have found that economic growth drives MS accumulation (64,81,96–101) for many nations including Japan (98), China (76,99), the US (64) and the UK (81), adopting regression models to statistically relate stock accumulation to economic growth and draw robust conclusions surrounding the observed trends. For example, a regression model has been used to reveal dramatic increases to both in-use aluminium stocks per capita and per GDP since the beginning of the 20th century (64). National trends in in-use stocks have also been shown for units of analysis of cities and prefectures (76,98), with a bottom-up approach highlighting trends of increasing built environment MS by sector and an overall trend of increasing MS with economic growth in cities (76). Socioeconomic drivers of MS accumulation have also been evaluated using IPAT analysis. This considers the driving forces of population, P, affluence, A, and technology, T, often measured in terms of GDP and which have been combined with bottom-up stock accounting approaches to assess the environmental impact, I , of the built environment (76,98). Generally, these studies are motivated by the need to decouple economic growth from resource use to alleviate pressures on natural resources and highlight the significant challenge of decoupling in the context of sustainable development (20,21). However, the rationale for continued economic growth is increasingly in question (43,63,102) and has led to calls for alternative strategies to sustainable development such as sufficiency and de-growth (13,103).

GDP is now increasingly accepted as a poor proxy to wellbeing (102) and studies have begun to relate resource use to other socioeconomic factors such as population density as well as social wellbeing measures, such as the Human Development Index (HDI)[2], which is most frequently used to measure and track national trends in human development (104,105). A global cross-sectional analysis of the relationship between the HDI and in-use stocks of steel, aluminium and cement reveal an inverse L-shape relationship, see Figure 2.1 (75). Results show that initial increases in the accumulation of built environment stocks are associated with significant increases in development until stocks reach high levels and development levels off. The regression model firstly highlights the significance of countries of the Global South, such as India, in the global context. Many of these nations are at early stages of per capita stock consumption which correlate near-linearly with HDI (75). This suggests the crucial role of new additions to in-use stocks in improving wellbeing within these nations when pursuing improvement in HDI at incipient stages of growth. Secondly, it suggests a saturation point of MS beyond which levels of social wellbeing do not increase significantly, which may be a result of context-specific variation regarding the ways in which MS are provided or the continued pursuit of economic growth. This has been demonstrated for the case of the UK, where a recent study compares GDP and the decomposed indicators of the HDI to aggregated UK-wide stocks within a dynamic MFA model (81). The results highlight that the wellbeing indicator of life satisfaction does not seem to be influenced by increased per capita stock accumulation or GDP across several decades. The motivation for pursuing increased HDI is therefore questionable when considering both resource consumption and actual improvements to living standards, given that it correlates near-linearly with GDP (106) and also overlooks living standards in terms of access to basic services. The HDI focusses on gross-national income per capita as a measure of a decent standard of living, thus contradicting the decent living standards literature presented in section 2.3.1.1. Further, data published by the United Nations Development Programme (UNDP) shows that access to electricity correlates near-linearly with GDP per capita until service access is saturated (106). From here GDP is shown to continue to increase, a relationship much like the identified

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[2] The HDI considers life expectancy, literacy and education, and income as three core dimensions of wellbeing and thus considers two dimensions beyond GDP (107,226). The dimensions are combined into a composite index using a geometric average, as described in section 2.3.2.

inverse L-shape relationship between the HDI and in-use stocks. This reinforces the notion that continued economic growth in pursuit of wellbeing may be severely detrimental to natural resource reservoirs whilst resulting in little-to-no increase in wellbeing, supporting the eudaimonic perspective of wellbeing as discussed in section 2.3.2. However, without an adequate understanding of living standards in relation to stock use, it is difficult to validate whether living standards improve as stocks increase past saturated levels of HDI given the previous contradictions. As such, it is important to elaborate an understanding of the relationship between living standards and stock use in terms of basic services. This may enable the identification of pathways to sustainable development such that nations under-performing in outcomes of basic needs can achieve high levels of wellbeing whilst limiting ‘over-consumption’ of in-use stocks.

Recent progress within SEM research has therefore shown that social wellbeing is not just a result of growing GDP or the annual flows of resources but is also related to the services provided by stocks (13,43,107,108). While the demand for services was initially identified as a key driver for stock accumulation in dynamic MFA, this has more recently led to the concept of the stock-flow-service nexus which seeks to better integrate the role of material stocks and their associated service into the assessment of sustainable resource management strategies.

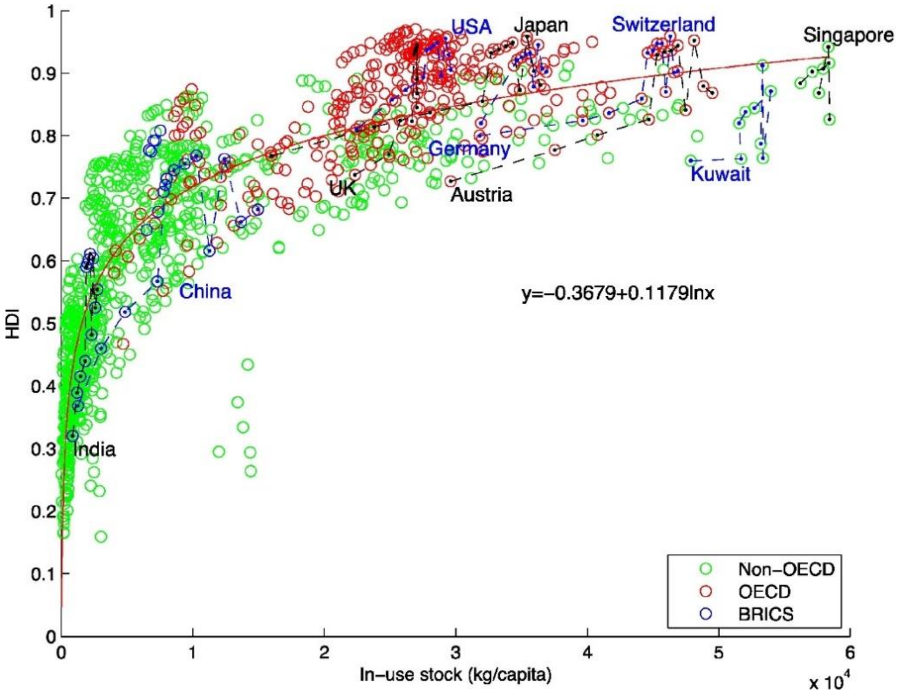

Figure 2.1: The relationship between in-use stocks of aluminium, cement and steel and the HDI (75).

2.3.1 Stock-flow-service nexus

The stock-flow-service nexus (SFS-nexus) is a recent and important contribution in the field of SEM research to approach the decoupling of societal wellbeing and resource demand. It acknowledges that sustainable development involves significant changes in socioeconomic metabolism in terms of the stocks and flows of energy and material and the related human, or societal, activities (13). While it is centered around the introduction of stocks and associated services into flow-centered assessments, it begins to broaden the perspectives of SEM from economic growth to stock-specific services and thus acknowledges the benefits of MS to human wellbeing. The SFS-nexus has recently extended into the conceptual frameworks of basic needs (109,110) and practice-theory (111). The integration of resource use into Ends-Means concepts was initially developed by Donella Meadows as a spectrum to measure sustainable development (112). This conceptualizes resource use within the Daly Triangle through a linear process from ultimate means, e.g., natural capital, to ultimate ends, e.g., human wellbeing, thus relating the use of natural resources to living standards, see Figure 2.2.

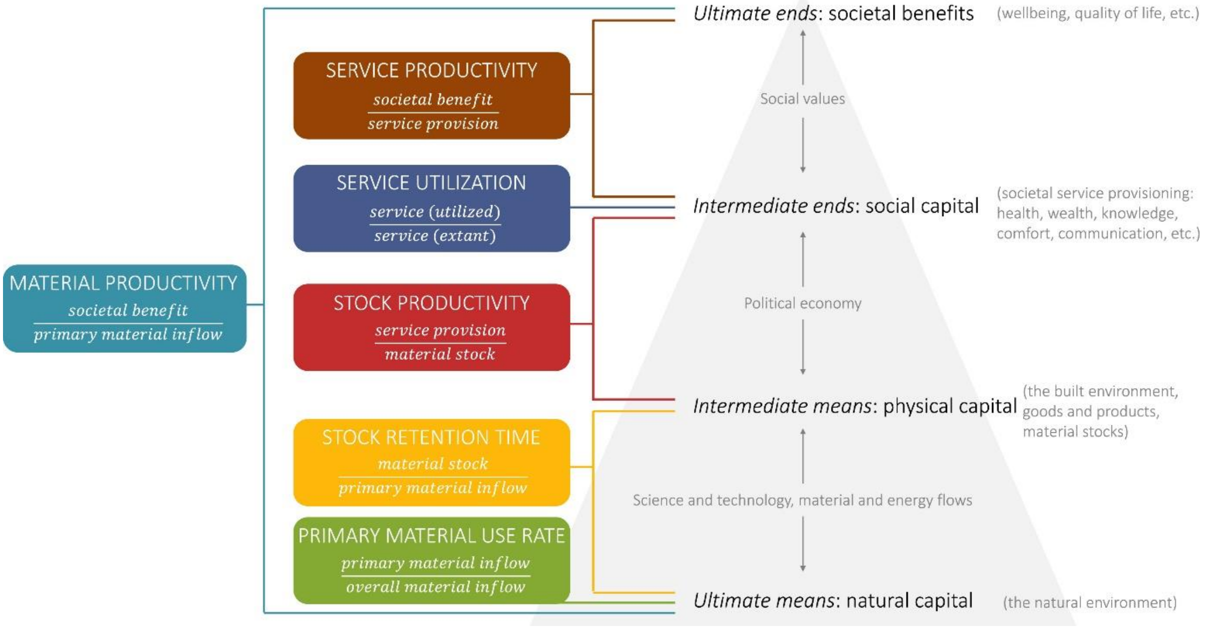

Figure 2.2: The six material indicators relating natural capital to service provisioning within the Ends-Means spectrum (110).

Since then it has been expanded to highlight the role of both physical and social provisioning systems as a bridge between biophysical resource use and various needs to satisfy wellbeing (109). Important work has further expanded the SFS-nexus by associating the stocks and flows of materials with the associated service provision and formalizing a flexible set of indicators which characterize processes through the Ends-Means spectrum, as shown in Figure 2.2 (110). However, this is yet to extend into quantified assessments of living standards and material stock accumulation which go beyond measures of income and consumption such as GDP. Nonetheless, the progression of SEM research through the integration of Ends-Means and basic needs within the stock-flow-service nexus provides a theoretical framework with which to integrate measures of development with the associated material and energy use.

2.3.1.1 The challenge of societal service provisioning and wellbeing in the stock-flow-service nexus

To date, many stock-flow-service nexus orientated studies measure outcomes of *services* by adopting existing metrics which aim to indicate wellbeing[3]. The majority of such work has adopted GDP as the proxy for societal services or societal benefit, i.e., the intermediate and ultimate ends of the Ends-Means spectrum. Studies beginning to extend the definition of *services* to basic human needs have focused on global trends and have therefore adopted well-established metrics such as the Human Development Index (75) and Social Progress Index (SPI) (46) as proxies. A recent study has illustrated cross-sectional global trends of in-use concrete MS and social progress measured by the SPI[4], which goes beyond monetary measures such as GDP to more accurately account for the fulfilment of basic human needs foundational to wellbeing (43,107). The results show the broad trend of living standards measured by the SPI and the accumulation concrete MS, where high levels of SPI are achieved up to levels of around 75 tons/capita, see Figure 2.3. The trend is observed up to this level for non-high-income countries, beyond which high-income countries achieve high levels of SPI with no clear relationship to in-use stocks. Again, this indicates a saturation point, as with the HDI (75), where stocks are near linearly related up to high levels of wellbeing but which continue to accumulate despite wellbeing levelling off. Similar global

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[3] A major conceptual challenge within research fields addressing human development is the quantification of wellbeing, or quality of life, i.e., the ultimate ends. As such, a common and widely accepted approach is to develop metrics which *indicate* wellbeing via the outcomes relating to intermediate ends, such as having adequate amenities and assets which are *conducive* but not *deterministic* of a certain level of wellbeing. This is discussed further in section 2.3.2.

[4] The SPI is a composite index which provides a framework for monitoring social progress by considering three core dimensions: basic human needs, fundamentals of wellbeing, and opportunities and indicates these dimensions with measures of access to adequate shelter, water, sanitation and nutrition, as well as safety, health, education, rights and freedom and access to knowledge and information to assess social progress (195).

trends have also been shown for per capita energy use in relation to numerous wellbeing indicators such as access to electricity and sanitation (113), as well as for life expectancy in relation to carbon emissions (114). While the SPI begins to integrate *outcomes* relating to the provision of such services, such as having access to adequate shelter or water, the relationship between MS and the service itself is obscured by many other indicators included within the index, such as access to advanced education and personal freedom and choice. Such dimensions are imperative to minimum living standards but they may not directly relate to the MS in question or built environment MS in general. There is therefore a clear need for targeted assessments of service provision outcomes which are more closely related to the associated MS to better understand the role and scale of MS provision in ensuring minimum standards of living.

While not specifically addressing the SFS-nexus paradigm, studies have recently proposed a universal set of irreducible dimensions conducive to decent living standards (DLS) (115,116) which more specifically relate the provision of MS with dimensions of wellbeing. The dimensions comprise 'universal satisfiers' which demand minimum household and collective requirements where appropriate and which are benchmarked by the minimum required characteristics to achieve dimensions[5] (116). Although it is possible to debate such requirements due to context-specific needs and constraints, the underlying rationale is difficult to dispute and provides a basis with which to better consolidate wellbeing indicators and MS. Such indicators have recently been adopted within material and energy models nationally revealing the relative scale of challenges to DLS. Important results have revealed that a greater proportion of the global population are deprived in indicators of DLS than are income poor (8). These results are related to the energy requirements to bridge gaps in DLS which highlight the significant scale of required material upgrades and thus the need for equitable development to reduce the need for growth (8). The results also further support the rationale to go beyond income to better capture stock-service relationships and the clear need to understand these trends at national and sub-national scales to identify pathways towards equitable development. Bottom-up approaches have been applied to assess the national energy requirements needed to meet DLS through the provision of adequate

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[5] For example, minimum floor space as a universal satisfier for which the household requirement is $30m^2$ at a minimum and $10m^2$ per additional person above three members, and the collective requirement of industrial organization and technology for such infrastructure provision (116).

infrastructure and housing in India, Brazil and South Africa (117) as well as to meet housing demands in India (118). Similar assessments have been conducted at the city-level, estimating the material implications of closing deficits in living standards through a bottom-up approach in comparison to assessments of current city-wide cement flows for two Indian cities (4). Single indicators, such as the percentage of the population lacking access to individual services, have therefore been used to highlight key implications for urban development and policy (119–121). Such studies are essential to shed light on the scale of challenges relating to basic service access and provide a framework with which to define societal services in terms of basic needs relating to the provision of built environment MS.

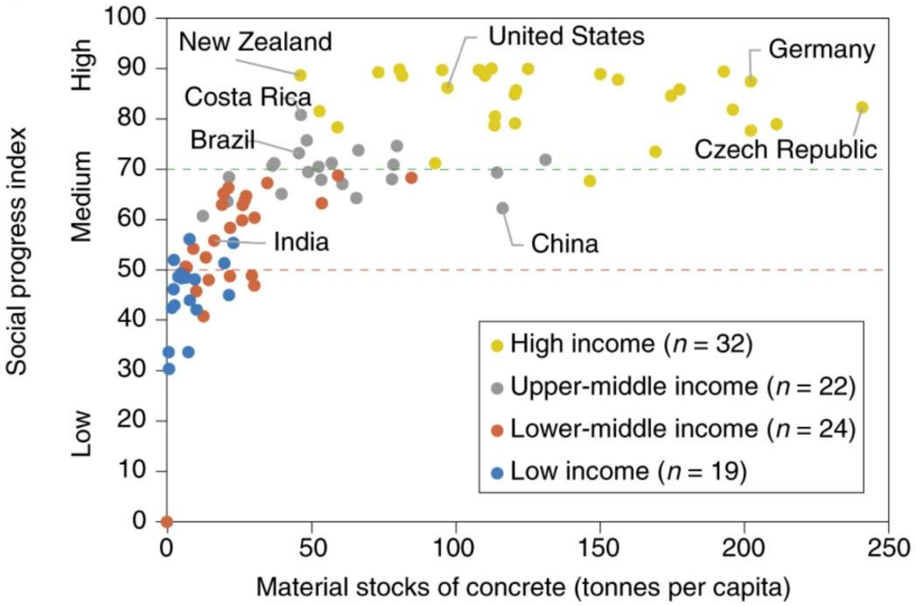

Figure 2.3: Material stocks of concrete and social progress for 97 countries (46).

While conceptual frameworks are developing, there remains key shortcomings of the existing literature addressing the relationship between MS and services, i.e., between the intermediate means and the intermediate, and ultimate, ends as in Figure 2.2. Many studies consider only economic growth, or GDP, as a measure of wellbeing or service provision, which we argue is inappropriate for measuring minimum standards of living in the following section. Studies have begun to address this by relating in-use stocks to national wellbeing metrics such as the SPI and HDI. However, such studies have so far only revealed Global trends and do not clearly define the stock-service relationship in question. This is because of nationally aggregated assessment of MS which do not define the end-use of MS as well as the use of dimensions within metrics which may not relate specifically to the MS in questions.

This limits insight into the national trends of such coupling which consider the role of service-specific MS in providing adequate services to achieve specific dimensions of wellbeing. As such, an empirical understanding of the relationship between resource provisioning and basic needs outcomes is limited and is needed to better understand national and sub-national trends in resource use and minimum living standards. Much of the current focus in this direction has been on closing existing deficits in living standards through the provision of services to minimum benchmark requirements. While there is a clear need for further empirical evidence in this direction, such national and city-wide assessments fall short at offering insight into existing national trends and quantifying key characteristics of built environment MS provision in terms of basic needs outcomes. This is needed as the previously discussed MSA studies in the Global South have highlighted the importance of capturing MS characteristics to better understand implications for equitable and sustainable resource use in urban development plans.

Overall, the current literature provides limited insight into the current coupling of minimum living standards and the provision of built environment MS and therefore the potential strategies to decouple the observed global trends. Adequately capturing service outcomes and relating these to resource use is therefore a clear challenge to SFS-nexus research and points to the need to develop robust monitoring frameworks with which to integrate built environment MSA. We now turn to key concepts and methodological considerations regarding the monitoring of outcomes relating to built environment MS.

2.3.2 Monitoring development outcomes relating to built environment stocks

As we have discussed, *development* is often measured using metrics reflecting monetary outcomes such as GDP per capita within SFS-nexus research. This is generally motivated by a *hedonic* wellbeing perspective that “more is better” thus assuming that increasing consumption, or rising income, can improve wellbeing (122). However, it is now generally agreed that measures need to go beyond such metrics as they not do not necessarily relate to the ability of individuals to buy goods and services and lack the ability to identify conditions that enable lives to flourish (123,124). Because of this, the focus of development measures has recently shifted from an assessment of income and consumption, often at national scales, towards approaches that attempt to measure the ways in which households live and work within their environment. This progression has largely been underpinned by the ‘capability approach' (125,126) following a *eudaimonic* perspective of wellbeing (122) which, as proposed in the pioneering work of Amartya Sen, defines *development* as an expansion of capability. This refers to an individual's or group of individual's functioning's, i.e., the observed 'beings' or 'doings' such as being sheltered, and their capability, i.e., the freedoms and opportunities, to realize such functioning's (127,128). Basic capabilities, or basic needs, generally refer to "the freedom to make choices necessary for survival and to avoid or escape poverty or other serious deprivation" for which material poverty severely exacerbates (123). Such basic capabilities, e.g., having electricity within the household, provide the first steps for individuals to then achieve more enhanced and empowering capabilities, e.g., access to improved technology (123). However, the approach precludes a list of basic capabilities and a process by which to identify such dimensions and therefore places importance on the judgement of value in the dimensions considered to expand capabilities (124). Despite this, Sen acknowledges that many dimensions of basic capabilities may be relevant and apply to every society, but that these must still fundamentally be a result of public debate and reasoning (126). Further, the measurement of *capabilities* is itself a contentious topic given that individuals may have the ability to perform various activities but choose not to. In the context of basic human needs and rights, *functioning's* are often the focus given that it is widely assumed those with the opportunity to achieve basic capabilities would rarely choose not to, thus assessments of basic capabilities are often *outcome-oriented* (128). Considering the definition of basic capabilities in the context of built environment service provisioning, the measurement of societal service provisioning e.g., having access to adequate housing, implicitly indicates achievement of dimensions of basic capabilities, e.g., being adequately sheltered, and thus indicates a degree of quality of life. Although such measures may not directly quantify wellbeing, it is difficult to debate the inadequacy of achieving such basic capabilities for fundamental levels of wellbeing.

Various indices have now emerged assessing human development, with many studies adopting index- and indicator-orientated frameworks to measure basic needs outcomes in relation to the services provided by built environment MS (6,129–131). The combination of individual dimensions into a single metric, or composite index, is a common approach when adopting indicators to monitor development outcomes (132). However, composite indices are often critiqued for implying substitutability between dimensions which is an important limitation of such metrics (130). Many adopt the multiplicative, or geometric, mean to aggregate indicators popularized by the HDI which begins to capture outcomes such that the emphasis is on the achievement of all dimensions and that they are not substitutional (6). Many also adopt unweighted dimensions of basic service access within composite indices (6,7,131) which avoids the normative judgement of the relative importance of the selected dimensions. Both approaches are appropriate when assessing achievement in basic needs as these are generally considered non-substitutional and of equal importance for achieving minimum living standards. Avoiding composite indices reduces most studies to the assessment of individual indicators; these have provided detailed assessments of the relationship between service-specific access and in-use stocks (130) and the resource requirements to fill deficits in access rates (4). However, in-use stock data is often recorded for aggregated sectors and therefore limits the analysis of service specific stock accumulation. Further, single composite metrics offer insight into overall basic needs outcomes associated with particular MS and the relative contribution of these dimensions to overall basic needs.

2.3.2.1 The statistical implications of monitoring development outcomes

Metrics such as the SPI have proven useful for an understanding of global trends in terms of basic needs outcomes but do not offer adequate resolution to capture context-specific relationships and variations within nations with which to better inform sustainable resource use. As these global trends have shown, as well as context-specific stock accounting studies, there is a clear need to further integrate service outcomes into SFS-nexus research at national and sub-national scales to better capture context-specific outcomes, resource use, and therefore challenges and opportunities for sustainable development. Many studies have adopted the well-established methodological approach of measuring human outcomes by assessing the average achievement of indicators in an area (6,120,133), an approach typified by the HDI discussed earlier. Studies in the Global South have focused on basic service access and have monitored average outcomes relating to household level access to built environment services such as access to water, housing and sanitation (134). Studies have also formulated broader metrics to include access to other services such as educational and financial facilities (120,133,135). However, the myriad of studies assessing basic needs outcomes sub-nationally generally do so at individual spatial scales and with isolated metrics (133,136–139). For example, studies have adopted average measures within GIS to understand the clustering of deprivation within Delhi (133) and have used multidimensional poverty metrics to evaluate the scale and clustering of deprivation in a single South African province (138). A central challenge to the monitoring of social outcomes is tied to inequality due to the outcomes among a population being more varied than when evaluated by averages (140). The presence of inequalities may impact the representativeness of average measures such that policy may become regressive and have unintended consequences for those furthest behind as highlighted in the distributional effects literature (140–143). This may be exacerbated by the fact that city growth is generally associated with increased inequality in access to urban infrastructure (7,34), as discussed in Section 2.1, and which has implications for the achievement of interconnected SDGs, as discussed in the following section.

The limitations of individual scales and metrics have been noted by scholars and sparked a move towards multilevel procedures which account for variation in outcomes by context, e.g., do cities or districts make a difference to outcomes, and by composition, e.g., is it what the city is composed of, such as higher income earners, that makes a difference, as well as reflecting inter-scale connections, e.g., is it the broader contexts of the districts for which cities belong (144). Multilevel approaches have enabled studies to capture both the context and composition of areas, for example to better understand how outcomes of illiteracy relate to compositional characteristics compared to contextual characteristics (145). Recent studies have adopted a multiscale model considering contextual effects using an average composite index monitoring the provision of urban infrastructure and housing to understand processes of urbanization in terms of average outcomes and associated inequalities (6,7). By adopting a multiscale approach, the authors are able to assess various characteristics of urbanization in terms of urban infrastructure whilst capturing unintended multiscale consequences of reducing inequalities. The multiscale studies (6,7) therefore present an approach to capture the potential variation in outcomes across spatial scales within nations and therefore addresses the modifiable areal unit problem (MAUP). MAUP is a persistent limitation pertaining to the use of areal data referring to the sensitivity of the analysis to the scale and number of aggregated units (146,147). Such analysis may offer important insight into the variation in the relationship between in-use stocks and wellbeing by assessing national trends in terms of cities or states for example, going beyond the overarching trends discussed in section 2.3.1. This is also an important consideration in assessments of sustainable development as the choice of urban unit, or the geographical scale to which we aggregate data, may have implications for urban policy (148). Thus, providing insight into the variation in perceived outcomes at different administrative scales is important for policy making as governing bodies residing at different levels may be better equipped to coordinate planning efforts. This may also be important for integrating social provisioning systems within SFS-nexus research as they present opportunities for detailed insight into equitable resource allocation strategies, for example by evaluating whether state- or city-level governing bodies are best placed to yield most effective results. However, assessments of trends concerning the provision of MS and development, such as with in-use stocks and GDP discussed previously, are often focused on individual scales of analysis within nations, such as districts or cities, which limits an understanding of the appropriate scale of intervention, as well as a systematic description of the observed trends. Further, although useful to identify problem *areas*, the reliance of average measures on small-area statistics such as censuses may limit the description of development at the individual or household level (149,150). This may incur ecological fallacy[6] by overlooking the distribution of service access among urban dwellers and impair analyses of sustainable development by inaccurately reflecting the experience of individuals. This is particularly important when considering resource allocations to alleviate poverty, as poverty is often experienced multidimensionally and tackling this is shown to require a significant increase in global CO_2 emissions (151). Focussing on average measures or on individual scales of analysis has now been shown to be insufficient to enable analysis of equitable urban development by hiding increasing inequalities within communities as average levels increase (7). The choice of metric and the scale of analysis is therefore important to ensure that assessments capture perceived variations in outcomes and do not overlook those furthest behind.

An important advancement in this context is the formulation of multidimensional poverty measures which expand our understanding of development outcomes by identifying and accounting for those 'left behind' in particular dimensions within a population (152,153). Sen's work has led to multidimensional measures (154) which account for the often overlapping nature of deprivation, the measurement of which is required to address the interconnected goals of reducing inequality and eradicating poverty (152,155). Poverty measures are now widespread in programmes of poverty analysis and monitoring across the Global South, marked by the introduction of the Multidimensional Poverty Index (MPI) (156).

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[6] Ecological fallacy is a widespread challenge in studies adopting aggregate data and refers to the potential methodological error associated with individual-level assumptions based on area-level analysis (147). As discussed in section 2.3.2.1, ecological fallacy is noted by many scholars as a key consideration in the monitoring of developing outcomes, particularly associated with severe deprivation of basic services or in relation to interconnected SDGs (160). However, its consideration in empirical analyses of development outcomes remains limited.

The novelty of this index is owed to the Alkire-Foster method which offers a flexible approach to assess simultaneous deprivations and provide insight into the challenges that multidimensionally poor individuals experience (157). It is generally based on a counting approach, outlined in section 3.2.5, which adopts survey data to capture individual or household deprivations simultaneously. Despite survey data being significantly less extensive than areal data such as censuses, it is argued that multidimensional poverty measures also add value to other metrics and can be used to compliment average measures to reveal the complexity of simultaneous deprivations among households (158). While average metrics have been used in combination with multiscale analyses to account for aggregation effects and reflect inter-urban inequalities, aggregation of outcomes among individuals or households is inherent within average composite indices adopting areal data. Therefore, there remains uncertainty in the perceived intra-urban outcomes and associated challenges. Evaluating the multidimensionality of deprivations may add valuable insight into the variation of outcomes within urban areas by measuring the severity of deprivation among households. However, there remains limited application of such metrics as a means of complementing average measures to shed light on the concentration of deprivation. Such assessments may also offer valuable insight into achieving the interconnected Sustainable Development Goals many of which rely on basic needs and urban infrastructure.

2.3.2.2 Implications for the Sustainable Development Goals

The 2030 Agenda for Sustainable Development saw 193 Governments committing to achieving 17 Sustainable Development Goals (SDGs) and pledging to the global ambition of leaving no one behind (159). The SDGs have now become universally accepted reference points for member states to track and monitor progress towards sustainable levels of development (1). To deliver the overarching aim of leaving no one behind it is crucial to routinely report progress towards the goals such that challenges and opportunities enabling equitable development can be evaluated within urban areas. The implications for monitoring progress towards the global agenda is that assessments of average outcomes may overlook trade-offs and synergies between indicators and incur ecological fallacy due to the use of areal data and thus overlook those furthest behind. As such, scholars now argue the need to capture intra-urban inequalities (160), assess interlinkages between SDGs (161), and capture heterogeneities within and between dimensions (6,161). This is essential to address potentially unintended consequences resulting from intervention strategies and policy frameworks (162), as discussed in section 2.3.2.1 regarding distributional effects. These recommendations point to the need to develop alternative and flexible approaches to ensure the efficacy of indicators as a policy instrument (132), with scholars arguing that frameworks providing alternative understandings of the same problem are needed to address interconnected problems (163).

Studies have now noted the monitoring imperative and progress in this area has begun to recognise the interconnected challenges of multiple SDGs. The SDGs and their associated indicators have been related to basic services (6,164) and synergies and trade-offs within and between goals have been identified (165–167). For example, SDG 1, associated with ending poverty, has been shown to be most synergistic with other goals, with SDG 12, relating to responsible resource consumption and production, associated with the most trade-offs (168). This is owed to the need to achieve many basic societal outcomes with increased resource consumption and studies have now begun to identify the crucial role that the construction industry plays in delivering the SDGs (169,170). Thus, the challenges to achieving interconnected SDGs parallel the gaps in our understanding of the relationship between basic service access and the associated resource use. However, while the SDGs have increased efforts to eradicate poverty and improve standards of living, the resource implications of such goals remain poorly understood and with limited associated goals and indicators within the SDG framework. Without a systematic understanding of the relationship between social outcomes and resource provisioning, insight into the scale of challenges across nations will remain limited. First steps in this direction have recently integrated SDGs into assessment of inclusive development to minimum service requirements at the national level (117) and for a limited number of cities (4). However, further assessments of resource requirements to meet interconnected goals are needed to shed light on inclusive development, particularly considering existing trends to reveal ongoing challenges.

2.4 Summary and research needs

The following summarizes the state-of-the-art outlined previously and synthesizes the identified research gaps with the research questions and objectives stated in Chapter 1.

2.4 Summary of research needs

In this chapter, we have firstly discussed the widespread empirical evidence of the challenges and opportunities growing cities face regarding socioeconomic development and material use. The beginning of this chapter has therefore, through a brief review of urban scaling literature, provided scientific evidence to support the value of placing the living standards versus material use debate within cities. This is particularly the case for cities of the Global South where unprecedented urbanization rates are expected in the coming decades. From here, the proceeding chapters sought to outline the state-of-the-art of SEM research, highlighting the existing gaps regarding the quantification of built environment MS and understanding its relationship to living standards.

In section 2.2.1, the review of literature has revealed the significance of built environment MS in the context of sustainable resource consumption. The literature forming such an understanding within the Global South is presented and evaluated in section 2.2.3. In this context, we have seen the widespread uptake, and thus the suitability of, the bottom-up material stock analysis approach, reviewed in section 2.2.2, to understand key characteristics of MS accumulation and reveal challenges and opportunities to sustainable resource use in the future. Such assessments of built environment MS provision within cities of the Global South have begun to reveal challenges to the efficiency of future urban development. For example, we have seen that the existence of lock-in effects resulting from long-lasting MS as well as the composition of stocks holds important implications for resource efficient development. However, the existing literature remains limited for many nations of the Global South and there therefore remains a clear need for further empirical studies in many nations, particularly in combination with assessments of living standards, to further understand pathways to equitable and resource efficient MS provisioning.

Section 2.3 reviews the literature beginning to relate built environment MS to measures of socioeconomic development. Here we have seen that the pursuit of economic growth has driven the accumulation of in-use built environment MS across scales, from nations to cities. However, we have seen that many now argue the need to go beyond measures of economic growth to better understand the relationship between service provision and the associated in-use built environment MS. This has been a key motivation of stock-flow-service nexus research presented in section 2.3.1, where we see that only recently have studies begun to assess energy and material consumption associated with service provision. The research to-date has revealed a global trend of in-use MS growing in conjunction with living standards which highlights alarming trends, particularly for those nations in the Global South which are at incipient stages of such growth. However, without going beyond broad metrics of development and economic growth on a global scale, the implications for sustainable development in terms of adequate service provision, i.e., the provision of basic needs, remains unclear for many nations. We have therefore seen that there remains a clear need for further empirical studies addressing this relationship at sub-national scales and providing more comprehensive assessments of service provisioning which better defines the stock-flow-service nexus in question. Further, existing literature has quantified the resource demand for providing basic needs based on minimum service provisioning nationally. Such studies have highlighted the significant challenge of service provisioning to ensure minimum living standards on global resource consumption. However, there remains a lack of insight into the required quantity of built environment MS based on existing trends of basic service provision for many nations and therefore an understanding of the extent to which minimum service provisioning may itself reduce resource demand.

In section 2.3.2, the review of literature monitoring development outcomes has revealed methodological approaches with which to ensure improved assessments of service provision within stock-flow-service nexus research. We have seen how key methodologies are able to capture the variation in measured outcomes and enhance the policy implications of such assessments. Specifically, this relates to the analysis of outcomes across scales of analysis as well as by using complementary metrics which may also offer improved insight into the achievement of interconnected SDGs. This is particularly important given that cities are now becoming central to achieving the Global Agenda. The review of such methodologies highlights the lack of comprehensive insight into service provisioning within and across many nations and thus the shortcomings of existing assessments of service provision within SFS-nexus research. As such, there remains a clear gap in the integration of assessments of service provision, or basic needs outcomes, within MS assessments.

There therefore remains a clear gap in our understanding of the relationship between the provision of built environment MS and the associated standards of living. There is a clear need to quantify such coupling sub-nationally to understand challenges and opportunities to sustainable development within nations of the Global South such that the resource requirements to meet minimum living standards are achieved in ways that limit overconsumption of built environment MS in the future.

2.4 Summary of research needs

Table 2.1: The identified research gaps and the associated research questions and objectives addressed in the respective chapters.

Chapter	Summary of research gap	Research question	Summary of objectives
3	Lack of a comprehensive quantification of the extent to which minimum standards of living associated with the provision of built environment MS are achieved within many nations, particularly considering the implications of scale and metric formulation to reveal national trends.	To what extent do households in India experience deficits in basic needs relating to non-mobile built environment stocks?	Measure household deprivation to basic services provided by non-mobile built environment MS across scales using complementary metrics.
4	Lack of insight into the coupling of built environment MS and minimum living standards at national and sub-national scales.	Does a relationship exist between the composition of non-mobile built environment MS and basic needs outcomes?	Quantify the relationship between household deprivation to basic services and the composition of built environment MS.
5	Lack of city and sub-city analysis of built environment MS accumulation, particularly within India, and its relationship to minimum standards of living.	What is the built environment material stock accumulation within a city with high basic needs outcomes in India?	Quantify built environment MS at the city- and sub-city scale and examine the extent to which this has facilitated high standards of living.
6	Lack of a quantified understanding of the MS requirements following existing national trends of MS provision and the consequent impacts on minimum living standards.	What are the MS requirements and consequent impacts on basic needs resulting from the upgrade of inadequate housing nationally?	Based on the existing trends identified in Chapters 4 and 5, quantify the required MS to upgrade inadequate housing and the changes to standards of living nationally.

3 Scale and inequality of urban infrastructure and housing provision

3.1 Introduction

As we have discussed in Chapter 2, there is a need to better capture standards of living resulting from basic service provisioning, i.e., basic needs outcomes, within stock-flow-service nexus (SFS-nexus) research such that benefits of sector-specific services and associated material stocks (MS) can be related. Here, we aim to comprehensively take account of the living standards relating to non-mobile built environment MS and therefore seek to answer the following research question by furthering the measurement of service provision within the stock-flow-service nexus:

- To what extent do households experience deficits in basic needs outcomes relating to non-mobile built-environment material stocks?

We do so by integrating key methodological considerations for measuring development outcomes. This enables the stock-service relationship to be clearly defined and understood within a national context such that policy implications are enhanced beyond national averages. Currently, the use of existing macro-scale metrics may obscure such analysis and thus the policy implications of results for numerous reasons. Firstly, monetary measures such as GDP do not directly quantify the extent to which societal services associated with MS provisioning provide outcomes of living standards and are generally deemed poor proxies for assessing such human outcomes (19,102). This points to the use of existing metrics assessing outcomes of service provisioning, such as the Social Progress Index, which emphasize the role of societal services in meeting basic needs. However, such metrics include multiple dimensions or indicators which do not themselves relate to MS provisioning and therefore do not relate to the stock-service relationship in question. Adopting such metrics may therefore result in an unclear definition of the SFS-nexus in question and obscure the perceived relationship between the provision of MS and standards of living. Additionally, such metrics are often applied at single and often highly aggregated scales of analysis, i.e., nationally, which may overlook key characteristics of service provision due to the presence of inequalities, which are central to many challenges surrounding the measurement of development outcomes (6), as discussed in section 2.3.2. This may result in regressive policy regarding the perceived requirements for MS which has disproportional impacts for those furthest behind. This points to the need to adopt multiscale frameworks that go beyond national averages by using context-specific metrics, agreed upon by many scholars assessing basic needs and monitoring progress towards the Sustainable Development Goals (6,7,19,132,163).

As we have discussed in section 2.3.2, basic needs generally refer to 'functionings' essential to survival and avoiding serious deprivation (123,128). As such, dimensions of basic needs are often measured through outcome-orientated approaches (128) and feature in studies addressing challenges faced by informal settlements or slum populations[7] (133,134,171). A variety of metrics have been formulated within the literature addressing deprivation and urbanization to measure outcomes relating to basic needs in the Global South (6,7,131,133,134). While the number of dimensions of basic needs varies between studies, access to basic services, namely: housing, sanitation, water and electricity, has been a common measure of basic needs in the Global South (6,7,130,131,133,138) all of which which relate to key non-mobile built environment MS. Non-mobile built environment material stocks are defined as stationary stocks of material within the built environment such as buildings and infrastructure and broadly relate to residential and non-residential buildings, as well as transport, communication, and energy infrastructure. Such basic service provisioning is also considered by the UN as essential for expanding basic capabilities (123) and is indicated by SDG 1.4.1 which measures the proportion of the population with access to basic services. This SDG indicator is itself related to many service-specific indicators which assess the proportion of the population with access to adequate housing, water supply, sanitation, and electricity (159,172). Further, these dimensions are included within the *shelter* and *living standards* dimensions of the decent living standards (DLS) literature which propose material requirements for an irreducible set of dimensions conducive to a minimum standard of living (116). The dimensions relate to adequate access to housing, electricity[8], water and sanitation and have informed the selection of indicators with which to assess the energy requirements for decent living standards nationally in India, South Africa and Brazil (117). The measurement of such basic service access is therefore a common approach to assess basic needs outcomes in the Global South and clearly defines the SFS-nexus in relation

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[7] It is important to note that studies often define slum populations as those deprived of basic human needs, however studies have also shown that such deprivation is not necessarily concentrated within slum populations and may be a widespread challenge across urban areas in the Global South (4,6).

[8] While electricity access may be indirectly related to built environment MS, it does rely on generation and transmission infrastructure which inherently rely on activities of non-mobile built environment MS such as the building of power stations and the laying of cables. It is also proposed as a key collective provisioning system for which households rely upon within the DLS literature (116).

to basic needs provided by non-mobile built environment MS. Formalizing these dimensions into a composite index using the methods discussed in section 2.3.2 may offer additional insight into overall basic needs outcomes as well as the relative contribution of dimensions to overall basic needs, thus offering insight into specific stock-service implications.

There is also a clear need to go beyond average measures of outcomes at single scales of analysis or within single urban areas. This is needed to better capture characteristics of service provision to develop a comprehensive understanding of equitable built environment MS provisioning (6,7,19) and ensuring no one is left behind as part of the commitment to the Global Agenda (159). Multiscale approaches have been proposed which reveal key policy implications by addressing concerns surrounding distributional effects (6,7). The multiscale framework assesses inter-urban inequalities to reveal both overall trends of service provision at sub-national scales and their variation across scales. This addresses limitations associated with the aggregation of areal units which presents opportunities to better capture implications for social provisioning systems, such as governing bodies, to inform equitable resource provisioning, discussed in section 2.3.2.1. However, the methodological approach (6,7) relies on a single average measure and thus contains inherent ecological fallacies such that intra-urban challenges may be overlooked resulting in regressive policy. In order to go beyond inherent ecological fallacies incurred due to the reliance of average measures on areal data such as censuses, scholars now recommend the monitoring of outcomes using complementary metrics, arguing that frameworks providing alternative understandings of the same problem are needed to address interconnected problems (163). However, there remains limit application of complementary assessments to shed light on various characteristics of living standards. The comparison of multidimensional deprivation, capturing the intra-urban distribution of societal service provision among households, with such multiscale assessments may shed light on the complexity of intra- and inter-urban outcomes and better capture distributional challenges relating to the provision of services (158).

3.2 Methodology

Here we combine existing methodologies in a new context to test the developed approach and comprehensively monitor the extent to which non-mobile built environment services are provided within urban India. Firstly, we adopt an average measure of basic needs outcomes across scales of analysis (6) to quantify service outcomes and capture their variation in the national context. We then compare outcomes measured by averages with a novel multidimensional poverty metric to provide enhanced insight into the intra-urban challenges, complementing the observed national trends at various administrative scales.

3.2.1 Data sources

Two key sources of household data provided by the Government of India (GoI) are used to assess basic needs outcomes. Firstly, we use the comprehensive data provided within the Census of India for the year 2011 (173) to measure the average basic needs outcomes and associated inequality. We adopt data pertaining to household access to amenities and assets which records the percentage of households with access to various basic services. From this dataset we are able to identify the dimensions discussed previously, which are presented in Table 3.1. We therefore adopt the census data to formulate a *sustainable development index* (SDI) (6) measuring the average household outcomes of basic needs relating to water, sanitation, housing, and electricity.

Table 3.1: Dimensions used to formulate the sustainable development index (SDI) measuring the average outcomes of basic service access using census data for the year 2011 (173). The definitions broadly relate to those from analyses in South Africa and Brazil (6) and are related to their respective SDGs and indicators based on their definition and identified interconnectivity presented by the UN (123,159,172).

Dimension	Definition	SDG reference	
Sanitation	Flush/pour latrine (piped sewer system, septic tank or other) or pit latrine with slab/ventilated improvement	SDG 6.2.1	SDG 1.4.1
Main source of drinking water	Tap water from treated source	SDG 6.1.1	
Availability of drinking water source*	Drinking water found within the premises	SDG 6.1.1	
Housing	Permanent housing	SDG 11.1.1	
Electricity	Electricity used for lighting	SDG 7.1.1	

**Availability of drinking water source is combined with the main source of drinking water indicator in previous studies in Brazil and South Africa due to the aggregation of each indicator in the respective census datasets* (6)*. The Census of India records this indicator separately and is therefore included explicitly within the SDI. We present Spearman and Pearson correlation to identify appropriate water dimensions within section A.2 of Appendix A.*

The National Sample Survey (NSS) (174) is then used to formulate a *decent living standards index* (DLSI). The NSS records all shelter and living standards dimensions from the DLS framework, which are presented in Table 3.2. The NSS is a nation-wide survey recording estimates on household characteristics such as the condition of the structure and the adequacy of the ventilation. The survey was compiled between July 2008 and June 2009 and was conducted using the interview method of data collection from a random sample of households. It covers the whole of the Indian Union except a selection of villages to which this study is not sensitive given that villages are defined as rural and we focus here on the urban areas of India. The sampling covers 56,374 households and corresponds to 4,734 Urban Frame Survey blocks which are used to define sample areas within towns and cities (174). As such, the dataset is less comprehensive than the census and therefore the comparison of both indices omits a selection of towns and cities as well as states.

Table 3.2: Dimensions used to formulate the decent living standards index (DLSI) measuring the multidimensional deprivation of households using NSS data (174). The definition of dimensions presented by the NSS are used to indicate each dimension and are verified in relation to the definitions presented in the decent living standards literature (116).

DLS dimension	**Household requirement**	**Definition as per the NSS**	**DLS definitions** (116)
Shelter	Solid walls and roofs	If both the walls and roofs are constructed from: brick/stone/limestone, timber, or cement/RBC/RCC then the household is considered to have access to solid walls and roofs.	Solid walls and roofs: brick, wood, concrete, or cement/steel construction
Living conditions	Sufficient, safe space	Total floor area of the household, ft^2	Minimum of $30m^2$ and $10m^2$ per additional person, above a household size of three
	Basic comfort (bounded temperature/ humidity)	If the majority of the rooms have at least one or more windows enabling cross ventilation	Modern heating/cooling equipment, if necessary, to remain within comfortable conditions
	Water Location of drinking water Sufficiency of drinking water*	A household will be considered as having an adequate source of drinking water if the main source of drinking water is from a tap, within the premises, and which is sufficient throughout the year.	Adequate, reliable water supply (minimum of 50L per capita per day) from accessible water source
	Sanitation	A household will be considered as having access to an adequate latrine if the type of latrine is a service, pit or septic tank/flush facility.	In-house improved toilets
	Electricity	A household will be considered as having an electric supply if it has electricity facilities for domestic use.	Electrical supply as a collective requirement

3.2.2 Scales of analysis

The GoI outline the multiple sector interventions at different administrative scales in their recent Reforms in Urban Planning Capacity (175). Various responsibilities reside at different administrative scales, generally ranging from the design of policy frameworks at the national and state level down to specific urban planning projects, such as master plans and urban redevelopment plans at the local administrative scale, see Table 3.3. These multiple sector planning responsibilities broadly range from national or state level responsibilities for envisioning the future development of the country which precipitates down through administrative scales, to the detailed planning of urban interventions at the local urban area, i.e., towns and cities.

Table 3.3: Examples of responsibilities of levels of planning across administrative scales as outlined by the Government of India (175).

Planning level/administrative scale	Example of responsibilities
Town and city level/Municipal Corporations	Land use planning such as development plans, master plans, building construction permits and redevelopment of inner-city areas. Mobility planning such as planning of bus/rail transit systems. Environmental infrastructure planning such as water supply and sanitation infrastructure plans.
Regional level/districts	District development plans, planning of highways and transportation. Regional infrastructure such as the planning of highways and transportation infrastructure.
National/state level	Policy framework such as National Urban Transport Policy and National Housing and Habitat Policy. Design of programs such as the rejuvenation of urban areas and the Smart Cities Mission as well as strategic and project planning.

The census of India provides comprehensive coverage of access rates to basic services across urban India for each administrative scale which are identified by a location code. The location code directory of the Indian Census is formulated as per the recommendations of the Metadata and Data Standards Committee which adopts a new coding pattern for various administrative divisions which generally relates to governmental organizations (173). The scale of urban administrative units begins with *wards,* which are the lowest aggregation of urban areas local to *towns,* which are themselves grouped into *sub-districts,* further into *districts,* and finally into *states,* illustrated in Figure 3.1.

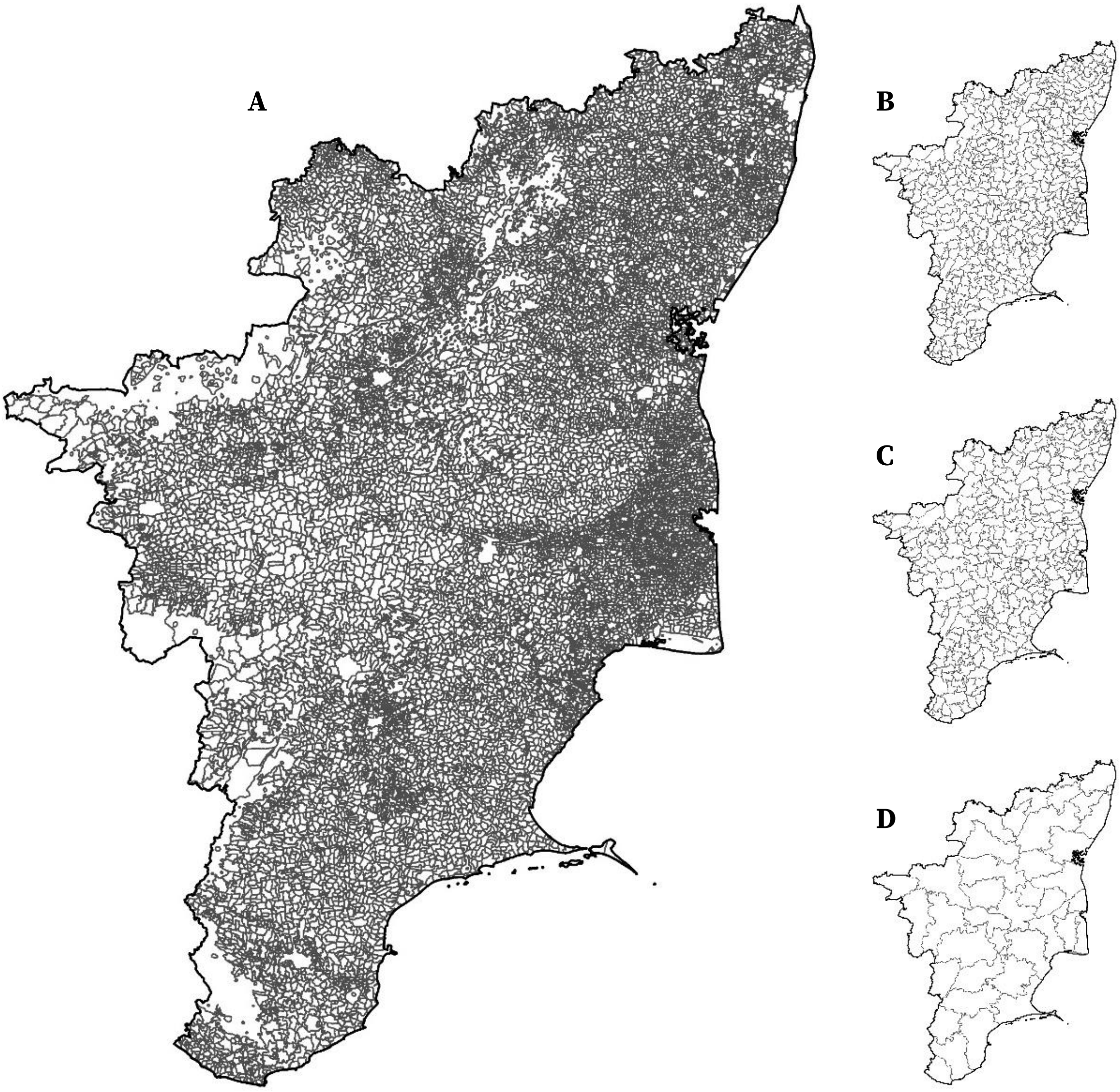


Figure 3.1: Indicative diagram of the administrative scales of (A) wards, (B) urban local bodies, i.e., towns and cities, (C) sub-districts, and (D) districts, for the state of Tamil Nadu. Note that the boundary of the figures indicates the state boundary for Tamil Nadu. The evaluation of scale effects follows the aggregation of wards, i.e., the administrative units within figure A, to the various administrative scales from B-D.

Towns are defined either as statutory towns, census towns or cities. Statutory towns relate to administrative units defined by a statute or local governing body such as a Municipal Corporation. Census towns are defined by the simultaneous achievement of three criteria: 1) a minimum population of 5,000 persons, 2) 75% or above of the male main working population engaged in non-agricultural pursuits, and 3) a population density of at least 400 persons/km^2. Cities are then classified as census towns with a population of 100,000 or above (173). We do not further disaggregate census towns by the varying definitions and therefore refer to the scale of towns as towns and cities. The NSS data adopts a different location code directory which lists the regional and sub-regional office, the name of the district and the associated state. The listed sub-regions correspond to a less extensive set of towns and cities compared the census dataset which can be aggregated into states corresponding with the census data. It is therefore possible to consolidate a selection of towns and cities within the NSS dataset to those towns and cities, and corresponding states, within the census dataset. This means that the measured outcomes are placed at the scales of intervention for which key responsibilities reside as per the GoI which may therefore enhance the policy implications of future service provision.

3.2.3 Initial data processing

To assess inter-urban inequality and multiscale effects, we aggregated the wards, i.e., the local urban areas of India, to their respective towns and cities, sub-districts, districts, and states. As we will see, inter-urban inequality is measured using the multiscale methodology developed in a previous study (6) which relates the mean and standard deviation of access rates for each aggregated scale. We therefore initially process the appropriate urban areas for analysis by including those towns or cities containing at least 30 wards as a rule-of-thumb to increase the confidence interval of the dataset when assessing the mean and standard deviation of basic needs outcomes. We present sensitivity analysis of this assumption on the results within *section A.3.2* of *Appendix A*. We then consolidate scales of analysis with the NSS data by manually comparing sub-regional office names with towns or cities present within the census dataset. These are then further aggregated into their corresponding states and verified through manual inspection of state names within the NSS and census dataset. The NSS indicates that states are divided into regions “by grouping contiguous districts similar in respect of population density and crop pattern” (174). While data on the geographical coverage of both datasets is unavailable, it is reasonable to assume that the urban areas evaluated for both metrics cover the same administrative area and are broadly coherent. The results of the initial data processing are presented in Table 3.4 and Table 3.5, providing summary statistics for the census and NSS datasets respectively. It is important to note that towns and cities as well as states are the only consistent scale of analysis between datasets.

Table 3.4: Summary data of household counts for wards, towns/cities, sub-districts, districts, and states. See Appendix A Table A.8 for a summary of the overlapping divisions and a sensitivity analysis of the results to the overlapping administrative divisions.

Statistics	Wards	Towns/cities	Sub-districts	Districts	States
No. of data points	23,192	524	486	321	24
Maximum	156,619	2,101,831	2,101,831	2,101,831	8,684,761
Minimum	1	6,289	6,289	8,518	17,807
Mean	1,759	77,853	83,941	127,087	1,699,798
Std. dev.	3,614	176,993	189,193	245,757	2,004,313

Table 3.5: Summary data for the NSS data of households, listing the number of towns/cities and states which are coherent with the census data administrative divisions and the respective household counts.

Statistics	Towns/cities	States
No. of data points	117	21
Maximum	3,614	7,937
Minimum	72	275
Mean	373	2,079
Std. dev.	473	1,908

3.2.4 Sustainable development index

We firstly formulate an average measure of basic needs outcomes using census data recording the percentage of households within each ward with access to the respective service. The SDI is formalised into a composite index which measures the average achievement of basic needs outcomes within a given urban area. The areal household access data is bound between 0 and 1 indicating a range of access in respective dimensions from 0% to 100% respectively. The dimensions are then aggregated via a geometric mean, *equation 1*, to create the final index for all wards which are present within towns and cities containing over 30 wards. We also note the evolution of the HDI from an arithmetic to a geometric mean and carry out sensitivity analysis to illustrate the implications of this on the estimated average inequality, presented within *section A.3.2* of *Appendix A*.

$$X_i = \sqrt[n]{\prod_{j=1}^{n} X_i^j} \qquad [1]$$

Equation 1 shows the aggregation of n dimensions, for area i, to calculate the SDI, X_i. No weighting is used for the SDI and therefore the overall index is a measure of the non-weighted average achievement of the normalised dimensions (176). As we have discussed in Chapter 2, the geometric mean is often adopted to capture outcomes such that the emphasis is on the achievement of all dimensions, implying that they are not substitutional, with no weighting adopted to avoid the normative judgement of the relative importance of each dimension (131). This is fitting with the notion that universal access to basic services is required as part of achieving the various SDGs and for providing a minimum standard of living. We therefore formalise the SDI as in *equation 2,* with dimensions listed in Table 3.1 and with the adopted definitions of achievement being coherent with the literature addressing minimum standards of living (6,116,177) as well as broader monitoring imperatives such as the MPI (178) and SDGs (159).

$$X_i = \sqrt[5]{X_i^{water} X_i^{water\ location} X_i^{housing} X_i^{sanitation} X_i^{electricity}} \qquad [2]$$

3.2.4.1 Inter-urban inequality and basic needs profiles

We explore the national basic needs profile of basic needs outcomes by evaluating the average inter-urban inequality in the SDI across administrative scales. We follow the overarching methodology outlined in previous studies assessing inequality of basic needs outcomes in South Africa and Brazil which measure the relative levels of spatial inequality in basic service access between regions (6). The SDI is bound between 0 and 1 when considering area, i, to have either presence, X_i = 1 or absence, X_i = 0, of basic services. The definition of the SDI is such that the variance must be a function of the mean, tending to zero when infrastructure services are provided universally, X_i = 1, or are completely absent, X_i = 0. The variance of X is therefore typically maximum where the mean SDI, $\bar{X}_i$, is equal to 0.5 owing to a greater number of possible variations in access within area, i, leading to a greater possible dispersion from the mean, i.e., when half of the data points have access to services, X_i = 1, and the other half have access to services, X_i = 0. We can therefore parameterize the standard deviation of X_i, σ_i as:

$$\sigma_i = b_i \sqrt{\bar{X}_i\,(1 - \bar{X}_i)} \qquad [3]$$

where the square root corresponds to the standard deviation of a random Bernoulli process (6). As a result, the maximum and minimum variance for each value of $\bar{X}$ is $b = 1$ and $b = 0$ respectively. The properties of the standard deviation dictate that $b \geq 0$ and therefore profiles of outcomes are characterized by b_i given $\bar{X}_i$. Figure 3.2 illustrates how basic needs profiles in the space of $(\bar{X}_i, \sigma_i)$ are formed and relate to the inequality index, b_i. We calculate the average inequality index, b, for each scale by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ which is used to characterise profiles as a function of space and time as outcomes change in each unit i and the values $(\bar{X}_i, \sigma_i)$ tend to (1,0). Given we use cross-sectional data here, we consider the dimension of space indicated by the administrative regions given within the census data and limit the analysis to the year 2011. We also conduct this analysis for the decomposed SDI and therefore evaluate the inequality in dimensions that comprise overall basic needs. The basic needs profile exhibits behaviour typical of a Kuznets curve (179) where the profile of maximum inequality, $b = 1$, peaks where $\bar{X}_i = 0.5$, and reaches maximum and minimum where $(\bar{X}_i, \sigma_i)$ is (1,0) and (0,0) respectively.

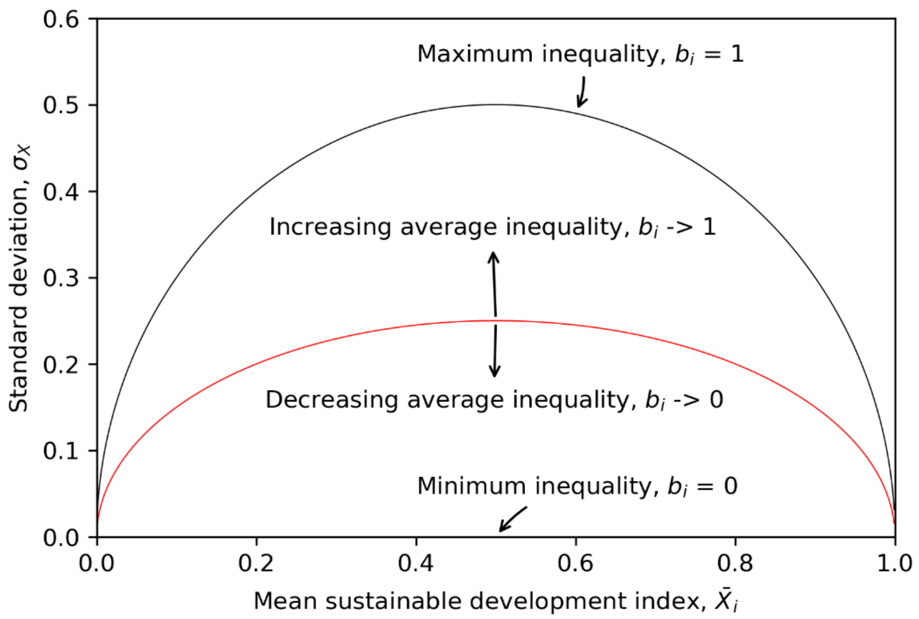


Figure 3.2: Illustration of the plotted national basic needs profile which are calculated for different aggregated urban units. The basic needs profile is characterised by the average inequality index, b, calculated by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ where the intercept is fixed at zero. The regression uses population weighted least squares (WLS) regression and White-Huber-Eicker standard errors to account for heteroskedasticity in errors, *see Appendix A*.

3.2.5 Decent living standards index (DLSI)

We complement the analysis of basic needs outcomes by going beyond the average assessment of the SDI, which contains inherent statistical limitations due to the reliance on areal data, by computing an associated DLSI. The index is formulated by adopting the Alkire-Foster method (180) and in doing so captures the distribution of service access among households *within* urban areas. The index formalizes the dimensions of shelter and living conditions within DLS into a multidimensional poverty index for the first time. It therefore provides additional resolution of the deficits in basic needs among households by integrating two further dimensions relating to floor space and ventilation strategies within households and measuring intra-urban distributional challenges. The methodology and available data also enable the separate dimensions for water type and location, as in the SDI, to be formalised into a single dimension. The approach is outlined below using an example of four dimensions and the notation style as used by the United Nations Development Programme for clarity and transparency (158).

3.2.5.1 Definition of achievement and the deprivation matrix

Firstly, dimension profiles are created for each household. This contains raw data for each dimension at the household level, formally represented in the achievement matrix. Using definitions of achievement as outlined in Table 3.2, the deprivation cut-off for each dimension, z_j, is set and a binary score assigned to each dimension for all households. This results in the deprivation matrix, g_0, that lists each household as either deprived, scoring 1, or not deprived, scoring 0, in each dimension, thus containing x_{ij} variables for all dimensions for each household. This is shown more formally below:

$$x_{ij} = \begin{cases} 1 & if\ x_{ij} < z_j \\ 0 & otherwise \end{cases}$$

$$g_0 = \begin{array}{ccccc} X_1 & X_2 & X_3 & X_4 & Household\ no. \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 2 \end{array}$$

where x_{ij} is the value of achievement for household, i, in dimension, j, and g_0 exemplifies the formalization of all x_{ij} variables into the example deprivation matrix.

3.2.5.2 Weighted deprivation matrix and deprivation score

Weights can be introduced to each of the dimensions. In this case, the index contains equally weighted dimensions for the reasons discussed previously. Thus, the weight vector, w, is as shown below. The sum of the weighted deprivations for each household is calculated and stored in the weighted deprivation matrix, $\bar{g}_0$, and the deprivation score, c_i, assigned to the household.

$$w = [0.25 \quad 0.25 \quad 0.25 \quad 0.25]$$

$$\bar{g}_0 = \begin{array}{cccccc} X_1 & X_2 & X_3 & X_4 & c_i & \mathit{Household\ no.} \\ 0.25 & 0.25 & 0.25 & 0 & 0.75 & 1 \\ 0.25 & 0 & 0 & 0 & 0.25 & 2 \end{array}$$

3.2.5.3 Censored deprivation matrix

A poverty cut-off vector, k, can then be used to define the extent to which a household must be deprived to be classed as poor. In this case, the value k, represents the minimum number of dimensions a household must be deprived in to be classed as poor and is expressed as a fraction due to the equal weighting used. This is shown formally below and exemplified for the case where households must be deprived in at least two out of the four dimensions, $k = 0.5$. It is important to note here that censoring is not relevant when those considered poor are defined by deprivation in at least one dimension, i.e., where $k = 0.25$, commonly referred to as the '*union approach*' (158). In the presented results, we adopt the union approach to compare deficits in basic needs with the SDI and use poverty cut offs to examine the extent to which dimension-specific deprivation contributes to overall deficits in basic needs.

$$\rho_i = \begin{cases} 1 & if\ c_i \geq k \\ 0 & otherwise \end{cases}$$

$$\bar{g}_0^{(k=0.5)} = \begin{array}{cccccc} X_1 & X_2 & X_3 & X_4 & c_i & \mathit{Household\ no.} \\ 0.25 & 0.25 & 0.25 & 0 & 0.75 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{array}$$

3.2.5.4 Calculating the incidence and intensity of poverty

The incidence of poverty, H, is calculated as the percentage of the population identified as poor out of the total population, as shown in equation 4:

$$H = \frac{q}{n} \qquad [4]$$

where q is the number of households identified as multidimensionally poor and n is the total number of households.

The intensity of poverty, A, is calculated as the average number of weighted indicators poor households are deprived in. This is therefore calculated as the average of the weighted deprivation scores among households identified as poor, shown in equation 5:

$$A = \sum_{i=1}^{n} c_i(k)/q \qquad [5]$$

The product of both factors H and A is the DLSI for the considered aggregated urban area, i.e., the specific town or state. Both factors of the final DLSI are therefore sensitive to the poverty cut-off. The DLSI is bound between 0 and 1, with 0 indicating no multidimensional poverty among households, and 1 indicating maximum multidimensional poverty among households. It is important to note here that the limits of basic needs outcomes are opposite to the SDI due to the DLSI measuring deprivation and the SDI measuring achievement. The two-household example results in a city-level $DLSI = H \text{ x } A = 50\% \, x \, 75\% = 0.375$.

$$DLSI = \frac{1}{n} \sum_{i=1}^{n} c_i(k) \qquad [6]$$

3.2.6 Summary of methods

3.2.6.1 Sustainable Development Index Calculation

1. Obtain access rates for treated tap water, water location, shelter, electricity and sanitation from the amenities and assets dataset provided in the census of India 2011 (173).
2. Aggregate household access rates (%) within each ward, for each dimension, as per the definition of access rates used in previous studies (6).
3. Form the composite SDI for all wards belonging to towns and cities containing at least 30 wards, by aggregating access rates for each dimension using a geometric mean, *see equation 2*.
4. Quantify the mean and standard deviation of the composite index by aggregating the SDI values for wards belonging firstly to 1) towns and cities, 2) subdistricts, 3) districts, and 4) states.

3.2.6.2 Inter-urban Inequality Index Calculation

1. Model the relationship between the mean, $\bar{X}_i$, and standard deviation, σ_i, of the SDI as per the Bernoulli process.
2. Using weighted least squares, regress σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ at each scale to calculate the inter-urban inequality index for each administrative scale.
3. Follow step 2 using the standard deviation and mean access rates per dimension to calculate the administrative scale and dimension specific inter-urban inequality index.

3.2.6.3 Decent Living Standards Index Calculation

1. Obtain access rates to services for each household from the National Survey Sample dataset.
2. Score each household as deprived in the service, i.e., scoring 1 if access is not achieved as per the DLS definitions, or not deprived in the service, i.e., scoring 0, for all dimensions.

3. Introduce equal weighting for dimensions, i.e., a weight of 0.167 for each dimension given there are 6 dimensions present, and multiply the value prescribed as in the previous step.
4. Sum the household deprivation score calculated in the previous two steps across all dimensions, i.e., the weighted deprivation score for all dimensions per household.
5. For each town, city, and state for which both the NSS and census are coherent, calculated the proportion of households which are deprived in at least one dimension, i.e., number of household with a score of 0.167 or higher divided by the total number of households.
6. For each town, city, and state, calculate the intensity of poverty as the average number of dimensions that the identified poor households are deprived in.
7. Finally, calculate the DLSI as the product of the values calculated in steps 5 and 6 for each town, city, and state
8. Note: step 5 is amended to understand the intensity of poverty as in Figure 3.7. This is achieved by changing the definition of poor households to those deprived in any combination of deprivation in services above deprivation in only one dimension, e.g., deprived in at least n/6 dimensions with n increasing from 1 to 6.

3.3 Results

3.3.1 Scale of service provision and associated inequality

The national level SDI is found to be 0.77 which indicates that societal services of non-mobile built environment MS results in basic needs outcomes benefiting 77% of urban households on average. This corresponds to household access rates of 84%, 79%, 62%, 71% and 93% for adequate access to housing, sanitation, treated tap water, water within the household, and electricity respectively. However, the multiscale analysis of the SDI reveals complex sub-national societal service provision and highlights the ongoing challenge of equitable built environment MS provisioning within India. By firstly focusing on the overarching trends within towns and cities, the results begin to reveal that larger towns and cities tend to have greater basic needs outcomes on average than smaller towns and cities measured by their population size. This is illustrated in Figure 3.3, where we see larger areas, i.e., larger data points, are generally located towards the bottom right of the national basic needs profile, i.e., where $(\bar{X}_i, \sigma_i)$ tends to (1,0). Also, the results show that smaller towns and cities tend to be located towards the centre of the profile, achieving intermediate outcomes with relatively high dispersion among neighbourhoods. This is verified in Figure 3.4, which indicates that larger cities tend to provide greater access to services to their residents. However, Figure 3.4 also highlights significant variation in outcomes among smaller towns and cities, with many smaller towns and cities achieving near universal basic needs outcomes. The results therefore firstly reveal that deficits in such outcomes are lower and less varied among larger urban areas and tend to be significantly higher and more varied in smaller urban areas.

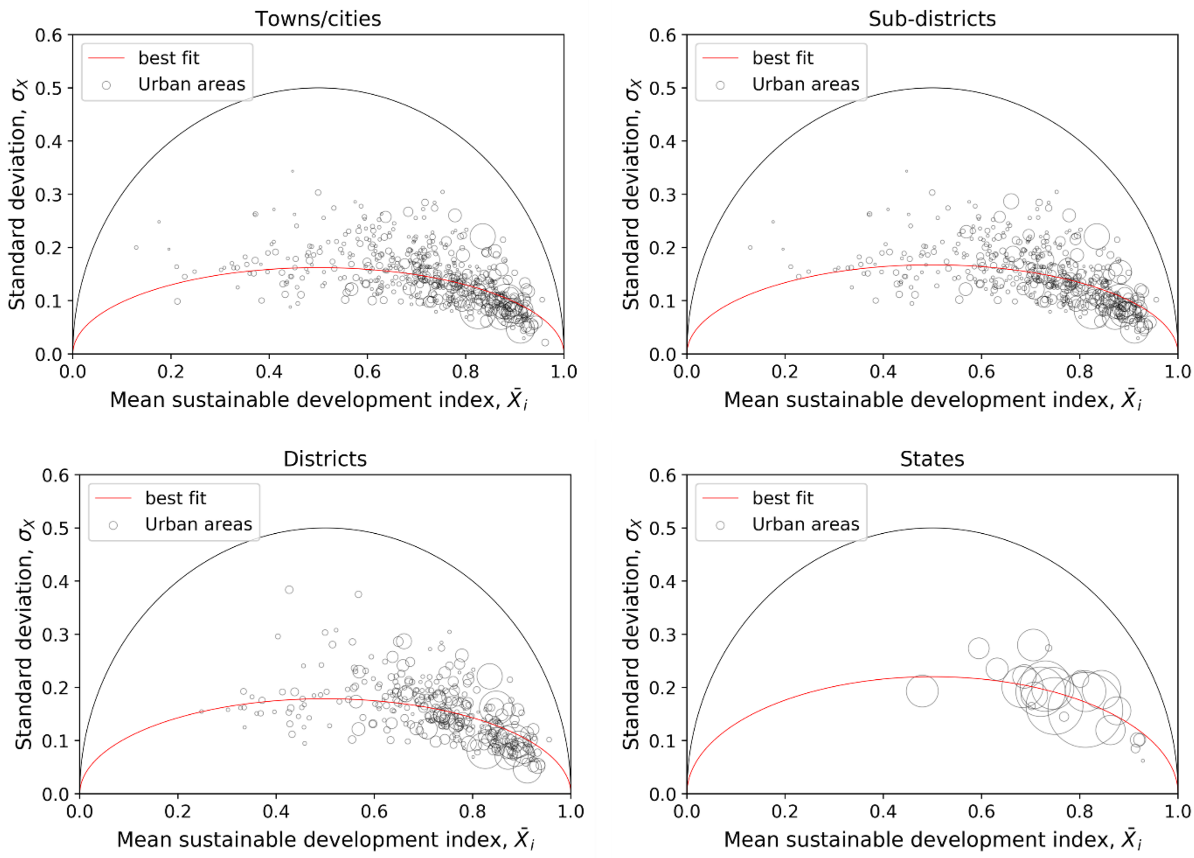


Figure 3.3: The relationship between the standard deviation of the SDI, σ_i, and the mean SDI, $\bar{X}_i$, for different administrative scales. The profiles are calculated using SDI values for wards contained within each city. The size of the circle is proportional to the total urban population. The upper black line is the boundary of maximum inequality, b = 1, and the lower black line, the x-axis, is the boundary of minimum inequality, b = 0. The red line represents the line of best fit calculated by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ using population WLS regression.

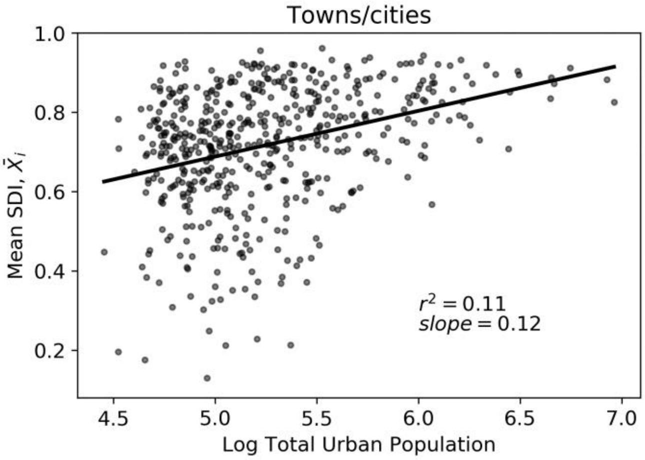
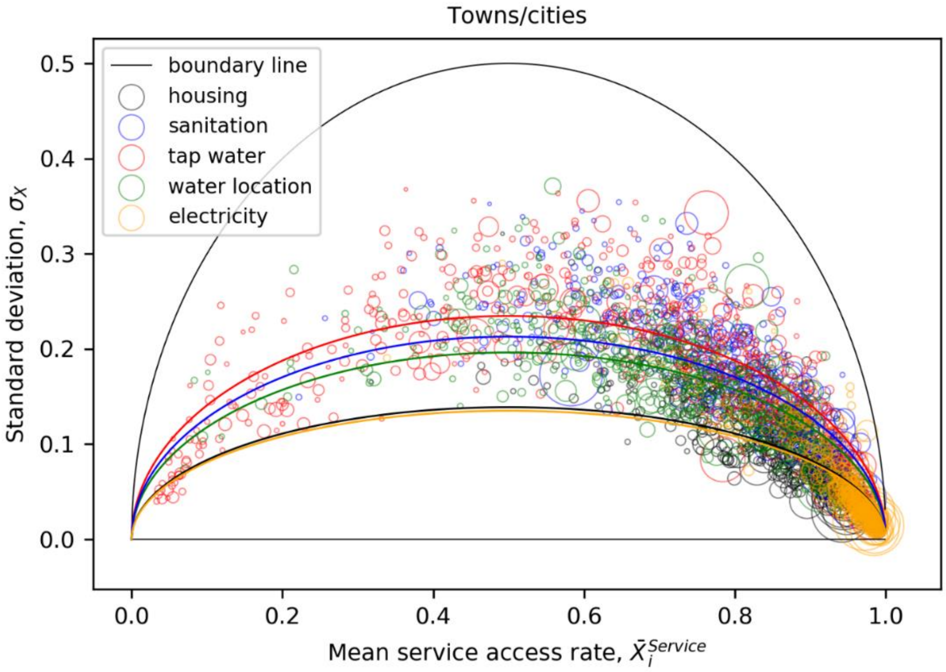
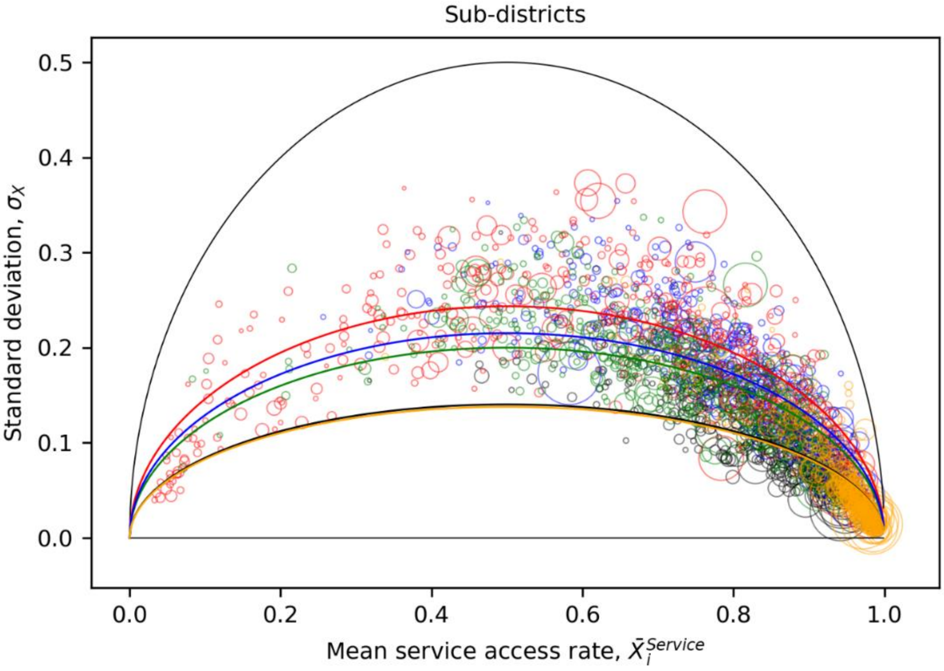


Figure 3.4: The observed trend of the mean SDI, $\bar{X}_i$, versus the logarithmically transformed total urban population for towns and cities evaluated using OLS regression.

The average inter-urban inequality at the scale of towns and cities, $b = 0.32$, is found such that outcomes are distributed in a way that is closer to an equal distribution of limited outcomes, i.e., where $b < 0.5$ and with a variation in mean outcomes, as opposed to an all-or-nothing manner, i.e., where $b > 0.5$. This also highlights that inequality among Indian towns and cities is significantly lower than those in Brazil, $b = 0.58$, and South Africa, $b = 0.57$ (6) indicated by the average inequality index. The spatial structure of these outcomes is assessed by evaluating the national profile for wards aggregated at the levels of sub-districts, districts, and states. This reveals significantly larger inequality among states than at lower scales, with outcomes statistically indistinguishable from each other between towns and cities, sub-districts and districts, see Table 3.6. The multiscale analysis of average basic needs outcomes therefore finds that deficits in basic needs are more significant between states than other scales. This is because of a higher variation in access rates among states which results in a statistically significant difference in average inequality at this scale, indicating that built environment MS provisioning is more of a regional challenge within India. This is also consistent with the findings in Brazil and South Africa (6).

By decomposing the SDI, it is possible to identify the relative challenge of each dimension to overall basic needs outcomes, with results revealing that access to water and sanitation are most challenging to basic needs, see Figure 3.5. These dimensions experience the most significant inter-urban inequalities at each scale and therefore have much higher variation in access rates compared to housing and electricity access. However, the results also highlight a significant mixing of outcomes across urban areas. This is particularly the case for water and sanitation dimensions which have a significant variation in the severity of challenges between urban areas of predominantly smaller populations, i.e., a range of mean access rates and dispersion of access rates among smaller data points shown in Figure 3.5.





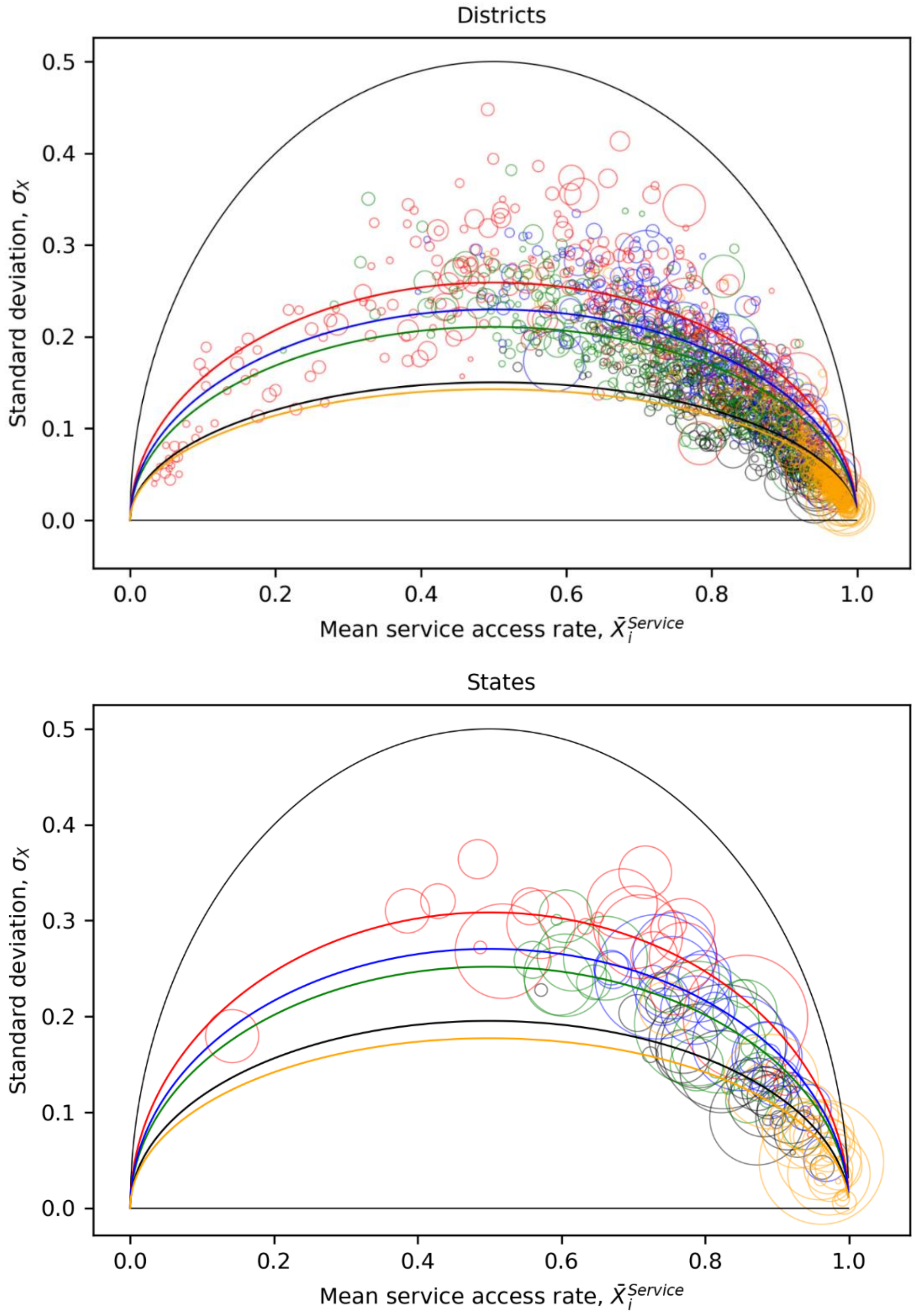


Figure 3.5: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising SDI at each administrative scale, indicated at the top of each of the subplots. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

The trajectories for each dimension are calculated by regressing $\sigma_i^{service}$ on $\sqrt{\bar{X}_i^{service} - (\bar{X}_i{}^{service})^2}$ using population WLS regression.

The relative challenge of each dimension remains the same across scales, with access to electricity being largely a solved problem and with the most equally distributed access across urban areas, with access to treated tap water being the most challenging and unequally distributed. The results also show that the distribution of treated tap water at the state-level is closer to an all-or-nothing case and reveals the increased scale of unequitable built environment stock provisioning at this level. While inequality indices specific to each dimension of the SDI are not calculated for Brazil and South Africa, there are key differences between all three nations highlighting context-specific implications for built environment stock provision. For example, deficits in permanent housing and sanitation are found to be most significant in Brazil and South Africa respectively, whereas deficits in access to water infrastructure are most challenging in India. There also seems to be significantly higher inequality in the provisioning of these services in these nations, whereas India has a more even distribution of, albeit limited, access to respective services. However, due the nature of data and aggregation methods of the SDI, there remains ecological fallacy such that the distribution of access rates among households *within* the urban areas considered may be overlooked. We now turn to the DLSI to reveal the joint distribution of deficits in basic needs among households.

Table 3.6: Average inequality among dimensions for each scale of analysis calculated by regressing $\sigma_i^{service}$ on $\sqrt{\bar{X}_i^{service} - (\bar{X}_i^{\,service})^2}$ using population WLS regression.

Scale	Dimension	Estimate, b	95% CI	Fit, r^2
Towns/cities	SDI	0.32	[0.30, 0.35]	0.91
	Treated tap water	0.47	[0.44, 0.50]	0.93
	Sanitation	0.43	[0.40, 0.45]	0.94
	Water location	0.39	[0.37, 0.41]	0.94
	Housing	0.28	[0.27, 0.29]	0.90
	Electricity	0.27	[0.25, 0.29]	0.84
Sub-districts	SDI	0.33	[0.31, 0.36]	0.91
	Treated tap water	0.49	[0.45, 0.52]	0.93
	Sanitation	0.43	[0.41, 0.46]	0.95
	Water location	0.40	[0.38, 0.42]	0.94
	Housing	0.28	[0.27, 0.29]	0.90
	Electricity	0.28	[0.26, 0.30]	0.85
Districts	SDI	0.36	[0.33, 0.38]	0.91
	Treated tap water	0.51	[0.48, 0.54]	0.93
	Sanitation	0.45	[0.42, 0.49]	0.95
	Water location	0.42	[0.39, 0.44]	0.94
	Housing	0.30	[0.28, 0.32]	0.91
	Electricity	0.29	[0.27, 0.31]	0.86
States	SDI	0.44	[0.41, 0.47]	0.98
	Treated tap water	0.61	[0.57, 0.65]	0.99
	Sanitation	0.54	[0.51, 0.56]	0.99
	Water location	0.50	[0.47, 0.53]	0.99
	Housing	0.39	[0.35, 0.43]	0.98
	Electricity	0.36	[0.28, 0.43]	0.94

3.3.2 Multidimensional deprivation in basic needs

The results of the DLSI reveal a variety of outcomes associated with non-mobile built environment service provision among households for towns and cities as well as states. The incidence and intensity of poverty are firstly measured by identifying poor households as those which are deprived in at least one dimension of the DLSI, i.e., poverty cut-off as per the union approach, $k = 1/6$. The results presented in Figure 3.6 reveal that multidimensional deficits in service access remains a significant challenge within the urban areas of India, with poor households generally deprived in at least one-third of all dimensions on average, i.e., $A > 0.33$. Nearly all urban areas have over 75% of the sampled urban population deprived in at least one dimension of DLS, however the incidence and intensity of deprivation varies significantly and highlights varying scale of challenges across urban areas.

Figure 3.7 reveals that access to adequate housing and a minimum floor area within the household contribute most significantly to multidimensional deprivation in housing and urban infrastructure provision nationally, closely followed by adequate sanitation and water. By increasing the poverty cut-off, k, the results incrementally reveal the dimensions contributing to extreme deprivation. This shows that adequate ventilation and access to electricity within the household do not change significantly across poverty cut-offs. Households experiencing deprivation in such dimensions are generally deprived in up to four dimensions, indicated by a similar percentage of poor households deprived in these dimensions across poverty cut-offs. This indicates that a lack of adequate ventilation and in particular electricity supply may be appropriate indicators of extreme deficits in basic needs outcomes. The DLSI also agrees with the SDI in that water and sanitation are key challenges to overall basic needs outcomes. However, the DLSI reveals that deprivation in characteristics of adequate housing may be more challenging to overall basic needs than other dimensions, unlike the trends identified by the SDI. Figure 3.7 shows that such deprivation accounts for a significant share of multidimensional poverty among households, indicated by the relative height of the bars, i.e., deprivation in each dimension, across the various poverty cut-offs, i.e., the proportion of dimensions households are deprived in to be classed as poor. Adequate shelter and floor space are shown to contribute a significant proportion of deficits in basic needs nationally and are the most prevalent deprivations among households with at least one deprivation, i.e., $k = 1/6$. Further, deprivations in floor area and adequate shelter are found to be highly prevalent among households experiencing multidimensional deprivation, i.e., $k > 1/6$.

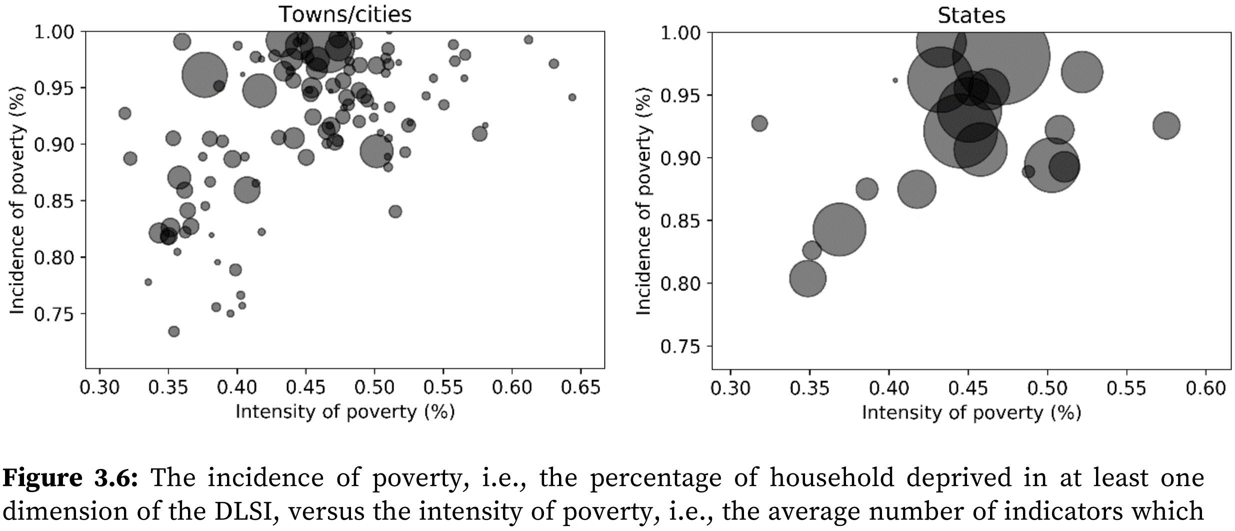


Figure 3.6: The incidence of poverty, i.e., the percentage of household deprived in at least one dimension of the DLSI, versus the intensity of poverty, i.e., the average number of indicators which those identified as poor are deprived in.

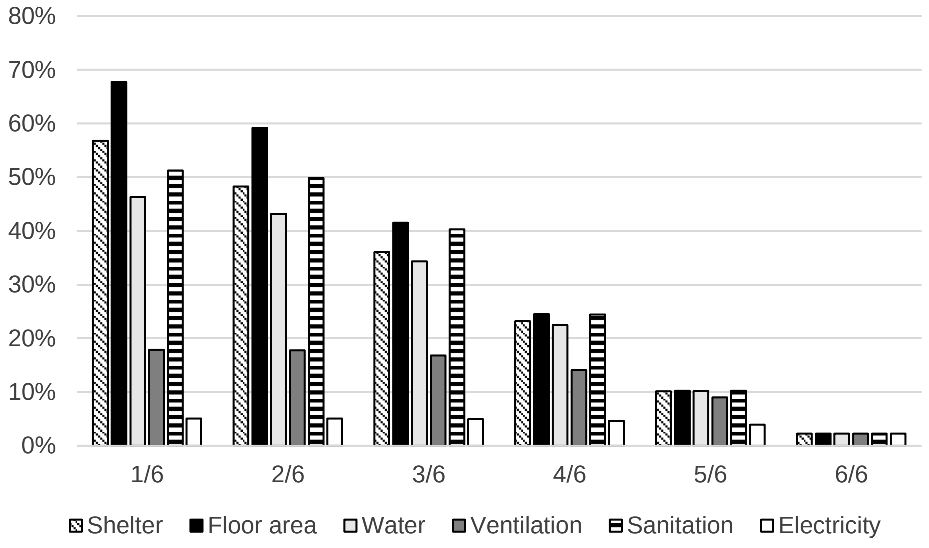


Figure 3.7: Percentage of the population who are DLSI poor and deprivation by indicator. The poverty cut-off is used to define the proportion of dimensions required to be defined as poor e.g., 2/6 corresponds to households being defined as DLSI poor if deprived in at least 2 out of 6 dimensions.

The SDI and DLSI are compared in Figure 3.8 where a general trend of increased average outcomes and reduced multidimensional poverty is observed. However, there remains significant variation in this relationship. Figure 3.8 reveals a high variance in the DLSI across urban areas for high levels of the SDI. This suggests complex intra-urban inequalities in terms of the distribution of access rates among households for areas achieving high average outcomes. Areas achieving high average outcomes therefore do not always indicate low levels of multidimensional poverty among households, with some urban areas experiencing significant multidimensional poverty in DLS among households despite near universal access rates on average. For example, the Municipal Corporation of Vijayawada, with a population of over one million, achieves high average outcomes, $SDI = 0.93$, as well as high overlapping deprivations, $DLSI = 0.46$. Whereas, the Municipal Corporation of Patiala, with a population a little over half of that of Vijayawada, exhibits the lowest rate of overlapping deprivations, $DLSI = 0.26$, whilst achieving high average outcomes, $SDI = 0.92$. Therefore, while the multiscale assessment has highlighted ongoing inter-urban challenges, results of the DLSI have revealed persistent and complex intra-urban challenges which may be significantly overlooked by averages.

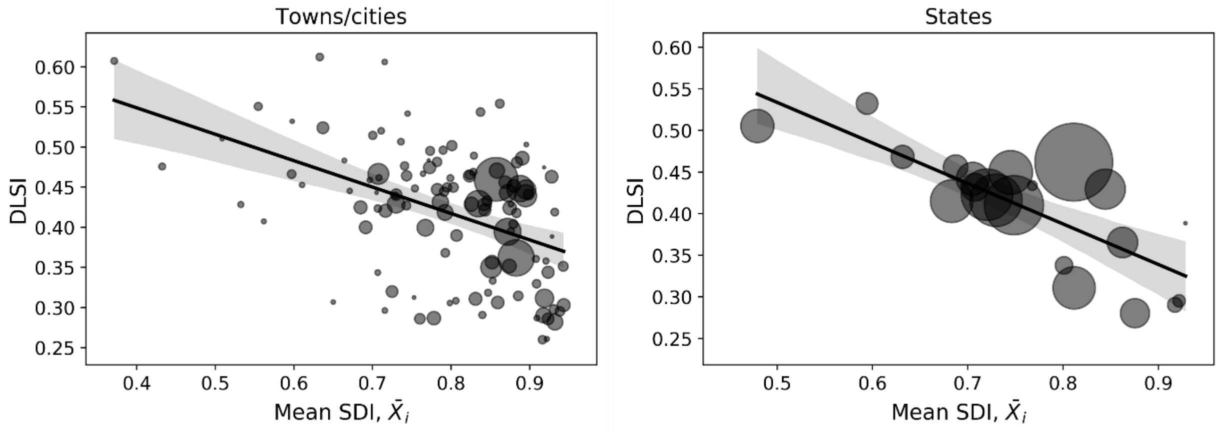


Figure 3.8: Correlation of average basic needs outcomes with multidimensional deprivation measured by the mean SDI and DLSI respectively. The shaded area indicates the 95% confidence interval of the regression to illustrate the variability in this relationship.

3.4 Discussion

3.4.1 Ensuring universal basic needs and the achievement of SDGs

Existing studies have highlighted challenges to achieving universal basic needs in India are associated with urbanization, particularly within metropolitan areas (34). Others have addressed basic needs outcomes among a selection of urban areas, generally at single spatial scales or for a case study city, highlighting city-specific challenges regarding social outcomes. However, we have seen here that policy aiming at ensuring universal basic needs may be limited if only concentrated to single spatial scales and more specifically to towns and cities. The results have shown that the overall provisioning of non-mobile built environment stock remains a challenge to basic needs in India for urban areas across all spatial scales. However, the multiscale analysis of the assessed outcomes has revealed the regionality of this challenge and therefore that inequalities in the provision of stocks are less challenging among towns and cities than for states. The results have also shown that larger towns and cities tend to have significantly lower deficits in basic needs than smaller towns and cities on average. However, there also remains variation in service provision, particularly among smaller urban areas, as well as in terms of intra-urban service distributions among households. This highlights the potential multiscale consequences of built environment stock provisioning within urban areas, such that focussing on single scales of analysis may have unintended consequences across scales. These results therefore direct the policy lens towards a more integrated approach, aiming to ensure improvements to national basic needs by addressing regional inequalities through equitable resource provisioning more locally. This may be enabled through the hierarchical responsibilities of governance within India highlighted in Table 3.3. National- and state-level urban planning responsibilities relate to the rejuvenation of urban areas, with towns and cities being responsible for environmental infrastructure planning. National planning may therefore be best placed to identify states which require targeted intervention, for example through the analysis of national basic needs profiles, and coordinating this with local planning departments, for example through complementary analysis adopting multidimensional measures within cities, to ensure an efficient provision of built environment MS within local neighborhoods. The focus on states and cities in terms of integrated multiscale policy making is further supported given that observations at sub-district and district scales are not statistically distinguishable from those at city scales. This is generally a result of the specification of administrative boundaries, where large urban areas in India are often identified as cities, sub-districts and sometimes districts simultaneously. This may benefit such areas as they may therefore be best placed to coordinate planning efforts within administrative frameworks; however, these larger urban areas tend to have higher basic needs outcomes on average and may not require significant intervention. We have seen through the SDI that the provisioning of water and sanitation infrastructure may prove most effective at improving basic needs outcomes initially and may reduce inter-urban inequalities most significantly. However, a one-size-fits-all approach may be inappropriate and result in regressive policy, for example by overlooking the most deprived households which experience deficits in housing and electricity. This is highlighted through the complex characteristics of service-specific provisioning within the national basic needs profiles, and that the complementary assessment of overlapping deprivations has revealed significant deficits in adequate housing.

The discussed findings also hold implications for achieving SDGs relating to non-mobile built environment stocks. The SDI and associated national basic needs profiles highlight progress towards the achievement of SDG 1.4.1, *proportion of population living in households with access to basic services,* and its related indicators, with the inequality index addressing SDG 10, i.e., *reduce inequalities within and among countries*, nationally. The observed deficits reveal existing tensions between achieving SDG 1.4.1 due to deficits in SDGs 6.1.1, *proportion of population using safely managed drinking water services,* and 6.2.1, *proportion of population using safely managed sanitation services,* while also highlighting the progress made so far in SDGs 7.1.1, *proportion of population with access to electricity,* and 11.1.1, *proportion of urban population living in slums, informal settlements or inadequate housing*. Quantifying the required stock provisioning, and thus the associated material flows, is essential to reveal the magnitude of challenges associated with SDG 12, *ensure sustainable consumption and production patterns,* in the context of universally achieving SDGs. The global agenda also commits to ensuring no one is left behind and thus highlights the role of multidimensional metrics in SFS-nexus assessments to ensure equitable resource provisioning. Without such insight, SDGs 11.1.1 and 7.1.1 may be overlooked within national scale assessments and thus those in severe deprivation may be left behind.

3.5 Limitations and concluding remarks

In this chapter, we have noted the limitations of existing assessments of service provisioning within SFS-nexus research, namely the use of macro-scale metrics which are often not stock-service-specific and applied at single spatial scales. To combat the existing limitations, we have firstly developed metrics which clearly define the SFS-nexus in question by considering the specific stock-service relationship. This has built on the limitations noted within literature (102,132,160,161), specifically relating to the use of GDP as a proxy for social benefit when understanding SFS-nexus relations. We have then integrated key methodological considerations from the literature measuring social outcomes to capture the scale and inequality of deficits in basic needs associated with the provision of material stocks. In doing so, we are able to highlight key policy implications which would otherwise be overlooked and form the basis with which to integrate the material stock and flow requirements to social outcomes. The framework also enables improvements to such outcomes to be assessed by relating specific resource requirements to the service and tracks associated changes to basic needs outcomes. The integration of complementary metrics then enables a flexible approach to more targeted assessments within urban areas by further reducing ecological fallacy and assessing overlapping deprivation. However, there remains limitations regarding the assessment of societal service provisioning.

Firstly, the study does not assess the spatial distribution of societal services. The results are therefore unable to provide insight into whether the geographical location of urban areas impacts basic needs outcomes. For example, whether service provisioning has resulted in higher basic needs outcomes in coastal regions, or within northern states. Further, an understanding of the concentration of deprivation within and across urban areas is unknown. As such, it is not possible to elaborate further on inter-urban inequalities and understand the relationship between high spatial clustering and inequality in service access, i.e., do larger cities tend to have higher spatial clustering of deprivations whilst experiencing high intra-urban inequality? By providing additional resolution to the understanding of basic needs outcomes across cities and its relationship to inequality city-wide, policymakers may be better placed to identify areas to nucleate solutions to basic service access i.e., focus on upgrading large areas of deprivation within cities, or by selecting those most deprived areas which are spread across the city. Despite this, the results here identify deprived areas and position these within the national context. This means that policymakers are able to understand the relative scale of challenges in terms of dimensions and urban areas, thus formulating policy that targets specific services and areas. However, the additional spatial understanding may enable more effective policy by ensuring that SDG 10 is achieved across cities through planning by ensuring inequality between intra-city regions is limited.

Secondly, the NSS dataset used to formulate the DLSI contains only a limited number of urban households to report service provisioning. While the dataset is conducted through random sampling, the DLSI may be inherently unrepresentative of the total population in some cases. However, this limitation is difficult to overcome and is generally accepted among studies given multidimensional measures often adopt survey samples to measure overlapping deprivations. Further, the NSS data is aggregated by Urban Frame Survey blocks, which are different to the wards used to aggregate census data and is also collected two-to-three years prior to the census. As such, there may be differences in the population considered due to differences in the aggregation of the urban area as well as due to developments arising in the years between data collection. While it is difficult to corroborate such errors, further work should seek to evaluate the similarities and differences between census and NSS data collection areas, particularly within spatial analysis of development outcomes, to better account for potential variations in measured outcomes resulting from this.

Another key limitation is the cross-sectional nature of the study. The general trends imply that urban growth results in basic needs outcomes which follow the national basic needs profile for the respective scale, however this should be verified as new census data becomes available. In addition, without the use of longitudinal data it is difficult to evaluate overarching trends in service provisioning. Future studies may seek to integrate remote sensing with longitudinal data to assess whether existing spatial structures of non-mobile built environment stocks influence basic needs outcomes. Finally, while we only aim here to measure deficits in basic needs outcomes, it is not clear whether the composition of urban areas in terms of the materials used for built environment MS impacts the perceived outcomes, and thus whether there is truly a relationship between the outcomes of built environment MS provisioning and the resource used themselves. This is imperative for understanding challenges to the SFS-nexus, and to which we now turn.

4 Exploring the relationship between material stocks and basic needs outcomes

4.1 Introduction

In the previous chapter we have seen that significant deficits exist in terms of the service provision from non-mobile built environment MS within the urban areas of India. The empirical study has progressed the measurement of societal service provisioning within the SFS-nexus to enhance the policy implications of such research by integrating multiple methodological considerations associated with measuring development outcomes. In doing so, the study has revealed complex inter- and intra-urban challenges at different administrative scales and has presented an approach which may begin to relate MS characteristics to basic needs. However, it is not yet clear whether basic needs outcomes are impacted by the material composition of non-mobile built environment MS and if so, to what extent this relationship exists. The following study aims to provide first steps in this direction by answering the following research question:

- *Does there exist a relationship between the composition of non-mobile built environment MS and basic needs outcomes?*

In doing so, the study assesses the cross-sectional drivers of overall basic needs outcomes and individual dimensions of basic needs, e.g., sanitation and housing, in terms of the composition of non-mobile built environment MS. To-date, much of the empirical research quantifying the relationship between development and material use are focused on economic growth, generally adopting statistical models to quantify drivers of material use (64,76,98,99). Such studies have shown that the accumulation of built environment MS increases with economic growth and has led to various studies assessing progress towards decoupling this relationship and the potential strategies to achieve this (20). While studies have acknowledged the need to address living standards beyond measures of income and consumption, development metrics measuring outcomes of basic needs have only recently been related to built environment MS and have revealed alarming trends globally (46,75). Despite this, many studies adopt individual indicators of wellbeing, such as life satisfaction (81) and life expectancy (114) and provide insight into global or national trends only. As such, there remains a significant gap in our current understanding of basic needs and material use sub-nationally, particularly which also accounts for the limitations associated with existing metrics discussed in the previous chapter. This is important for elaborating national trends such that challenges specific to nations can be assessed to more comprehensively understand approaches to decouple nations from the observed Global trends. The study therefore builds on the analysis presented in the previous chapter, by quantifying the relationship between basic needs outcomes and the composition of built environment MS. To achieve this, data available from the census of India relating to the number of households constructed by their predominant materials is adopted. As such, basic needs outcomes are related to the prevalence of certain compositions of residential building MS.

Residential building MS are shown to comprise a significant share of overall built environment MS in developed economies such as Japan (11), the United Kingdom (66) and Denmark (53). Further, a significant demand for new buildings is expected in the coming decades (25), with over 400 million new urban dwellers expected within India to 2050 (5). The results of the previous chapter have also revealed that housing provision is generally more equitable and deficits generally lower than for urban infrastructure across urban areas, which indicates that the material provisioning for residential buildings has provided basic needs relatively successfully within India. Residential building MS compositions are therefore a valid indicator of a significant share of the total composition of built environment MS which may offer important insight into the existing national cross-sectional trends of MS and basic needs outcomes. By developing a regression model, the study quantifies this relationship across sub-national scales to reveal such trends and explores the coupling of built environment MS compositions with overall, as well as service-specific, basic needs outcomes. This is important for understanding the interdependent relationship between key Sustainable Development Goals (SDGs) which must be achieved simultaneously to ensure sustainable development as part of the Global Agenda (159). This provides the first empirical quantification of the relationship between the composition of built environment MS and basic needs outcomes across sub-national scales. This is true both within the case study region of urban India as well as globally.

The following section begins with a summary of the overarching approach to the study. A more detailed description of the methodology is then presented beginning with an overview of the available data sources to quantify the composition of residential building MS within the urban areas of India. Two key census datasets are described and discussed in terms of their relevance for answering the previously posited research question. Their implications for statistical modelling are then discussed and a description of the final regression model used to statistically relate basic needs outcomes and material compositions is then provided.

Following model selection, the results of the final regression model are presented and concluded with a discussion of the findings focused on the potential implications for urban planning and the relevance of the trends observed here to other nations.

4.2 Methodology

The overarching methodology here is to develop a multi-variable regression model to quantify the coupling of non-mobile built environment MS and basic needs outcomes. Firstly, basic needs outcomes are quantified by the SDI as in the previous chapter, see *equations 1* and *2*. The SDI is then related to the material composition of households, specifically the materials used to construct the walls, roofs, and floors of the residential building, using comprehensive census datasets to initially illustrate these trends among towns and cities. As we will see, there are various challenges for statistical modelling associated with the use of these datasets. As such, a more suitable dataset is adopted to formalize the final statistical model and quantify the relationship between the composition of households, i.e., residential building MS, and basic needs outcomes. The model is developed to ensure that realistic prediction are made by considering the limitations of standard linear regression models given the bounded nature of development metrics, i.e., bound in the range [0,1]. Further details of the data sources and processing, as well as the definition of the metric used to evaluate basic needs outcomes and the regression model selection process, are outlined in the following sections.

4.2.1 Data sources and processing

The census of India uniquely records two key datasets documenting counts of the number of households within each urban area by the predominant material used to construct building elements, e.g., walls. To firstly address the relative composition of each urban area, each dataset is processed into the percentage of households comprised by the respective materials.

The first dataset provides a count of the number of households by the predominant material used to construct walls, roofs, and floors. However, formalizing these dimensions into an empirical model to assess the relationship between the composition of non-mobile built environment MS and basic needs outcomes may prove problematic. The household counts are split across three subsets of the main census dataset recording access to amenities and assets. The dataset therefore documents the composition for each element separately, with the material categories across these elements being inconsistent, containing ten, nine and seven material categories for walls, roofs and floors respectively. Further, all three variables for a single material type cannot be computed into a single variable for a given urban area without inherently accounting for a greater number of households than are actually present, which would therefore be incoherent with the assessment of average basic needs outcomes. The first dataset is therefore omitted from the statistical model quantifying the relationship between basic needs outcomes and the composition of MS. However, this dataset records the MS composition for a more comprehensive set of towns and cities (8317) compared to the alternate dataset used for the statistical model (583). The first dataset is therefore adopted to initially illustrate general patterns in the relationship between basic needs outcomes and non-mobile built environment MS composition among towns and cities.

The second dataset provides a count of the number of households by the predominant material used to construct walls and roofs simultaneously. This therefore enables the analysis of MS compositions which are coherent with the actual number of households within the area considered and for a standardized set of material categories. The dataset contains 90 variables, combining ten material types for walls with nine material types for roofs. While the number of variables may prove problematic when formulating statistical models, an important characteristic of the data processing, i.e., transformation of counts into proportions of material use, is that increases to the prevalence of one variable would generally lead to reductions in others. This means that the composition of built environment MS can therefore be more readily assessed without overfitting the model. This refers to adequate model specification such that the final multivariable regression does not violate the principle of parsimony (181,182), i.e., ensuring that the model specification avoids too many redundant predictors which may tailor the model to fit the specific data. This also highlights a further limitation of the previously discussed dataset in regression modelling due to the non-proportionality between the three datasets. Importantly, the second dataset enables the composition of built environment MS to be better assessed compared with the previous dataset, as materials are grouped such that the composition can be better identified. Further, the dataset better captures the composition of residential building MS itself and may therefore provide improved insight into how the composition of the service itself may be coupled with basic needs, i.e., are certain compositions of housing more prevalent in areas higher achieving areas?

The second dataset, i.e., the material combinations dataset, is adopted to relate covariates to basic needs outcomes measured by the SDI. The SDI is calculated for each urban area at the scale of interest and is bound in the range [0,1], i.e., the SDI for a given city corresponds to the access rates of basic services for the given city as opposed to the mean access rates based on the neighborhood SDI values within the city, as presented in the previous chapter. As a reminder, this is shown formally in *equation 1* below.

$$X_i = \sqrt[n]{\prod_{j=1}^{n} X_i^j} \qquad [1]$$

Where the index, X_i, is formulated by aggregating n dimensions, for area i. As in the previous chapter, the metric formulation considers the non-weighted average achievement of the normalised dimensions (176) resulting the final index given in *equation 2.*

$$X_i = \sqrt[5]{X_i^{water} X_i^{water\ location} X_i^{housing} X_i^{sanitation} X_i^{electricity}} \qquad [2]$$

The basic needs outcomes measured by the SDI are then related the material composition variables within a statistical regression model to evaluate the existence, and quantify the magnitude of, the relationship. The model is applied at the scale of towns and cities, sub-districts, districts, and states, excluding the composition of wards for which categorical material data is not available within the second dataset.

4.2.2 Fractional response model

Regression models are commonly used to model the behavior of a response variable, when influenced by covariates. They have been used in socioeconomic metabolism research relating development metrics to in-use stocks (21,75), as well as for access to services such as sanitation in relation to per capita energy use (113) and for consumption-based emissions with socioeconomic factors such as income and population growth (114). Here, the dependent variable, i.e., the SDI, is a measure of the rates of prevalence and is therefore bound within the range [0,1]. Therefore, due to the model specification of standard regression models, regression coefficients may yield fitted values which lie outside the upper and lower bounds of the SDI, i.e., $SDI > 1$ or $SDI < 0$. Although such analysis still enables an indication of the direction of the perceived relationship, i.e., positive or negative impacts, the magnitude of the effects may be highly inaccurate due to unrealistic predictions. Further, proportional data like that of the SDI is often distributed in an asymmetrical manner such that they may display heteroskedastic behavior and thus yield standard linear regression inappropriate (183). As a key objective here is to *quantify* the relationship between the prevalence of built environment MS compositions and basic needs outcomes, it is appropriate to turn to fractional response models which concern outcomes bound within the range [0,1]. Such models assume values *within* the bounded range and therefore do not concern values equal to 0 or 1. However, this is appropriate here given that it would be unusual for urban areas to have a universal lack of access to at least one dimension, i.e., $SDI = 0$, or universal access to all dimension, i.e., $SDI = 1$. Specifically, beta regression is considered to model the behavior of average outcomes in terms of the prevalence of MS compositions within urban areas.

4.2.2.1 Beta regression

Beta regression is a relatively new fractional response model proposed by Ferrari and Cribari-Neto (184) which has been applied mainly within social science studies due to the often bounded nature of the response variables considered (185–187), i.e., proportion of high protein foods in diets (185). The general approach is to adopt a link function to map from the bounded space to a transformed space of 'real numbers'. From here we perform a typical linear regression by maximizing the log-likelihood assuming the data follows a beta distribution. It is therefore akin to linear regression in that it contains a distributional assumption for the response variable but overcomes the challenges of heteroscedasticity due to the beta distribution (186). Due to the versatility of the family of continuous probability distributions, or beta densities, bound between [0,1] as well as its ability to capture a range of uncertainties, scholars encourage its application to empirically understand a range of problems (183,184,188). Despite this, its application remains limited. As such, and given the increasing need to quantify such a relationship within SEM research, a brief description of the beta regression process is provided below.

The beta regression model is formalized using the generalized linear model approach. To begin, the regression model is defined by assuming the data for the response variable, i.e., the average basic needs outcomes measured by the SDI, is represented by the mean of a beta distribution μ_t. This means that the beta regression can be modelled as presented in *equation 3*.

$$g(\mu_t) = \sum_{i=1}^{n} x_{ti}\beta_i \tag{3}$$

Where g is the link function, β_i are the unknown regression parameters, x are the independent variables ranging from 1 to n, and t relates to the data point. The mean of the beta distribution describing the SDI, y, is therefore transformed by the chosen link function. As we will see, the result of the model selection maximizing the log-likelihood and Bayesian Information Criteria (BIC) yield the complementary log-log as the most appropriate link function here, given in *equation 4*. From here, the regression parameters, β_i, are estimated using a standard linear regression model by maximizing the log-likelihood. The model predictions are then interpreted by mapping back to the bounded space using the inverse link function, g^{-1}. However, before being able to conduct beta regression it is important to identify the appropriate link function and covariates which result in reliable predications of the perceived outcomes.

$$g(\mu) = \ln(-\ln(1-\mu)) \tag{4}$$

4.2.3 Model specification

The model is specified by identifying the appropriate covariates and link function at the scale of towns and cities. The final model is then used for analysis at the remaining scales as well as to evaluate the relationship between the prevalence of non-mobile built environment MS compositions and specific societal services. To begin, the range of SDI values are evaluated to identify the population of towns and cities enabling regression analysis. This reveals a single census town which achieves an SDI value outside the range $0 < SDI < 1$, with an $SDI = 0$. The town is therefore omitted from the analysis and assumed to have minimal impact on the overall results given that it only contains a total of 69 households. From here the importance of variables to be included within the model selection is assessed by adopting two key approaches, i.e., univariate analysis and the forward selection process. From here, the appropriate link function is evaluated resulting in the final beta regression model.

Finally, the derivatives with which to interpret the magnitude of the relationship[9] are calculated. The derivatives report the percentage change in the response variable, i.e., the SDI, for a unit increase in covariates, i.e., the prevalence of the material types identified as significant. This is required due to the linear regression analysis taking place in a mathematically transformed space. We conduct model selection and beta regression within the Stata software using the inbuilt beta regression function to specify covariates and link functions.

4.2.3.1 Variable processing

Often too many variables are included in instances where a large number of variables are available (189) resulting in various limitations such as overfitting as discussed in section 4.2.1 (181,182). This highlights the importance of systematically choosing appropriate variables in this instance given the significant number of available variables for modelling. Figure 4.1 shows the material used for walls and roofs and lists the mean composition of each material combination across the urban areas of the towns and cities of India. This shows that the composition of residential buildings in the form of brick walls and concrete roofs are most prevalent, accounting for the composition of 41% of all households within towns and cities on average and 45% of the total urban household composition of India. The second most prevalent material combination for households is brick and metal for walls and roofs respectively and accounts for only 8% of the total number of households on average. There are 90 listed household types which experience varying co-linearity, *see Appendix B*, with many accounting for a negligible proportion of the total households. Here the study concerns the composition of built environment MS and therefore including a significant number of variables which are rarely prevalent within the model selection itself may result in inaccurate variable selection. For the reasons regarding model overfitting and the proportionality of the dataset discussed in section 4.2.1, the number of covariates is reduced based on the average prevalence and by considering only those with a positive relationship with overall basic needs outcomes, i.e., variables with a positive regression coefficient. Univariate beta regression is firstly performed on those variables accounting for at least 1% of the composition of households on average among towns and cities, the results of which are presented in *Appendix B Table B.1*. These variables account for 14 out of the 90 available

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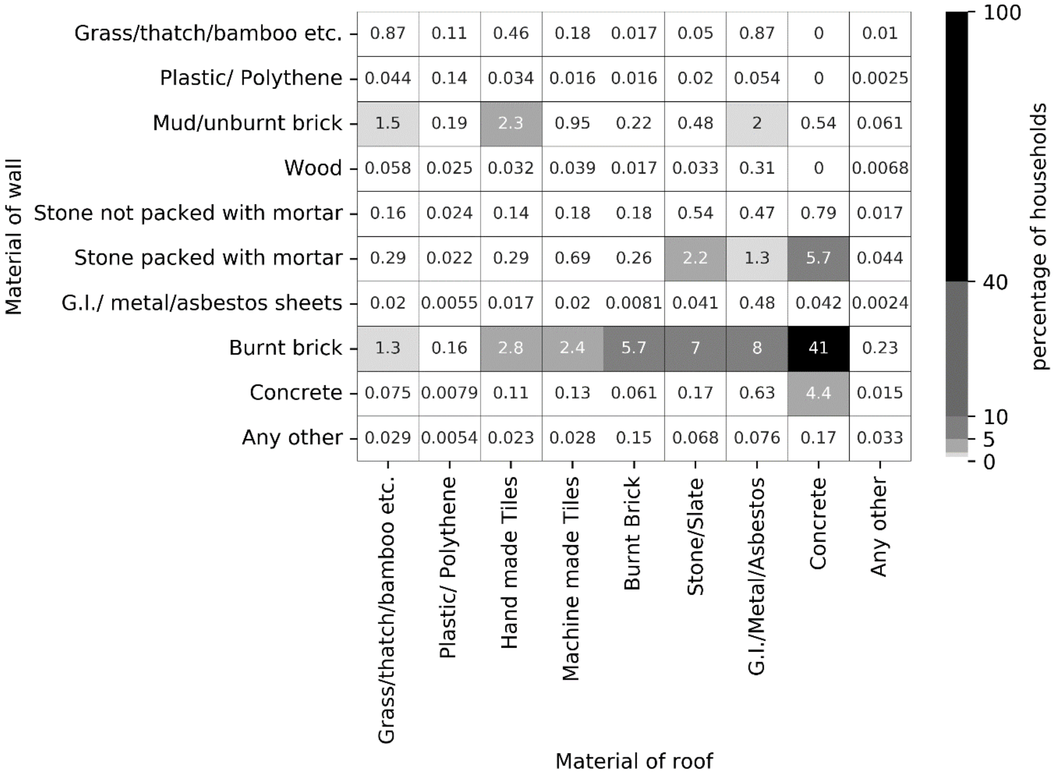
[9] More specifically, the derivatives refer to the average marginal effects.

variables corresponding to over 86% of the total households within the urban areas of India. The forward selection process is then performed for variables with a positive and significant impact on basic needs outcomes. This involves sequentially including variables with the greatest impact on basic needs outcomes identified within the univariate model and including only those with a positive and significant impact in the multivariable regression. As we will see, this results in two variables which are related to improved basic needs outcomes.



Material of wall \ Material of roof	Grass/thatch/bamboo etc.	Plastic/ Polythene	Hand made Tiles	Machine made Tiles	Burnt Brick	Stone/Slate	G.I./Metal/Asbestos	Concrete	Any other
Grass/thatch/bamboo etc.	0.87	0.11	0.46	0.18	0.017	0.05	0.87	0	0.01
Plastic/ Polythene	0.044	0.14	0.034	0.016	0.016	0.02	0.054	0	0.0025
Mud/unburnt brick	1.5	0.19	2.3	0.95	0.22	0.48	2	0.54	0.061
Wood	0.058	0.025	0.032	0.039	0.017	0.033	0.31	0	0.0068
Stone not packed with mortar	0.16	0.024	0.14	0.18	0.18	0.54	0.47	0.79	0.017
Stone packed with mortar	0.29	0.022	0.29	0.69	0.26	2.2	1.3	5.7	0.044
G.I./ metal/asbestos sheets	0.02	0.0055	0.017	0.02	0.0081	0.041	0.48	0.042	0.0024
Burnt brick	1.3	0.16	2.8	2.4	5.7	7	8	41	0.23
Concrete	0.075	0.0079	0.11	0.13	0.061	0.17	0.63	4.4	0.015
Any other	0.029	0.0054	0.023	0.028	0.15	0.068	0.076	0.17	0.033

Figure 4.1: The average prevalence of residential buildings comprised of a unique combination of wall and roof materials for the towns and cities of India. See Figure 4.5 and Appendix B Figure B.2 for the variation in the composition of the identified regression variables across towns and cities.

4.2.3.2 Link function

The final covariates are then included within the multi-variable beta regression to select an appropriate link function by maximizing the log-likelihood and minimizing the BIC. The beta regression model is evaluated using four key link functions, namely: the log-log, complementary log-log, logit, and probit link functions which are widely used in generalized linear models. The complementary log-log link function, shown in *equation 4*, is found to be most appropriate with the greatest log-likelihood and lowest BIC for the final variable selection at the scale of towns and cities and is used for models at other scales, with results of this process presented in *Appendix B Table B.2*. The final model is then used to quantify the relationship between the prevalence of MS compositions and the SDI as well as the individual dimensions of the SDI, i.e., water, sanitation, housing, and electricity access, across each scale of analysis.

4.2.4 Summary of methods

1. Quantify the SDI for each scale, i.e., towns and cities, subdistricts, districts, and states, as is calculated in the previous chapter for all wards, i.e., no aggregation of wards here.
2. Omit all areas that have an SDI of either 0 or 1, as this lies outside of the acceptable range for the dependent variable in beta regression.
3. Quantify the composition of urban areas in terms of the material used simultaneously for walls and roofs as per the census 2011 dataset recording the number of households by predominant material of wall and roof, i.e., percentage of households comprised of each combination of material types.
4. Conduct variable selection by firstly introducing only covariates which account for at least 1% of the composition of households on average among towns and cities. Secondly, perform univariate and multivariable beta regression, i.e., include all dimensions and each dimension separately, on these variables and identify those with a statistically significant impact on basic needs outcomes. Finally, adopt the forward selection process by introducing those variables which have a positive impact on basic needs outcomes, introducing these sequentially based on the size of the regression coefficients, i.e., include variables which have a positive impact and which seem to explain the largest variation in the SDI first.
5. The final variables are then selected as those which have a positive and significant impact on basic needs outcomes after step 4.

4.3 Results

The results firstly illustrate the relationship between the composition of non-mobile built environment MS and overall basic needs outcomes by evaluating the prevalence of the material types used for walls, roofs, and floors among households across the towns and cities of India. The results are presented in Figure 4.2, Figure 4.3, and Figure 4.4 respectively. Figure 4.2 shows that areas with a high composition of brick in walls tend to have high basic needs outcomes, see Appendix B Figure B.2. Figure 4.2 also indicates a negative correlation between the prevalence of mud and basic needs outcomes. Further, no areas exhibiting a high composition of mud, stone, wood, plastic, thatch/bamboo, or other materials in walls achieve high basic needs outcomes, i.e., SDI > 0.9, see Appendix B Figure B.2. Figure 4.3 reveals a slight positive correlation between the prevalence of concrete in roofs and basic needs outcomes and a negative correlation between handmade tiles and basic needs outcomes. Generally, we see that areas with a high achievement of basic needs outcomes, i.e., SDI > 0.9, are associated with a high prevalence of concrete roofs, brick walls, and cement or tiled floors, see Supplementary Information Figure B.2. Figure 4.4 reveals a slight positive correlation between the prevalence of brick and basic needs outcomes. Figure 4.4 also highlights that a high prevalence of mud floors indicates low levels of basic needs outcomes and reveals a negative association between the prevalence of mud floors and basic needs outcomes. This is further supported as there are no towns and cities with a high prevalence of mud as the predominant material for floors, i.e., >90%, and where basic needs outcomes are higher than 50% on average, i.e., $SDI > 0.5$. A similar association is found for concrete and handmade tiles for roofs. However, 14 towns and cities are identified where floor material is predominantly cement, i.e., >90%, and where basic needs outcomes are lower than 50% on average, i.e., $SDI < 0.5$. However, these correspond to areas with a significantly lower population than seen on average and similar trends for less substantial materials are not found, i.e., less substantial materials still appear to be not associated with high basic needs outcomes, see Appendix B Figure B.2.

The plots therefore reveal general trends where areas achieving high basic needs outcomes tend to have a high composition of more substantial materials such as brick, concrete and stone. For areas achieving high basic needs outcomes, i.e., SDI < 0.9, there tends to be a lack of prevalence of less permanent and manufactured materials, such as mud, handmade tiles and thatch/bamboo, and a higher prevalence of more solid and manufactured materials such as brick and concrete, with some areas exhibiting a high percentage of stone used for floors and walls achieving high basic needs outcomes, see Appendix Figures B2, B3 and B4 for subplots within the range of 0.9 < SDI < 1.0.

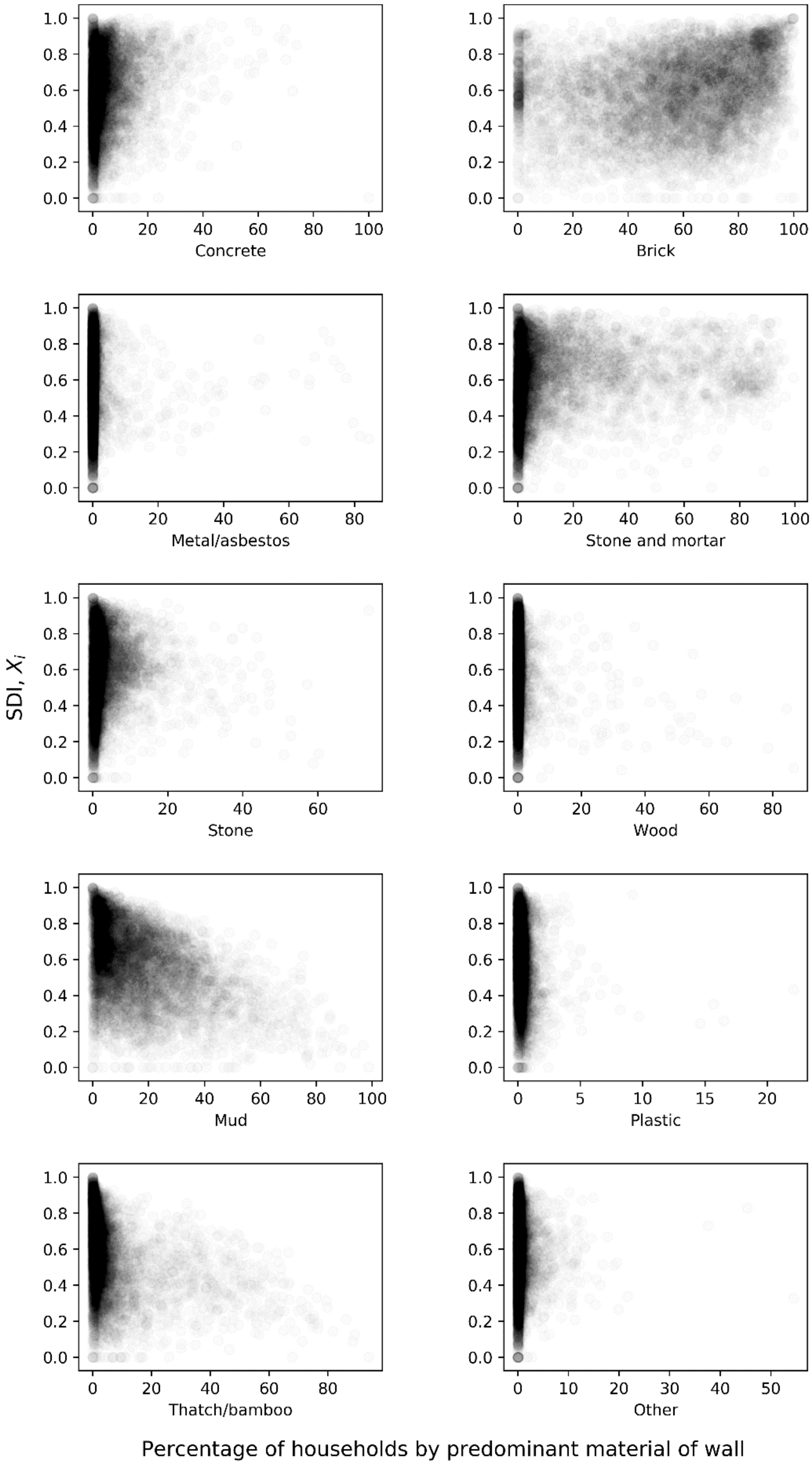


Figure 4.2: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of walls. Each data point corresponds to the proportion of households comprised of materials for the respective building element in a given area, thus the sum of the x-values for a given point in each panel results in 100%. See Figure B.2 for subplots for areas achieving SDI > 0.9.

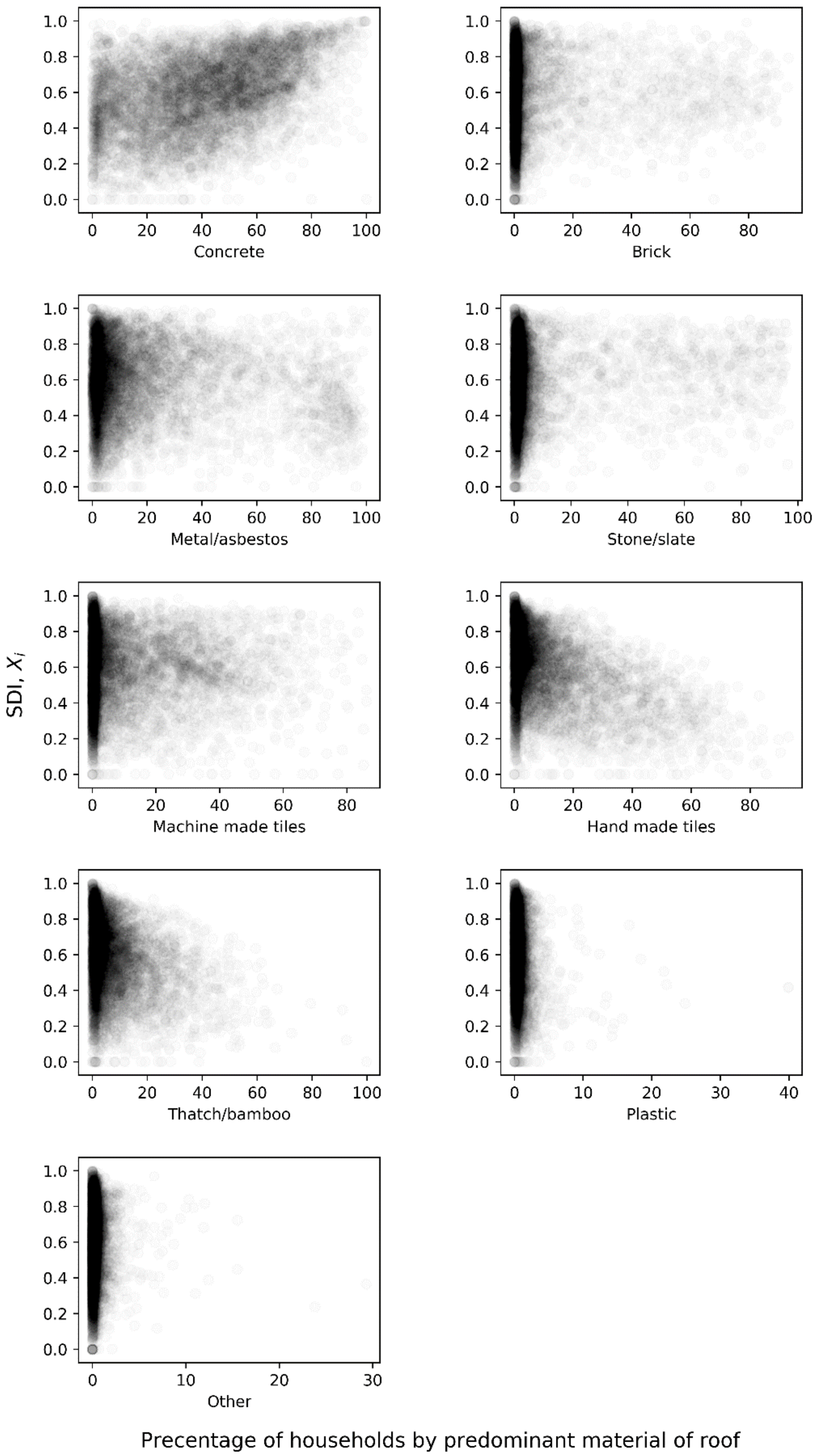


Figure 4.3: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of roofs. Each data point corresponds to the proportion of households comprised of materials for the respective building element in a given area, thus the sum of the x-values for a given point in each panel results in 100%. See Figure B.2 for subplots for areas achieving SDI > 0.9.

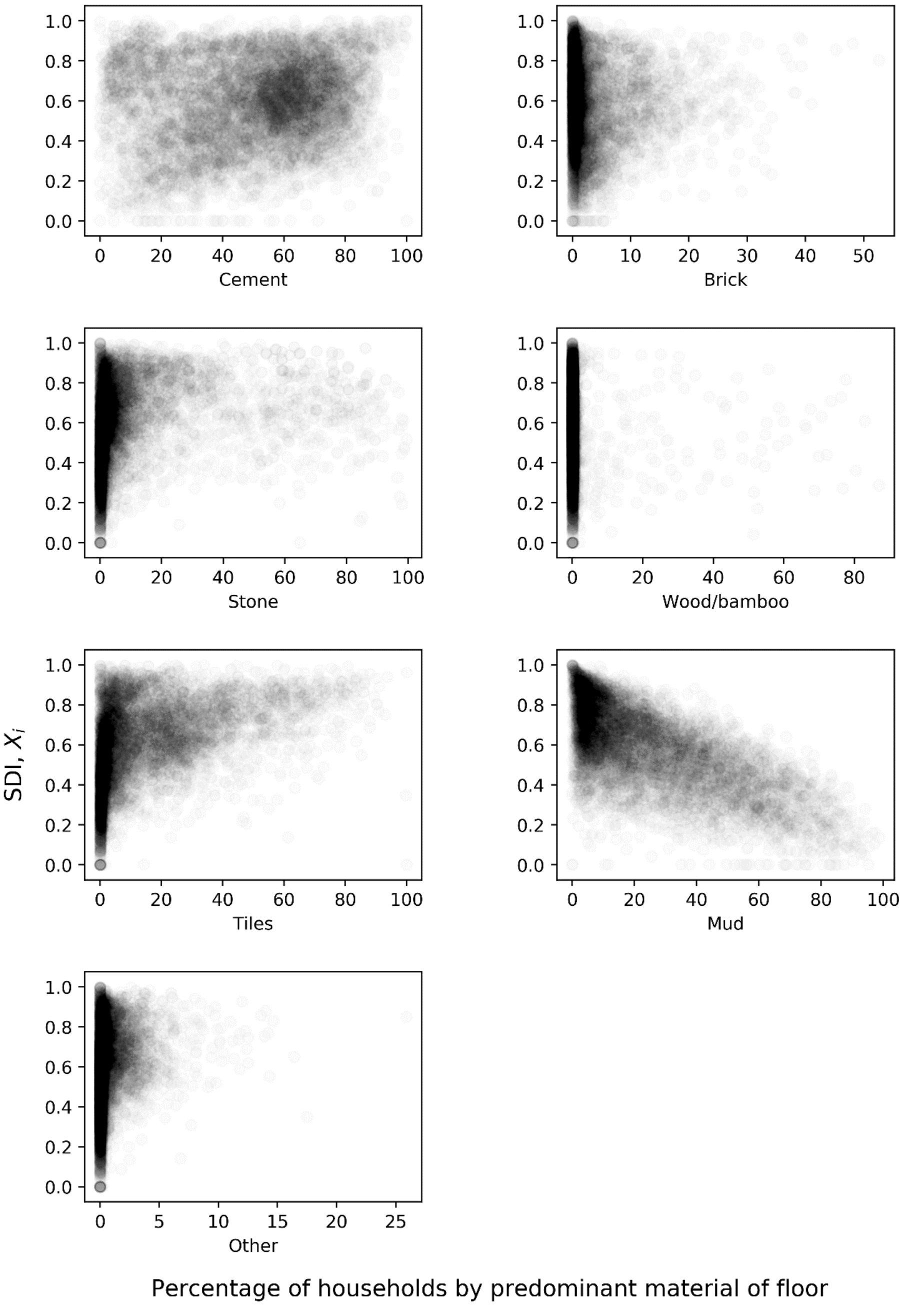


Figure 4.4: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of floors. Each data point corresponds to the proportion of households comprised of materials for the respective building element in a given area, thus the sum of the x-values for a given point in each panel results in 100%. See Figure B.2 for subplots for areas achieving SDI > 0.9.

4.3.1 Regression results

The results of the variable selection via the previously discussed model selection process reveal that the prevalence of brick wall and concrete roof households (BCHH) and concrete wall and concrete roof households (CCHH) is related to overall basic needs outcomes. The results show that increases in the composition of such households are associated with increases in basic needs outcomes. Univariate analysis reveals the opposite relationship for less common household compositions, such as those using mud for walls and metal sheets for roofs. However, these compositions are much less prevalent across the towns and cities of India and therefore do not describe a significant composition of the overall built environment MS. Further, due to the nature of the variables, an increased prevalence of BCHH and CCHH would lead to reductions in these compositions and vice-versa. Given this, and that the identified explanatory variables relate to a combination of only two key materials, the results reveal that a greater composition of brick and concrete MS is associated with greater achievement of overall basic needs outcomes. The magnitude of the relationship is quantified by computing the derivatives which more explicitly relates the composition of residential building MS to overall basic needs, see Table 4.1. The results reveal a general trend among towns and cities, with a 1% increase in the composition of BCHH associated with a 0.2% increase in the SDI on average, and a 1% increase in CCHH associated with a 0.5% increase in the SDI on average. This revels that areas containing a greater composition of brick and concrete MS tend to have marginally higher overall basic needs on average. Further, due to the composition of households, i.e., both household types containing concrete stocks, and that CCHH are associated with higher basic needs outcomes on average, the results also suggest that the prevalence of concrete stocks has grown in conjunction with overall basic needs outcomes to a greater extent than for brick stocks. The derivatives are statistically indistinguishable from each other across scales except for at the state-level where we see that the increased prevalence of CCHH does not have a statistically significant coupling to overall basic needs outcomes. In other words, at regional scales, the consumption of brick and concrete within the built environment has grown in conjunction with overall basic needs, but more locally we see that concrete consumption has co-occurred with overall basic needs to a greater extent. However, this may be explained by the model given that a reduced number of data points are available for states combined with the fact that CCHH is of significantly lower prevalence than BCHH, see Figure 4.5.

Table 4.1: Results of the beta regression across scales of analysis showing only the variables with a significant and positive impact on overall basic needs. Note: BCHH refers to brick wall and concrete roof household compositions and CCHH refers to concrete wall and concrete roof household compositions.

Scale of analysis	No. of observations	Household composition (wall, roof)	Average marginal effect	Standard error	95% confidence interval, x10^{-3}
Towns/cities	584	BCHH	0.0018	0.00025	[1.3, 2.3]
		CCHH	0.0049	0.00100	[2.9, 6.9]
Sub-districts	509	BCHH	0.0014	0.00026	[0.88, 1.9]
		CCHH	0.0060	0.00110	[3.8, 8.1]
Districts	356	BCHH	0.0013	0.00032	[0.69, 1.9]
		CCHH	0.0063	0.00130	[3.7, 8.8]
States	29	BCHH	0.0034	0.00120	[1.1, 5.6]
		CCHH*	0.0052	0.00320	[-1,1, 11.4]

**Note that CCHH is not found to be statistically significant at the state-level, i.e., the estimated p-value > 0.05.*

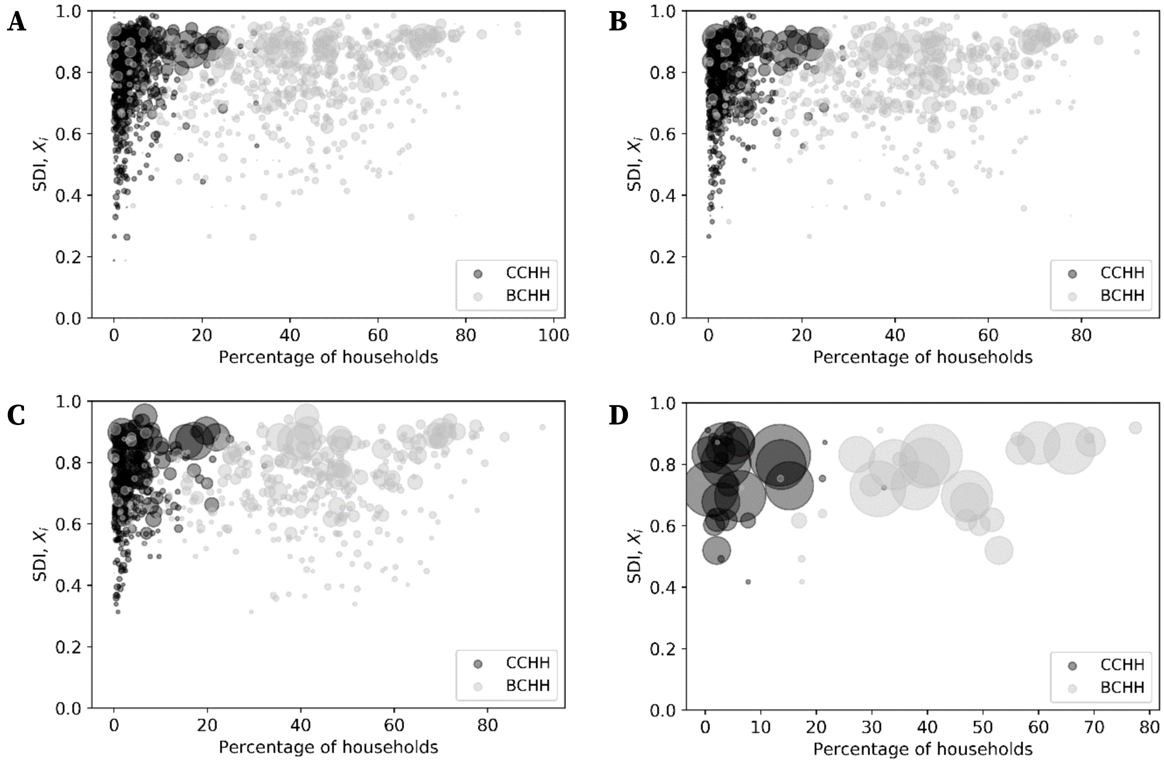


Figure 4.5: The percentage of BCHH and CCHH versus the SDI for (A) towns and cities, (B) sub-districts, (C) districts, and (D) states, with the size of the data point indicating the absolute number of households within the urban area.

We now further explore the relationship between the variables shown to have a significant and positive coupling with overall basic needs and the specific service outcomes which comprise basic needs. We therefore turn to the results of the regression on the decomposed SDI in relation to BCHH and CCHH, shown in Table 4.2. BCCH is shown to not only be empirically coupled to overall basic needs outcomes but also to the stock-specific services themselves. This indicates that a higher composition of brick within non-mobile built environment MS generally indicates higher basic service provisioning from the associated services. This holds true across all scales of analysis except at the state level where we see no significant impact of such material compositions and improved sanitation outcomes. A greater composition of CCHH is shown to be coupled with improved basic needs outcomes associated with access to sanitation, treated tap water, and electricity. However, the results show that CCHH is not associated with outcomes of housing or adequate water access in terms of the service location. The results also show that the relationship between the composition of MS and the specific services which comprise basic needs is less clear at the level states. Generally, BCHH remains empirically coupled to such services, however the results reveal that CCHH is only associated with improved access to electricity exhibiting a 0.3% increase in the SDI for a 1% increase in this composition on average. Thus, as with overall basic needs outcomes, a higher composition of brick and concrete within the built environment is associated with improved service-specific basic needs outcomes, with the significance of concrete stock provisioning diminishing at the state-level.

Table 4.2: Results of the service-specific beta regression across scales of analysis showing only the variables with a significant and positive impact on overall basic needs. Note: BCHH refers to brick wall and concrete roof household compositions and CCHH refers to concrete wall and concrete roof household compositions.

Scale of analysis	Dimension	Household composition	Average marginal effect
Towns/cities	Housing	BCHH	0.0012
		CCHH	N/A*
	Sanitation	BCHH	0.0013
		CCHH	0.0033
	Treated tap water	BCHH	0.0017
		CCHH	0.011
	Water location	BCHH	0.0016
		CCHH	N/A*
	Electricity	BCHH	0.00053
		CCHH	0.0024
Subdistricts	Housing	BCHH	0.00088
		CCHH	N/A*
	Sanitation	BCHH	0.0010
		CCHH	0.0047
	Treated tap water	BCHH	0.0012
		CCHH	0.013
	Water location	BCHH	0.0013
		CCHH	N/A*
	Electricity	BCHH	0.00056
		CCHH	0.0033
Districts	Housing	BCHH	0.00073
		CCHH	N/A*
	Sanitation	BCHH	0.0010
		CCHH	0.0047
	Treated tap water	BCHH	0.0012
		CCHH	0.015
	Water location	BCHH	0.00095
		CCHH	N/A*
	Electricity	BCHH	0.00088
		CCHH	0.0053
States	Housing	BCHH	0.0044
		CCHH	N/A*
	Sanitation	BCHH	N/A*
		CCHH	N/A*
	Treated tap water	BCHH	0.0048
		CCHH	N/A*
	Water location	BCHH	0.0028
		CCHH	N/A*
	Electricity	BCHH	0.00089
		CCHH	0.0025

**Note that N/A values are shown for variables which are not found to be statistically significant, i.e., p-value < 0.05.*

4.4 Discussion

4.4.1 Implications for in-use stocks – a comparison to global trends

The presented study has gone beyond existing macro-scale assessments to relate metrics specifically assessing service outputs from non-mobile built environment MS with their respective material composition. The empirical relationship quantified here highlights that urban areas with a high composition of non-mobile built environment services comprised of brick and concrete are associated with improved basic needs outcomes overall and in terms of specific services such as water, electricity, and sanitation. The relationship also doesn't vary significantly across sub-national scales and suggests that the relative increase in brick and concrete materials are associated with higher basic needs outcomes to a similar extent locally and more regionally. This is likely largely a result of policy choices regarding how residential building stocks are provided, e.g., standard practice and the availability of construction materials, suggesting little variation in construction practises across India in terms of material selection for key services. Current global trends indicate that India is still at incipient stages of in-use stock growth and improvements to living standards (46,75). As such, the results here indicate that, if current sub-national trends are to continue, India may expect to follow the global trajectory of in-use stocks and living standards. This has important implications for the stock-wise consumption of materials if current trends are to continue. . For example, the widespread provision of brick and concrete MS is to be expected in the future to improve living standards, with this provision increasing similarly at each scale relative to other material types. This raises concerns for policy interventions given that there seems to be considerable reliance on brick and concrete within built environment services and thus large disruption if such materials are to be replaced by low-carbon alternatives.

Specifically, the study has adopted residential building MS as an indicator of the material composition of non-mobile built environment stocks. Increases to the material composition of the built environment will be a result of either net additions to stocks, such as through the provision of new residential buildings in the identified compositions, or through demolition and replacement of existing stocks to upgrade housing. Upgrading housing through building retrofit may be much more unlikely due to the inadequacy of the current structural building materials. Both scenarios, separately or taken together, imply significant provisioning of carbon intensive materials due to existing inadequacies of current housing stocks, shown in the previous chapter, and the unprecedented rates of urbanization. While the results do illustrate variation, Figure 4.5 shows that larger urban areas tend to achieve greater basic needs outcomes and have a higher composition of BCHH and CCHH relative to smaller urban areas. Thus, growing urban populations may be expected to increase the relative composition of built environment MS towards brick and concrete in pursuit of improved living standards. This suggests further tensions in achieving interconnected SDGs in the context of increased demand for housing and highlights the importance of decoupling construction material use from improvements in living standards.

4.4.2 Implications for achieving the Sustainable Development Goals and opportunities for decoupling

Limiting future growth of in-use stocks whilst providing essential services to society is a key challenge for sustainable development globally. The national trends reveal that significant tensions exist within India regarding the achievement of interconnected SDGs. This is due to the empirical coupling of basic services, i.e., SDG 1.4.1, and the consumption of carbon-intensive resources, i.e., SDG 12. Further, basic services are interconnected to the service-specific goals for water, SDG 6.1.1, sanitation, SDG 6.2.1, housing, SDG 11.1.1, and electricity, SDG 7.1.1. Those areas achieving higher outcomes of basic service-related SDGs are shown to have a higher composition of carbon-intensive materials on average thus exacerbating progress towards SDG 12. This points to the need to develop improved indicators within the Global Agenda such that trade-offs associated with the provision of MS and minimum standards of living are captured and integrated within urban development plans. This is important given that the observed trends are likely a result of policy choices and that SDG 12 currently only addresses the material footprint per GDP, i.e., SDG 12.2.1, when considering the relationship between MS and development (159). This not only highlights the current importance of construction materials in terms of the SDGs, but also the importance of considering energy-saving alternatives. Studies in India have examined the extent to which alternative construction materials can improve lifecycle energy efficiency of buildings (118) and have shown potential reductions to national energy use adopting low-energy materials for urban four-story reinforced concrete residential buildings (117). This is particularly relevant here, given that the residential building compositions identified are generally coherent with those for urban housing archetypes within such assessments given that these compositions are shown to correspond to one to four story buildings present across various regions of India (86,190–192). Additionally, ensuring long lifetimes of such stocks would limit future demolition waste. This should be combined with characteristics of MS provisioning such that future development is not limited by potential lock-ins shown to exist within the MS accounting literature within the Global South (48). Such approaches may improve uptake of circular economic principles relating to buildings which are shown to be critical for achieving multiple interconnected sustainable development goals (193). Future work should therefore seek to build upon the existing literature examining energy-saving measures relating to construction materials and decent living standards (117,118) by quantifying the extent to which energy-savings measures may decouple living standards from resource use.

4.5 Limitations and concluding remarks

While the presented study is unable to quantify causation, i.e., whether the MS composition itself directly causes basic needs, studies have suggested that this is the case. A study assessing the impacts of a large-scale housing program in Mexico has shown that replacing mud floors with cement improves child and adult welfare and thus directly impacts basic needs (194). While the regression model does not capture the material used within floors, BCHH and CCHH are shown to be constructed with concrete floors across various regions of India (86,190–192). Further, such residential building compositions are argued as necessary for adequate housing provision among numerous studies (4,8,116,118,122). Therefore, the current trends suggest that the prevalence of BCHH and CCHH housing directly impacts basic needs outcomes. This further underlines the importance of this coupling within the Global context as discussed earlier, reinforcing the need to understand resource efficiency strategies in the context of providing basic needs. Future work should therefore seek to understand and quantify the impact of potential decoupling strategies, such as those identified within the decent living standards literature aiming to ensure minimum service provisioning (115–117), i.e., only providing what is required. Combining such analysis within India as new census data becomes available in coming years may offer greater resolution as to the development of India over the decade, as well as providing a quantification of the magnitude of decoupling and consequent sustainable development trajectory based on such strategies. It is also important to verify whether the trends observed here exist in other contexts, particularly in areas with high deficits in basic service provisioning. For example, in Peru where the urban areas of the Huancayo province are found to have low basic needs outcomes with particularly high deficits in access to water infrastructure (195), as shown for many urban areas of India in the previous chapter. Further, the province is situated nearby two districts within the Metropolitan area of Lima (48) which contain a significant proportion of brick masonry residential buildings, as found for India here. Additional studies may be also be valuable in the cities of Chiclayo (196) and Tacna (68) which also contain a significant proportion of brick masonry residential buildings.

A limitation of the developed model is that it is unable to handle instances in which basic service access is universal or where deprivation in access to basic services is universal, i.e., SDI = 0 and SDI = 1. This means that beta regression analysis in areas where such outcomes are prevalent would overlook those most severely deprived areas, or those most comprehensively developed areas, and thus over- and under-estimate the quantified relationship. However, this is likely to be very rare in developing urban areas given extreme urbanization and the processes that underpin this, such as increasing inequality and super-linear scaling of undesirable outcomes such as unaffordability of housing as discussed in Chapter 2. As such, it is likely that, when considering only basic services access, the developed metric and beta regression would be inappropriate for quantifying such a relationship in nations of the Global North where basic service access is largely universal, i.e., basic capabilities are achieved, and more improved services are strived for, i.e., the provision of services to expand enhanced capabilities such as improved network speed and accessibility. In this case, only one small urban area of 69 households is omitted from the model which achieves a composite score of 0 for basic needs outcomes. It also contains a higher-than-average composition of brick and metal households at 60% of the total town's urban households, as opposed to 8% on average across all towns and cities. However, there are no households constructed as BCHH or CCHH and, given the large number of data points in the analysis, the omission of this area from the model would have little-to-no significant change in the identified variables or the quantified relationship.

A central limitation of the study is that it falls short of a quantitative understanding of the relationship between material mass, associated environmental impacts, and basic needs outcomes. As such, the magnitude of material provisioning is not captured. Future work assessing characteristics of MS accumulation within the urban areas of India are crucial to understand the relative scale of challenges among basic needs dimensions in terms of the material and environmental impacts required. This would also offer an improved understanding as to the current implications for monitoring SDGs, e.g., by identifying improved material indicators to capture such trade-offs, and the appropriate pathways to ensure that interconnected SDGs can be achieved simultaneously. The quantification of material mass ranging from within local to city and more regional urban areas would also offer insight into whether a scale dependence exists in terms of the mass of material provided. The results suggest that policy choices in stock provision are similar at different scales, so basic needs outcomes are generally achieved through similar material usage. However, the size of the service, particularly the use of the service per capita, and the income levels of the inhabitants may influence material accumulation. For example, the Government of India provides housing based on income bands, which tend to have different floor area targets. Thus, lower-income groups may achieve the same service outcomes of "shelter" at lower material mass than others. Further, large urban areas tend to be more dense than more local areas and may therefore have lower MS requirements per capita. Higher-income groups within more local urban areas may therefore use similar materials to expand the provision of basic services but have much higher accumulation per capita than areas with a higher proportion of low-income housing and in larger urban areas. Thus, while we see that material types are provided similarly at all scales, it is important to understand the relative provision of MS in terms of mass and environmental impacts, to better understand whether such areas nucleate solutions for achieving interconnected SDGs associated with basic needs whilst limiting any drawbacks associated with SDG 12.

The observed trends found here and the results of the previous chapter also underline the importance of MSA studies when considering the provision of water and sanitation infrastructure. Future work may also seek to develop population weighted beta regression approaches such that the extent to which brick and concrete MS are provided across urban areas is better captured. This is important because larger urban areas tend to have a relatively high composition of brick and concrete MS as well as high basic needs outcomes compared to smaller areas. Additionally, we do not evaluate the spatial distribution of variables here which may reveal spatially dependent outcomes and patterns associated with higher MS compositions and basic needs outcomes. Given that India spans multiple climatic and seismic zones, resulting in various material, e.g., reinforced steel to resist earthquake loads, and energy requirements, e.g., additional cooling for hot climates, for residential buildings (118,191), future work should seek to verify the spatial distribution of MS sub-nationally to elaborate potential regional constraints associated with basic needs outcomes. While it is not expected that the material *composition* of housing differs significantly across different areas of India (86,190–192), such analysis may reveal regions which have their own context specific growth constraints and thus the required housing typology. For example, coastal regions may provide higher-rise residential units to densify activities within tourist areas and thus adopt more concrete and steel than areas which follow more sprawled developments and thus lower-rise and often brick built housing. The results therefore provide a broad understanding of the current relationship between the provision of built environment materials and development levels and thus a first step towards providing an enhanced understanding to inform policy. The results are therefore appropriate at the policy scales of states or the nation, which are responsible for the design of broad policy frameworks (175). However, they should be supplemented with spatial assessments such that solutions are not provided in ways that significantly increase inequality in basic service outcomes within regions.

In conclusion, the study has quantified the existing trends of MS use and basic needs outcomes within the urban areas of India. The results have revealed that MS are coupled with basic needs outcomes, where we have seen that urban areas with a greater prevalence of brick and concrete MS tend to have higher basic needs outcomes. This is likely a result of the policy choices in how the Indian Government provides housing and infrastructure services and reveals the tensions in achieving interconnected SDGs. Future work addressing strategies for decoupling of this relationship are therefore required, particularly integrated with MSA assessments such that the magnitude of material use can be understood in relation to outcomes of basic human needs.

5 Built environment material stocks in the context of high living standards

5.1 Introduction

The previously discussed results have shown that societal service provisioning relating to key non-mobile built environment MS remains a significant challenge in India and is a widespread challenge to basic needs outcomes across scales. We have also seen that a high prevalence of brick and concrete MS within the built environment, specifically within residential buildings, positively impacts basic needs outcomes. However, we are yet to quantify and therefore elaborate how the accumulation and characteristics of this MS has facilitated high basic needs outcomes. Here, the study aims to answer the following research question to provide an understanding of the composition and distribution of MS and its impact on basic needs outcomes in the context of high basic needs outcomes.

- What is the built environment material stock accumulation within a city with high basic needs outcomes in India?

As we have discussed in Chapter 2, focusing at city- and sub-city-scales is important to understand patterns of MS provisioning in the Global South with current studies revealing various characteristics of MS accumulation, implications for future resource use, and relationships to economic growth. However, there remains a significant lack of insight into built environment MS accumulation in India, as well as the relationship between such stocks and basic needs outcomes within cities. This may hold important policy implications for future urban development given the unprecedented rates of urbanization expected in the Global South (5) and the significant increase in urban infrastructure and housing MS required to 2050 within India (24). Following from the results presented in the previous chapter, a case study city is selected which has a high accumulation of brick and concrete MS and achieves near universal basic needs outcomes. The study focuses on residential building and road MS to capture those stocks ensuring residence and connectivity of people and places which is central to the design and functionality of urban areas. The study therefore reflects on characteristics of the urban form and provides comparisons to other cities in the Global South. We also discuss the relationship between the quantity of built environment MS and basic needs outcomes measured by the SDI, as in previous chapters, at sub-city scales and the implications for urban planning policy and future work assessing the relationship between MS and development levels.

A major contribution of the current body of work to SEM research is the quantification of built environment MS at the city-scale within India. As such, the study begins by firstly discussing the current state-of-the-art of MSA within India and its implications for the current study. From here a detailed explanation of the identified case study city and the adopted methodology to quantify MS is provided. Key findings are then outlined followed by a discussion surrounding the implications for urban planning and future studies addressing MS and basic needs outcomes within cities.

5.1.1 Material stock accounting in India

Built-environment stock research in India has, to date, largely focused on assessments of the material mass and embodied energy (EE) of individual residential buildings (86,192,197,198). 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., (191) and is often reported in studies focused on material use within buildings in India. Studies have also evaluated the potential for energy efficiency in buildings, focusing on construction material use (86,118) and operational energy demand (118). Bottom-up approaches have been used to estimate the resource requirements needed to provide minimum standards of living nationally (117,118). 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 demand for Delhi and Chandigarh (4). The bottom-up approach has also been applied nationally to estimate the energy requirements needed to meet basic standards of living through the provision of adequate infrastructure (117) and to meet housing demands (118). In-use copper stocks have also been estimated nationally using a remote sensing approach, i.e., night-time light observation data (199). 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 (4) and estimations of construction and demolition waste (25). There therefore remains a lack of an empirical understanding of the current composition and spatial distribution of MS within India’s cities. As we have seen in Chapter 2, this insight is important to understand patterns of material use and its impacts on living standards to understand the potential for resource efficient and equitable urban development. It is therefore important to begin to address these research gaps in India given the MS and consequent basic needs challenges associated with rapid urbanization.

5.2 Methodology

5.2.1 Case study area and scope

It is firstly important to identify an appropriate case study city with which to quantify MS at city- and sub-city scales. The Municipal Corporation of Chandigarh achieves high basic needs outcomes on average, with an overall city-wide SDI of 0.92. It is predominantly comprised of brick wall and concrete roof housing which accounts for 78% of the total housing, with concrete wall and roof housing accounting for 4% of the total housing as analyzed from the census of India (173). It therefore has a high prevalence of the housing types identified to be statistically coupled with basic needs outcomes in Chapter 4.

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 (200). 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 (173) and covering an area of approximately 99km^2 (173,201). According to the 2011 Census, the population density of the urban area of Chandigarh is approximately 9408 persons/ km^2 (173). The district is primarily constructed on alluvium (200,202) and is located in seismic zone IV which, in accordance with Indian design codes (203), controls aspects of building construction to ensure structural safety in the event of earthquakes and thus impacts MS provisioning.

Chandigarh was conceived in the mid-1900s and is one of the first planned cities in India (204). The city is constructed on a site originally containing 59 villages and is the result of the detailed master planning of Le Corbusier (205,206). 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 (207). 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 (205,207). The city is organized on the basis of regularly repeating neighbourhood units that are designed to be self-sufficient, with access to various amenities and assets within reasonable walking distance (205). These neighbourhood units, or *sectors,* are combined to form wards, the lowest administrative division within urban areas (173), see Figure 5.1. Sectors are typically 800x1200m (207) 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, *see Appendix C Figure C.5*. Stringent architectural controls have dictated the composition of housing resulting in a residential building stock that is homogenous in its construction type as discussed previously.

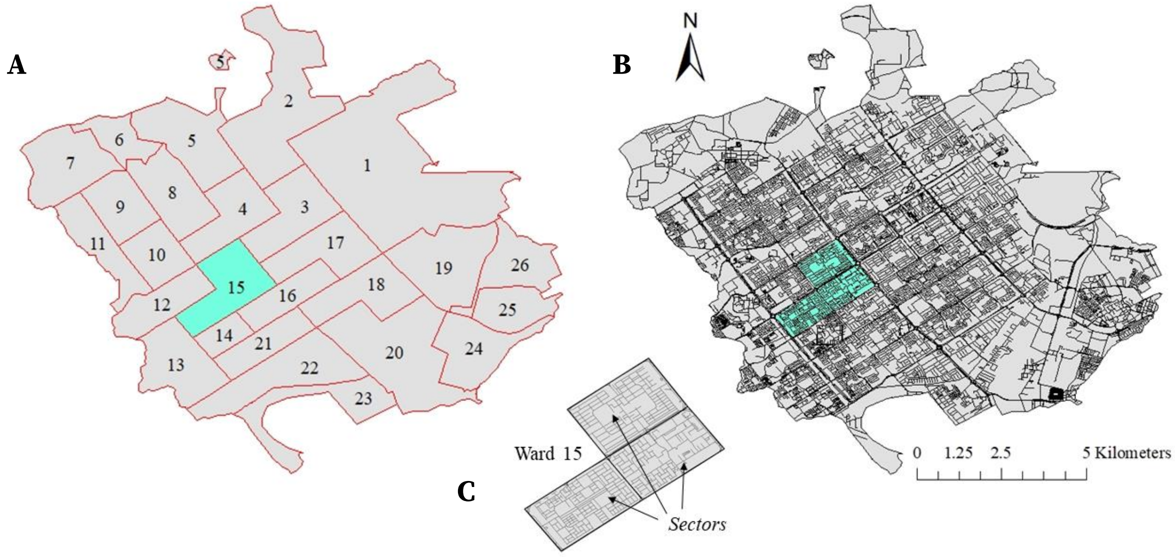


Figure 5.1: Map of the Municipal Corporation of Chandigarh as per the available georeferenced boundary data (201) showing (A) the administrative wards, (B) the road network, and (C) an example ward illustrating its composition of a number of sectors. Table 5.1 indicates the total study area and population for both stock types based on the data available. A detailed map of the administrative divisions of Chandigarh as per the Census of India (173) is provided in *Appendix C Figure C.6*.

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, built environment resource use and basic needs outcomes. Furthermore, it is a useful comparison to other stock studies to understand how rapid development has impacted the distribution of stock accumulation which may provide valuable insight into future urban development. Against this backdrop, the following study quantifies the residential building MS in Chandigarh using architectural control drawings and layout plans provided by the Chandigarh Administration (207) and georeferenced boundary data sourced from a publicly available online repository (201). While data pertaining to road construction is limited in India, the estimation of road MS in this context remains of value and therefore various data sources are adopted to fill this existing data gap, outlined in section 5.2.2. All 26 wards are included in the assessment of road MS, with a total of 9 wards omitted 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 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, see Table 5.1.

5.2.2 Bottom-up material stock accounting for residential buildings and roads

The MS in roads and residential buildings is quantified for the reference year 2011. As we will see in section 5.2.3, the number of housing plots has remained unchanged per sector since the completion of the masterplan, thus it is possible to provide a comparison of the stock accumulation to the population and area statistics available within the Census of India (173) and georeferenced data (201). The bottom-up MSA approach is adopted to characterize MS which is comparable with existing approaches (11,53), 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:

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

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 (208), 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 (68) as well as using a combination of data sources and indirect calculations to fill data gaps (67). The methodology is therefore adjusted to accommodate the available for data for both residential buildings, see Figure 5.2, and roads outlined in sections 5.2.3 and 5.2.4 respectively.

Table 5.1: Ward-level data for residential buildings and roads. Population data is retrieved from the Census of India (173) with areas provided within georeferenced data available in GitHub (201). The number of sectors refers to the number of sectors for which residential building MS can be computed due to data availability, with the actual total number of sectors shown in brackets. The number of plots is estimated using the sector-wise layout plans as described in section 5.2.3 and Figure 5.2. The total road length is calculated using OpenStreetMap data as outlined in section 5.2.4.

Ward No.	Population	Area (km^2)	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**

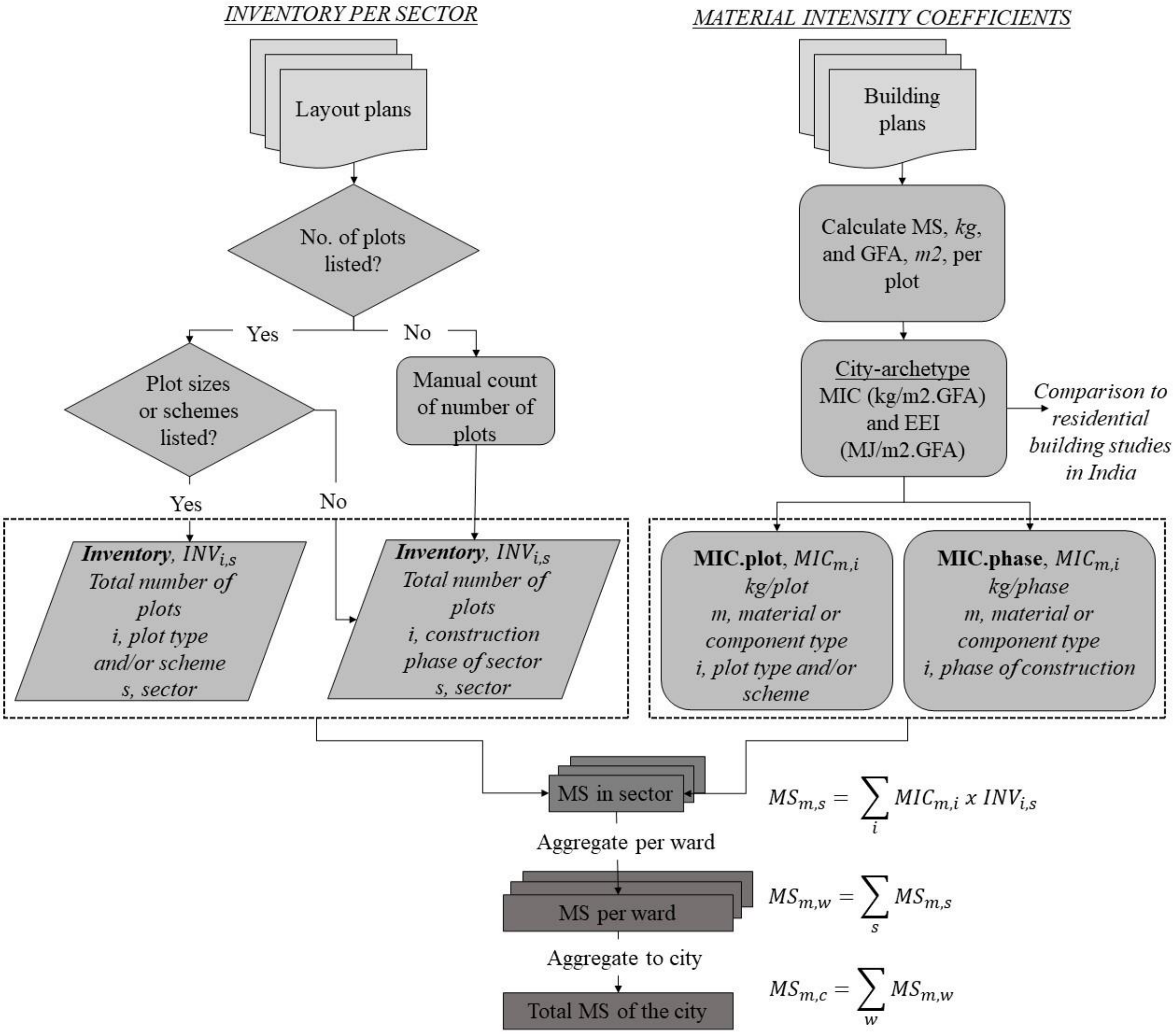


Figure 5.2: Bottom-up methodology for city -and sub-city level MS estimation of residential buildings (authors own). We also highlight the MIC calculation for the city-archetype to facilitate a comparison to broader studies in India. The total MS of each material or component, m, for residential building 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.

Due to the diversity of bottom-up MSA applications and data availability in different contexts, MICs are often inconsistent making them difficult to compare (87). It is therefore important 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. Material property data is adopted from existing studies in India (117,118), *see Appendix C Table C.1,* to calculate residential building MS and EE and reflect the prevailing material production and construction practices of India. From here the same building samples are used to create building archetypes specific to Chandigarh with which to further improve the accuracy of MS estimations at sub-city scales. The Municipal Corporation and its respective administrative wards are used to define the city- and sub-city scales respectively. The total MS and MS coefficients are calculated at these scales, i.e., MS per capita and MS per km^2, for each stock type based on the study area considered. Key assumptions are presented in *sections C.1.3* and *C.2.3* of the *Appendix C* for residential buildings and roads respectively.

5.2.3 Residential building material stock calculation

Architectural control drawings hosted by the Chandigarh Administration, *see section C.1* of *Appendix C,* are used to calculate product-level MICs and EEIs. 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 which is summed to arrive at a total mass of material or component. From here the total gross floor area (GFA) is calculated for each building and summed to result in the total floor area of the building archetype. We do so as defined in the literature addressing the transferability of MICs (87) which is of importance to bottom-up MS studies to ensure that MIC values can be compared, as discussed in Chapter 2 section 2.2.2. 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 the India-specific EE values (118).

The MICs must then be matched to the available inventory data to calculate city- and sub-city scale MS accumulation. 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 by 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 Figure C.1* of *Appendix C*. The building located on each plot is shown to be standardized by 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 Figure 5.3. Wards are omitted from the study where there is insufficient data available to describe the quantity or composition of inventory items thus limiting the extrapolation of MICs, see Table 5.1. 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 the 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. The average MS is used where archetypes contain more than one drawing sample, with maximum and minimum errors calculated using the maximum and minimum MS per archetype. Where building samples for plot types are unavailable, the plot is classified by the closest available plot size for the available building samples. Where plot types within sectors are unknown, a construction-phase-specific archetype, e.g., buildings constructed in phase 1 or phase 2, is calculated to estimate an average MIC for each building based on the standardized designs within each phase, see Figure 5.2. While masterplan documents are used dating from 1957 to 2005, records demonstrate that the masterplan of Chandigarh has been implemented over multiple decades (209), with no changes to the boundaries of the district and with continued urban growth experienced to the periphery of the city (200), i.e., outside of the 26 wards. Given that sectors are of fixed size and bound by the road network, with little room for densification as per the layout plans, it is assumed 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 5.1 (173). The method is shown more formally in Figure 5.2 and explained in greater detail in *section C.1* of *Appendix C*.

5.2.4 Road material stock calculation

The MS of roads within the Municipal Corporation of Chandigarh and its respective wards is estimated using OpenStreetMap (OSM) data to obtain the total length of different road types. The road data is dissected into the associated wards using available georeferenced ward boundary data (201). The study data covers all road types, excluding pedestrian and cycle paths, due to incomplete data, and therefore covers roads intended for vehicular use. Approximately 93% of the total available raw data, equal to approximately 1,923km, is included within the study. The road network in Chandigarh is classified into 'seven Vs' which categorise the hierarchy of the road network (205). These road types are homogenized into archetypes which are coherent with existing road MS studies by consolidating the classifications for standard road widths provided by the Indian Road Congress (IRC) (210) with those in other studies, such as Beijing (91) and Toronto (208). The road network of Chandigarh is therefore classified into urban expressways, arterial and sub-arterial roads, collector streets and local streets, *see Figure C.5* of *Appendix C*. Standard specifications for the 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. It is therefore necessary to 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 limited, however MIC values from a recent study in Vietnam may offer an appropriate estimation of road MS. The MIC values estimated for roads in Vietnam are adopted to calculate road MS relating to two key road compositions of varying widths (97). The road widths for each archetype are estimated using areal imagery from Google Earth which are combined with MIC values calculated within Vietnam (97) to create archetype-specific MICs, kg/m. The composition of roads are assumed based on road widths in relation to the MICs calculated in Vietnam (97) and the visual appearance from areal images which is verified with a study assessing pot hole samples within Chandigarh (211). 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.

5.2.5 Summary of methods

5.2.5.1 Ward and city-level residential building material stock calculation

1) Create archetypes by:
    a. Plot type, m^2, as per the master plan documents (212)
    b. Construction phase, i.e., whether the sector that the residential building is constructed in belongs to phase 1 or phase 2 of the masterplan.
2) Calculate MICs for each archetype, *kg/plot* or *kg/phase*, by:
    a. Quantifying the volume of foundations using structural drawings from the Chandigarh Housing Board (213), and the volume of internal and external walls, floors, and roofs as per the housing dimensions from the Chandigarh Administration Architectural Control Drawings (212).
    b. Multiply the density of construction materials provided in an and India study (118) with the total volume as calculated in the previous step.
    c. Quantify the MIC for each archetype, taking the average MIC for each archetype where multiple samples are available. Note that the maximum and minimum MIC values here are used to quantify the uncertainty in total MS calculations, see error bars in Figure 5.4.
3) Calculate inventory data by:
    a. Counting the number of plot types which appear within the architectural control drawings.
    b. Counting the total number of plots for sectors where the plot types are not listed on the architectural control, noting the sector to match to the construction phase number.
4) Quantify the total MS per ward by:
    a. Multiply the MIC values with the corresponding inventory data for each sector and aggregate values per material to the level of wards by using the census of India ward map (173).
5) Normalize total MS values per ward by:
    a. Dividing the total mass by the total population count within wards from the census data (173).
    b. Dividing the total mass by the total area of the ward as per the georeferenced boundary data sourced from a publicly available online repository (201)

5.2.5.2 Ward and city-level road material stock calculation

1) Create archetypes by:
    a. Obtaining the function of the road system as per the Chandigarh masterplan documents (212), comparing these to road archetypes of other studies (91,208) and the recommended lane widths for roads within India (210) to classify into generalizable archetypes, e.g., urban expressways.
    b. Quantifying the road width of each road type using Google Earth imagery, resulting in archetypes of roads classified by function, which are shown to have a standard width and composition.
2) Calculate MICs for each archetype, *kg/m*, by:
    a. Adopting MIC values from a recent study in Vietnam (97) given the lack of data, and verifying this with the composition of roads via a study on pot-hole samples within Chandigarh (211).
3) Calculate inventory data by:
    a. Obtaining the road length of Chandigarh's road system via OSM.
    b. Disaggregate the road length data as per the identified archetypes in the previous step.
4) Quantify the total MS per ward by:
    a. Disaggregate road lengths and types into wards using GIS software.
    b. Multiplying the road width and length for each archetype by the total length of each archetype for each ward of Chandigarh.
5) Normalize total MS values per ward by:
    a. Dividing the total mass by the total population count within wards from the census data (173).
    b. Dividing the total mass by the total area of the ward as per the georeferenced boundary data sourced from a publicly available online repository (201).

5.3 Results

We firstly turn to the results of 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 correspond 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 4.2 GJ/m^2. Material- and component-wise results show that there is little variation in MIC and EEI across building samples, see Figure 5.3 and *Figure C.3* of *Appendix C* respectively. Thus, the results reveal 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 Figure 5.3.

The EEI found is within the range of 3-5 GJ/m^2 for residential building in India (197), however the results highlight differences among other studies considering a similar archetype classification of residential building in India. Studies have calculated values ranging between 3.8-4.3 GJ/m^2 across a large range of built-up building areas (191) with others finding values of 3.5 GJ/m^2 and 3.4 GJ/m^2 for three- and four-story residential buildings within the same climatic and seismic zones as Chandigarh (86). Four-story residential buildings have recently been assessed within Vijayawada, a city in the south-east of India in different climatic and seismic zones to Chandigarh, with a value of approximately 3.1 GJ/m^2 (192), see

Table 5.2. It is important to note that, while it is possible 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. For example, studies fail to report the considered EE coefficient (191) or report EE values normalized by monetary cost (197). Specifically, here the EE for concrete is considered in terms of the total volume, *m^3*, as reported in a recent study (118) whereas others have adopted values disaggregated by bulk material such that the EE is instead recorded for cement and in terms of the total mass, *kg* (86). Such a lack of transparency across studies addressing material and energy use within India's residential building limits detailed comparison within and between regions.

Table 5.2: Comparison of embodied energy intensity, GJ/m^2.GFA, for residential buildings in India based on the city and seismic and climatic zone. Archetypes from other studies are selected which most closely relate to the composition of building archetypes within Chandigarh.

City	Seismic zone	Climatic zone	Archetype	EE (GJ/m2)	Reference
Chandigarh	IV	Composite	3-story, MFH, brick masonry envelope and RC structural frame	4.2	Present study
Delhi	IV	Composite	3-story, burnt clay brick masonry-based house	3.6	(86)
Allahabad	III	Composite	4-story, MFH, brick envelope and RC structural frame	7.4	(190)
N/A	N/A	Moderate	4-story, Rubble stone masonry foundation, RC frame structure with burnt brick masonry infill, RC roof and ceramic, mosaic tile flooring	3.8	(191)
N/A	N/A	Composite	1-story, Rubble stone masonry foundation, load bearing stone masonry structure, RC roof and cement concrete flooring, and Rubble stone masonry foundation, RC frame structure with burnt clay brick masonry infill, RC roof and mosaic tile flooring respectively	1.0- 4.1	(191)
Vijayawada	III	Warm and humid	3-story, RC framed structure with brickwork in sub- and super-structure	3.1	(192)

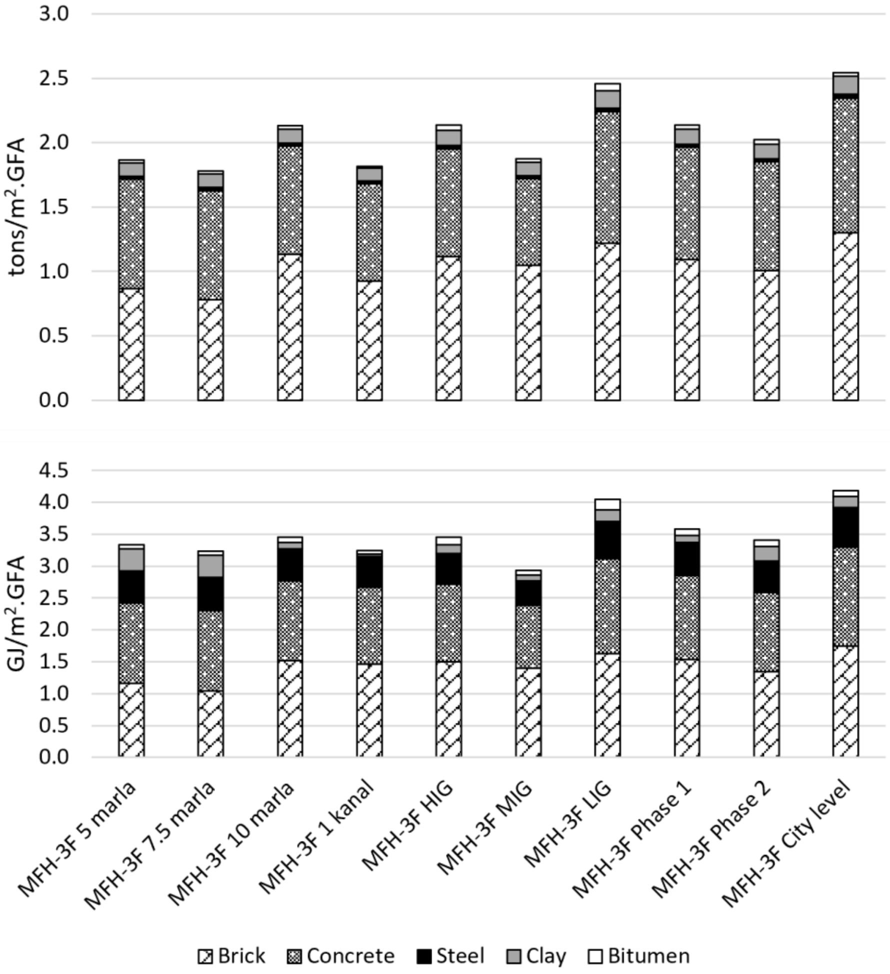


Figure 5.3: (Top) MIC disaggregated by materials, and (bottom) embodied energy intensity of materials for MFH-3F housing of brick walls and reinforced concrete floors and roofs, for MIC values in terms of building components *see Figure C.3* of *Appendix C*. Twelve building samples are used corresponding 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, MICs are also calculated 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.

5.3.1 Material stocks of residential buildings and roads in Chandigarh

We now turn to the estimated MS in residential buildings and roads at the city and sub-city scale. The results are discussed further in terms of the resulting urban form and opportunities for secondary resource use in sections 5.4.1 and 5.4.2 respectively. To estimate the MS of residential buildings within Chandigarh and its wards, more detailed residential building archetypes are created to disaggregate building samples by plot category or by development phase depending on the availability of inventory data, as outlined in section 5.2.3 and Figure 5.2. The total residential building MS is estimated for the year 2011, with a total of 41,040 plots estimated across the 17 wards for which data is available. The results reveal approximately 27.8 Mt of MS in residential buildings in Chandigarh, ranging 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 8% 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 5.4 shows the variation in stock accumulation between the wards of the Municipal Corporation of Chandigarh.

A total of 63.1Mt of MS is estimated to have accumulated within 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 5.5. 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 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 respectively, 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.

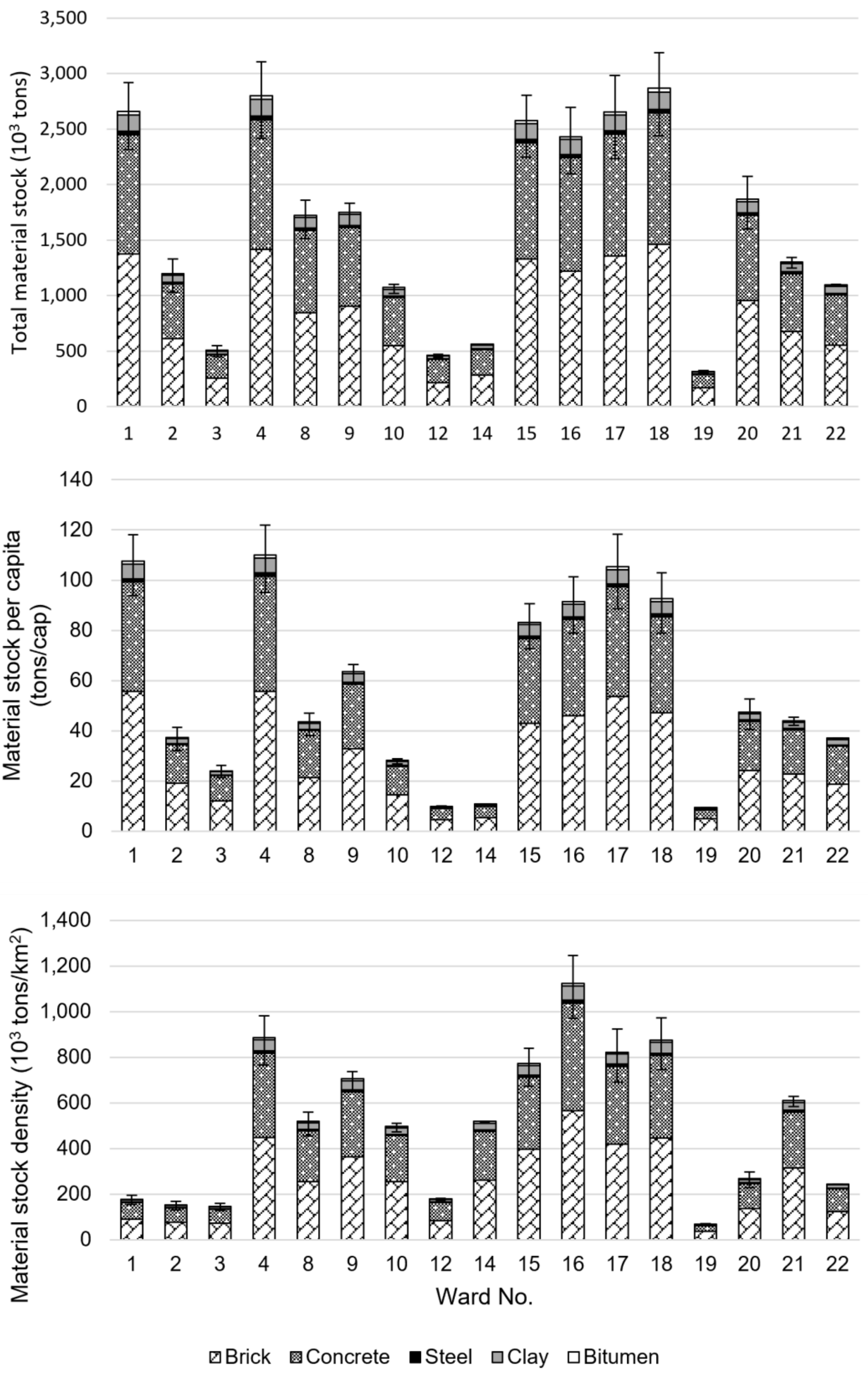


Figure 5.4: Material stock of residential buildings by material type across the wards of the Municipal Corporation of Chandigarh. (Top) Total stock accumulation, (middle) total per capita stocks, (bottom) material stock density. For a breakdown of results by building component refer to *Figure C.4* of *Appendix C*.

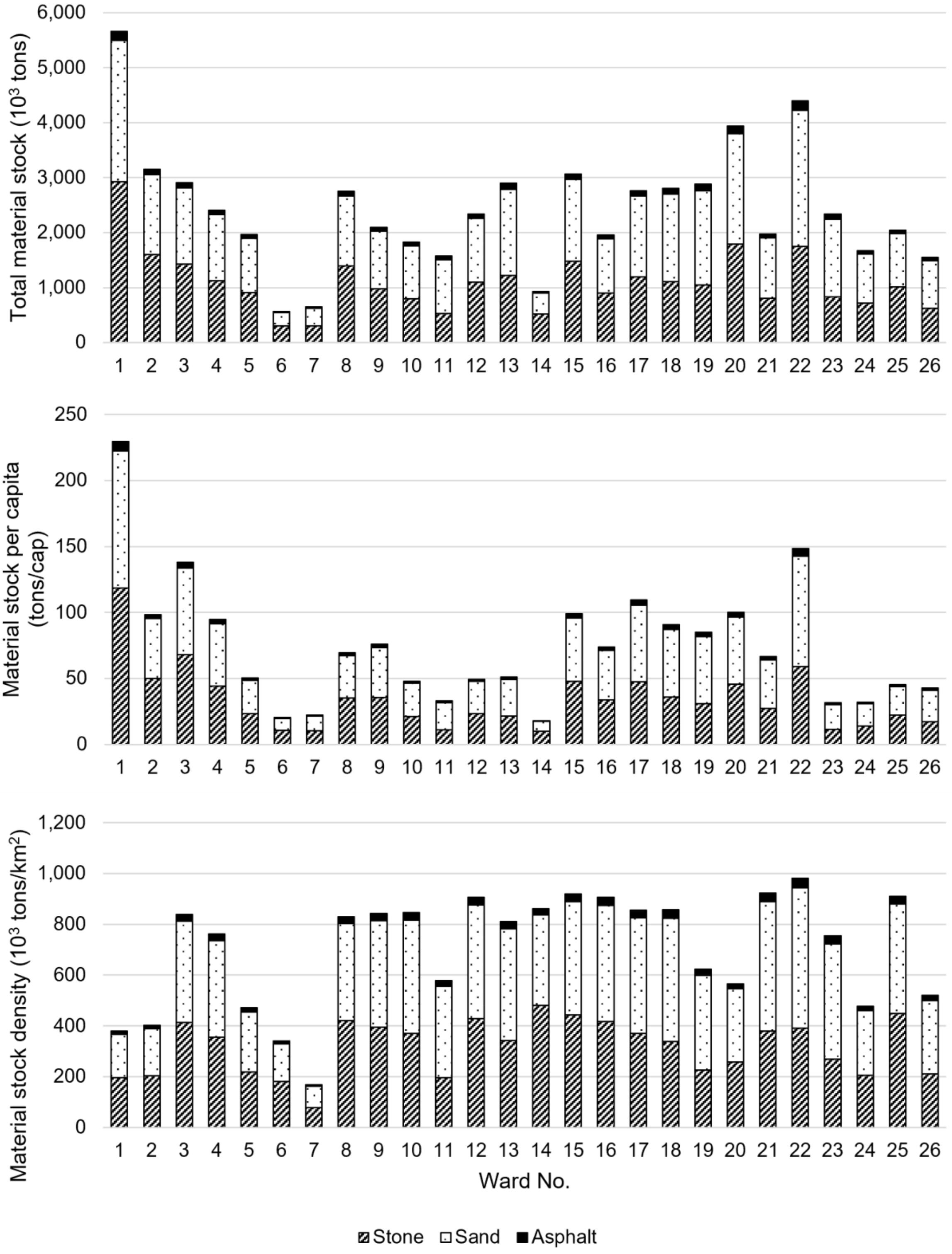


Figure 5.5: Material stock of roads by material across the wards of the Municipal Corporation of Chandigarh. (Top) Total stock accumulation, (middle) total per capita stocks, (bottom) material stock density.

5.4 Discussion

5.4.1 Composition and distribution of built environment stocks in cities

We have seen that the accumulation of MS in roads and residential buildings varies across the local areas of Chandigarh. Figure 5.6 Illustrates this further, showing that the relative composition of areas in terms of residential building and road MS varies significantly among wards. The ratio of this stock accumulation, i.e., the ratio of the total MS of roads to the total MS of residential buildings, varies from 0.8 to 5.7. This can be largely explained by the 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 a 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 large village burial site. This variation in the available residential floor space and the uniformity of road provision among wards through the 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 (93). 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 5.7. To explain this further, and despite limited studies to draw comparison to, the city-level road-to-building MS ratio is compared with other cities. The ratio is found to be 2.27 for Chandigarh, which is considerably larger than other studies such as the city centre (0.32) and outskirts of Odense (0.86) (53), Salford (0.29) (66) or Wakayama city centre (0.13) (66). This ratio suggests that built environment MS in Chandigarh's are 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 within the study of Odense (53). This finding corresponds with Chandigarh's restriction on high-rise buildings, discussed in section 5.2.1, which will inherently limit the density of urban development as floor space becomes limited and leads 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. Taking this into account, the ratio drops to 1.7. Additionally, when applying lower MIC values for roads from an alternate study in Vietnam (214), *see Table C.4* of *Appendix C*, the ratio further reduces to 1.0. However, this remains significantly higher than in other cities and underlines that the sprawled urban form is a key driving factor in the resulting MS accumulation. It is also important to note that the ratio accounts only for residential buildings, and it is therefore expected that the actual road-to-building stock ratio would reduce further.

The results also show that the per capita and per 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 (93) and Bandung (94) consider relatively low-rise housing compared to Rio de Janeiro (67) 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. The results also reveal that cities with a higher population density tend to have MS per km^2 and lower MS per capita for residential buildings, see Table C.5 and Figure C.6. This indicates denser populations tend to achieve a greater utilization of MS within more dense urban forms. The results do not reveal the same for roads, see Figure C.7, however, there remains a limited sample size and further work across other developing cities is needed. These results highlight that even though we find similarities in residential building MS accumulation and population densities, 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 to building MS than in other cities.

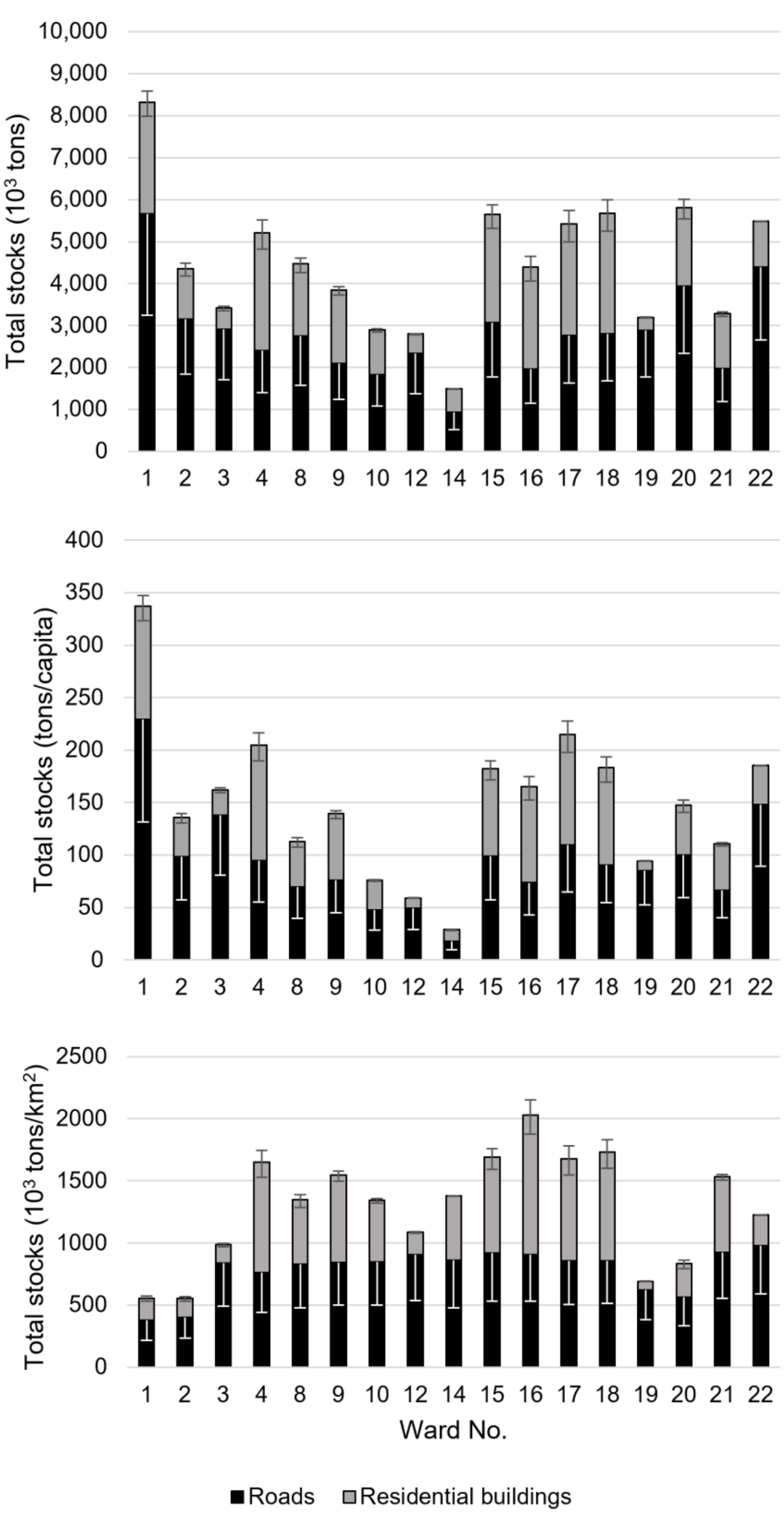


Figure 5.6: Relative accumulation of road and residential building material stocks the wards of the Municipal Corporation of Chandigarh. (Top) Total stock accumulation, (middle) total per capita stocks, (bottom) material stock density.

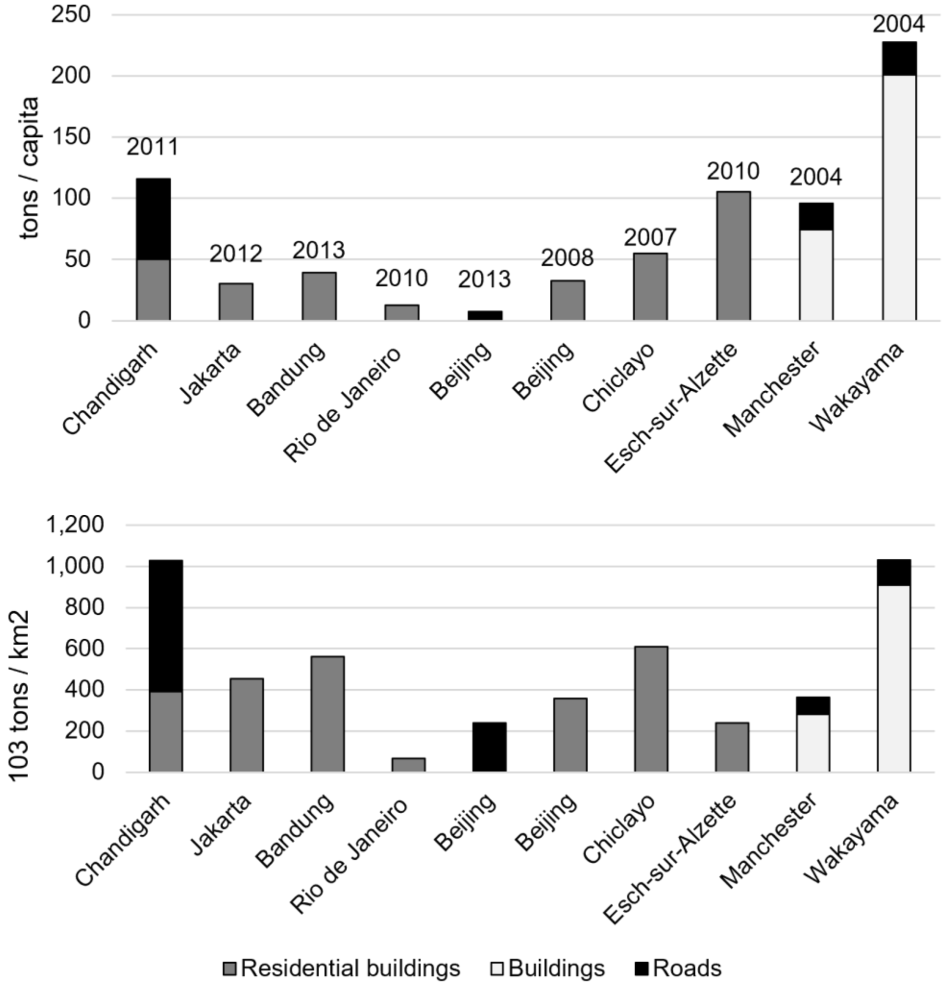


Figure 5.7: (Top) Material stock per capita and (bottom) material stock density comparison to other city-level studies (66,67,82,91,92,94,196). See *Table C.5* of *Appendix C* for data used to calculate MS coefficients and a comparison of the material stock coefficients respectively.

5.4.2 Secondary resource use and implications for resource efficiency

The results indicate that around 67% of the total MS of roads and residential buildings is below ground, i.e., it is used to construct either the base layer of roads or the foundations of residential buildings. The total underground MS of residential buildings and roads is 23% and 86% respectively, indicating that the majority of the total MS may be considered as “lost stocks” and thus offer limited potential for secondary reuse. Road MS dominates overall MS accumulation, and we find that this stock has 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 future resource efficiency strategies. Steel reinforcing generally limits the recoverability of components as materials are difficult to separate, as a result the reuse of foundations in-place 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 (209) may impact the quality and reusability of materials and components. 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. However, given that concrete elements are reinforced and that they contribute a significant proportion of the total MS accumulation within residential buildings, demolition waste of existing buildings may be significant.

Densification of urban areas is often cited as a key resource efficiency strategy due to a greater per capita utilization of existing built environment MS, which is verified within urban scaling literature concerning material efficiencies resulting from city growth, discussed in Chapter 2. The masterplan for Chandigarh to 2031 (209) 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. This would result in a greater efficiency in stock utilization given that a greater proportion of the population will be using existing road stocks. However, such opportunities are generally limited and may not offer an adequate long-term solution to urbanization and future resource efficiency. One longer-term option for densification could be through the vertical extension of existing buildings, however this would be unlikely given the various barriers to such implementation and that additional materials would likely be required to reinforce the existing structures to facilitate this (215). To overcome such growth constraints, replacing the existing low-rise development with higher-rise structures may be a feasible option, as shown within a study of Lince, Peru which exhibits similar growth constraints (48).

The urban form has therefore resulted in a considerable 'lock-in' effect which significantly restricts opportunities for future 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 by the demolition of existing buildings which have limited potential for future reuse. These results highlight the importance of understanding MS composition and distribution to predict future demolition waste, and to uncover the potential for secondary resource use within any redevelopment of the city.

5.4.3 Material stocks vs basic needs outcomes

We now turn to a comparison of the total stock accumulation and levels of basic needs outcomes within Chandigarh. The average basic needs outcomes are measured by the SDI as in previous chapters and the population density for wards are calculated utilizing the census data and the available georeferenced boundary data. The SDI and total MS accumulation for the wards of Chandigarh are mapped in Figure 5.8, revealing little to no pattern in total stock provision and basic needs outcomes. Chandigarh achieves relatively high basic needs outcomes for all wards, with total per capita stock values ranging from 29 to 337 tons in wards achieving near universal basic needs outcomes, i.e., $SDI -> 1.0$. However, the results also highlight specific concentrations of deprivation, with wards 13 and 20 achieving an SDI of 0.60 and 0.65 respectively which is due to a significant lack of water and sanitation infrastructure, despite relatively high housing and electricity access. Despite this, the results reveal a significant variation in the provision of MS among areas that achieve near universal basic needs outcomes, which begins to suggest levels of overconsumption in terms of basic needs outcomes. However, the increased provision of MS may be a consequence of other key factors. For example, the variation may be explained by the presence of non-residential building MS, as discussed in the previous section regarding the composition of local areas, which may necessitate the increased provision of road MS compared to other areas to ensure connectivity. This non-residential building MS may also be essential within broader context of the city, for example providing key services as places of work as well as educational and healthcare facilities.

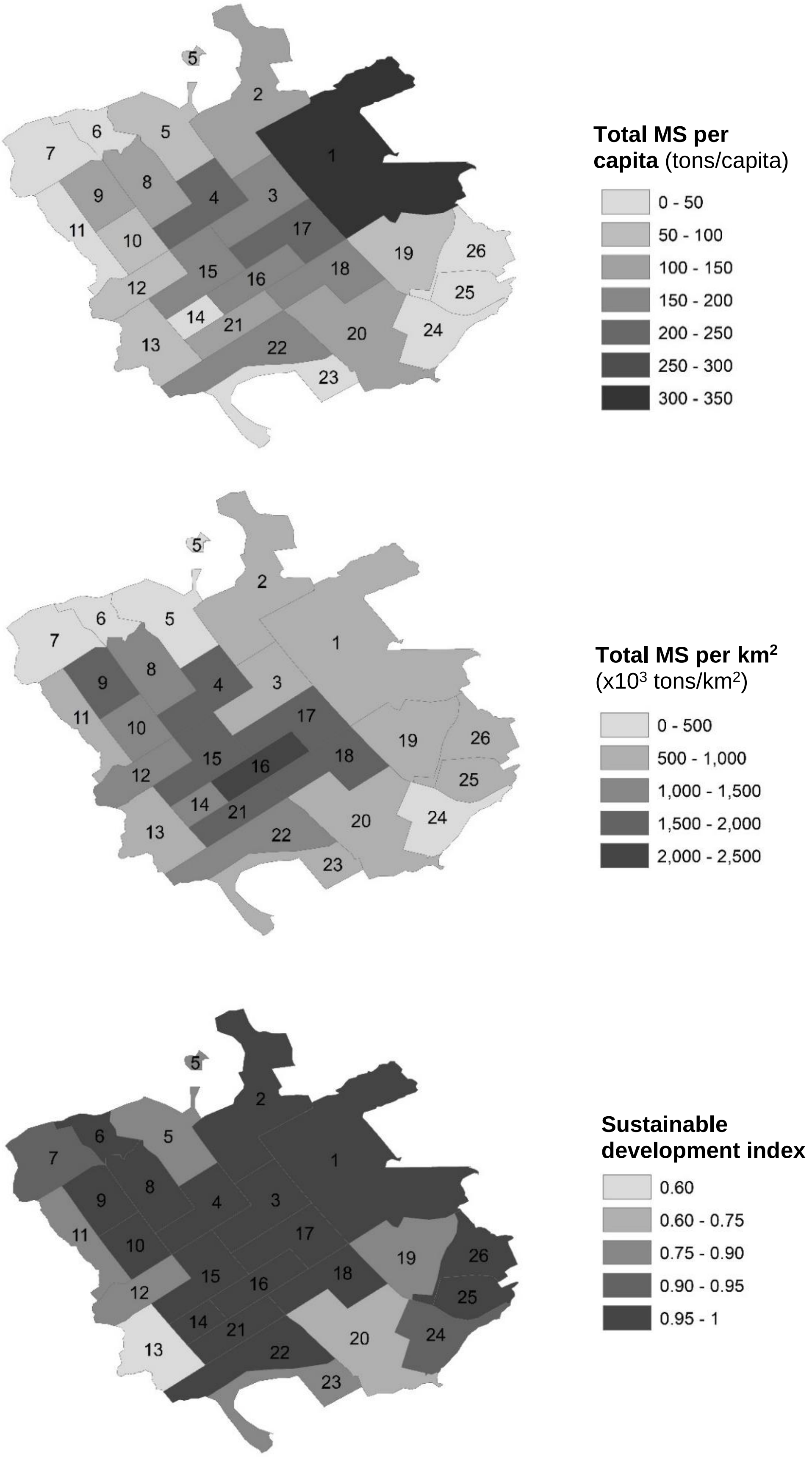


Figure 5.8: Spatial distribution of the (top) total MS per capita, (middle) total MS per square kilometre, and (bottom) average basic needs outcomes among the wards of Chandigarh. The results show little to no pattern in the total MS provision of roads and residential buildings and basic needs outcomes.

The total per capita stock accumulation is also investigated with regards to the population density of the wards to further explain this variation. The results reveal a general trend of more densely populated local areas utilizing stocks more efficiently, i.e., lower per capita stock accumulation in areas with higher population densities, see Figure 5.9. This is consistent with observations among cities which highlights that similar sub-city trends are also observed within urban areas. Further, the results do not show a clear trend associated with the observed basic needs outcomes, however this is to be expected given the relatively homogenous achievement of basic needs across Chandigarh as discussed previously. It is also found that ward 14 has a significantly larger population density and lower per capita stock accumulation than others. This may be a result of the variation in the ward compositions as discussed previously, with ward 14 being comprised of only one densely populated sector dedicated to residential buildings. The other half of the ward is dedicated to a village burial site and thus does not contain any further transport infrastructure.

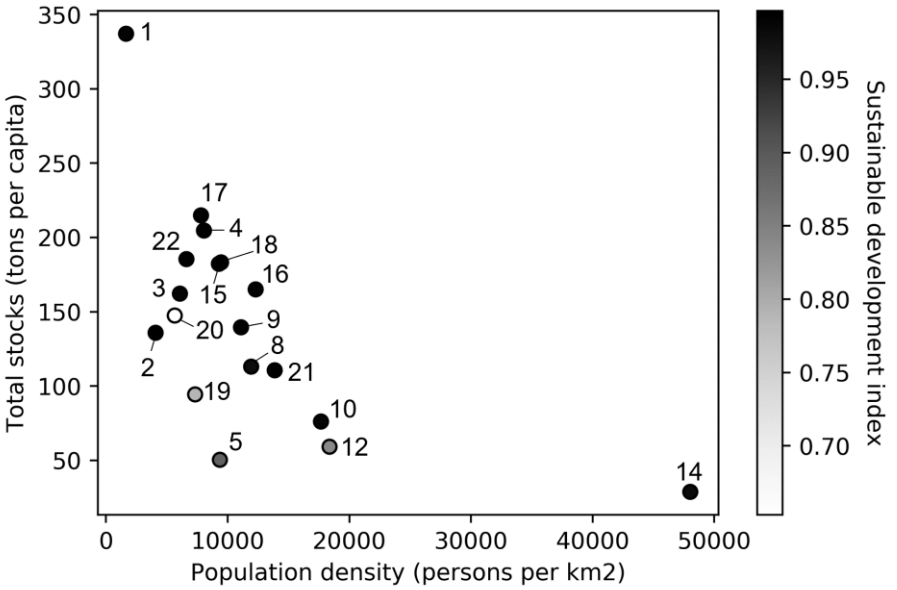


Figure 5.9: Total stocks per capita versus the population density for the wards of Chandigarh, where the colour of the point represents the average basic needs outcomes for the respective ward measured by the SDI as in previous chapters. Note that data labels correspond to the ward numbers.

5.5 Limitations and concluding remarks

It is important to note that the policy insights created here may not be directly transferable to other areas given the lack of existing city-planning and similar urban forms within India. Further MSA studies which related MS to basic needs outcomes are needed within areas which have experienced significant urbanization in recent years, for example in Greater Mumbai, to understand stock distribution and lock-in effects within more "organically" developed regions and the consequent implications on urban planning and policy. However, the principles relating to built environment MS provisioning identified within Chandigarh remain relevant for the construction of new areas given the GoI's clear desire to master plan new urban areas to ensure sustainable urbanization. Further, as we have seen in Chapter 4 and in building-level studies within India (86,190–192), the GoI is likely to adopt similar housing archetypes in terms of the construction materials selected and which may therefore continue to present the same lock-in challenges associated with reusing materials. Thus, the Policy Evidence for secondary resource use remains particularly relevant in different contexts.

A 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 which achieves high basic needs outcomes. Although the study has provided first steps in this direction, there remains limitations to understanding the accumulation of built-environment MS within India. As with many other bottom-up stock assessments, the lack of available data renders verification of the inventory and building level data limited. Areal imagery from Google Earth is unavailable in India to a level that allows the façade material to be identified and the available census data does not list the number of census houses per ward by their material composition. As such, it remains difficult to verify the plot number estimations across wards which may limit the accuracy of per capita stock assessments. Building inventory and archetype information is significantly lacking 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. Without a comprehensive understanding of the material composition and intensity of roads within India it is difficult to verify the findings of the ratio of the total road MS to total residential building MS. However, as we have discussed, the sensitivity analysis the MS estimations along with the homogenous low-rise development suggests that it is the sprawled urban environment that has led to such a high ratio compared to other areas.

To better capture the relationship of stock-service outcomes in terms of basic needs, it is important for future work to address the accumulation and distribution of urban infrastructure in Chandigarh. This may offer valuable insight into the relative composition of non-mobile built environment MS in relation to the key basic needs monitored by the SDI. This is important given that concentrations of deprivation in Chandigarh are a result of a lack of access to such MS, i.e., water and sanitation infrastructure. Additionally, important future work should seek to assess the topology of the city more comprehensively to better understand the dynamics of service provision in terms of MS. For example, further work may also evaluate the MS of non-residential buildings to better quantify the ratio of road to building MS, both for India and in comparison to other cities. This may also be integrated with assessments of connectivity of residential areas to non-residential services to offer an understanding of how mobility facilitated by the extensive road network may enable high living standards, e.g., through impacting travel to work times or access to water infrastructure. This would offer particularly valuable insight into how those more deprived neighbourhoods are able to utilize the provided MS. This therefore lends such assessments to the optimal reblocking methodology used to quantitatively assess and improve urban development through the physical access to places of work and residence (216). This has been adopted to assess challenges associated with the connectivity of slum populations to services within local case study areas of Africa (216), which if applied in Chandigarh may offer valuable insight into redevelopment strategies in terms of connectivity, i.e., the provision of MS in transport infrastructure as well as pipelines for water and sanitation infrastructure.

To conclude, we have seen 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 are comparable to other cities in the Global South, road MS have 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 significant amount of waste expected to be generated in India from the construction sector due to rapid urbanization (25) and the planned redevelopment of Chandigarh to 2031 (209). The presented study 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.

6 Adequate housing provision based on current trends

6.1 Introduction

In the previous chapters, we have seen the current trends of MS provision and basic needs outcomes within India. The coupling of brick and concrete residential building MS and basic needs outcomes across the urban areas of India has been quantified, as well as the significant material requirements for such residential building provision. Despite deficits in urban housing being generally much lower than key societal services from infrastructure, we have also seen the widespread challenge of adequate housing provision across the urban areas of India, particularly for those experiencing multidimensional deprivation of basic needs. Thus, the MS requirements for universal housing provision may itself be a significant challenge to sustainable development if current trends are to continue. The aim of the study here is therefore to build on the understanding of residential building MS provision and overall basic needs outcomes from previous chapters by answering the following research question:

- What are the material stock requirements and consequent impacts on basic needs resulting from the upgrade of inadequate housing nationally?

The provision of adequate housing is a universally recognized basic human need and a key target for sustainable development indicated by SDG 11.1.1 (159), with many studies addressing the challenge of housing provision from a low-cost housing perspective (86,198,217,218). More recently, as the decent living standards (DLS) literature has gained prominence, studies have begun to address energy requirements for adequate housing motivated by the demand for minimum standards of living and the achievement of SDGs (4,8,117,118,122). Parametric analyses have been used to quantify building-level material requirements and lifecycle energy implications for adequate housing provision in different climatic zones within India (118,219). Such studies have revealed the significant proportion of embodied energy on overall lifecycle energy requirements (118). Further, studies have revealed substantial national energy requirements required to provide DLS accounted for by construction materials within urban housing (8,117,118,122). The provision of adequate residential building materials is therefore shown widely across literature as a crucial challenge to future resource use in terms of providing minimum standards of living, particularly in regions of the Global South.

6.1 Introduction

The discussed studies have addressed the material requirements for adequate housing based on minimum requirements identified in the DLS literature, specifically through solid and durable housing construction providing a minimum floor space[10]. As such, the bottom-up approach has been prominent in assessment of closing deficits in DLS globally (8,122) nationally (117,118) and within case-study cities (4). This is often combined with scenario-based modelling which considers varying definitions of inadequate housing (4), different target years for universal provisioning of services (8), or implementation of varying degrees of energy-saving strategies to further reduce energy requirements (117,118,122). However, studies address the challenge of housing provision in terms of *sufficiency* through the adoption of minimum DLS requirements and thus consider only minimum service requirements. This is generally through the theoretical design of a single adequate urban housing archetype based on current construction practice, i.e., reinforced-concrete framing, and which provides the minimum required floor space, with more ambitious scenarios considering alternative material types. However, as we have seen shown in previous chapters, current trends of housing provision within India reveal that brick and concrete housing is most prevalent and which is a widely adopted housing type in areas achieving high basic needs outcomes. There is therefore a lack of a 'baseline' assessment of adequate housing provisioning based on current trends. Further, existing studies fall short in relating material requirements to improvements in overall basic needs, which would highlight the relative scale of challenges within and across nations. The discussed studies, as well as those illustrating global trends (46,75), suggest that nations at incipient stages of in-use stock growth, such as India, are likely to increase in-use stocks of substantial and carbon-intensive materials such as brick, concrete and steel in the coming decades. It is therefore important to evaluate the material implications of 'business as usual' within these nations and the extent to which such provisioning improves overall basic needs. This may offer insight into the extent to which DLS scenarios improve material and energy efficiency through the provision of *sufficient* services and in terms of energy-saving measures beyond this.

Here, the aim is to provide an indication as to the material requirements for upgrading inadequate housing based on existing adequate housing provision. While the study does not aim to provide an extensive account of the required MS in India due to significant data

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[10] As we will discuss, the required floor space varies between studies. However, the widely accepted values of $10m^2$ (117,118), $8.75m^2$ (4), or $15m^2$ per person (122) are often adopted.

limitations, it does seek to indicate general trends of housing provisioning and improvements to overall basic needs. As such, the study seeks an improved understanding as to the potential magnitude of material use to improve inadequate housing if current trends are to continue. In doing so, the study presents an approach which utilizes assessments of existing residential budlings and comprehensive census data. This therefore overcomes challenges associated with survey sample data, widely utilized within existing DLS studies, which requires interpolation or extrapolation to estimate overall deficits in adequate housing provision and thus may contain unrepresentative inventory data relating to inadequate housing. The approach considers the continued provisioning of adequate housing in the context of high basic needs outcomes. Scenarios adopted are formulated to indicate upper and lower bounds of material provision based on the coupling of MS compositions and basic needs within India. Nationally aggregated MS requirements are presented based on current trends to facilitate a comparison to existing in-use stocks in other nations and the potential energy requirements compared to DLS scenarios within India. From here, results are presented relating basic needs outcomes to MS requirements sub-nationally to reveal the scale of challenges associated with improved standards of living across urban areas.

6.2 Methodology

The quantification of MS required to provide adequate housing here quantifies the indicator for built capital (110) given that it is concerned with the built form of natural materials within the context of service provision, and not the quantification of the minerals explicitly extracted e.g., bricks for adequate housing as opposed to the constituent materials such as clay. The general approach is broadly similar to those existing methods assessing the energy requirements for improvements in decent living standards within developing countries (117,118,219). This follows a bottom-up approach to extrapolate the total MS requirements for adequate housing across the existing gaps in such provision. However, instead of normalizing material requirements by floor area, the material requirements per household are calculated. This is achieved by quantifying the material requirements per household based on the city-level results of Chandigarh presented in the previous chapter, thus considering household requirements within the context of high living standards and which meet the minimum DLS requirements. From here the gap in adequate housing provision is assessed based on the permanency of housing, as well as for upgrading urban areas based on the coupling of MS with basic needs presented in Chapter 4, i.e., upgrading housing which does not follow the identified trends. Nationally aggregated MS requirements are presented across each scenario and compared to the existing in-use stocks in other contexts. The MS required for upgrading non-permanent housing across sub-national scales are then assessed to reveal trends in the required MS provision and improvements to overall basic needs outcomes. This considers the scale-dependence of basic needs outcomes and the importance of such administrative scales in ensuring basic needs outcomes revealed in Chapter 3, therefore assessing such trends at the scales of towns and cities as well as states. National and city-level MS assessments are then compared to existing DLS requirements at the regional and city-level to reveal the extent to which minimum size requirements may begin to reduce the resource requirements for adequate housing within India.

6.2.1 Defining inadequate housing

Deficits in adequate housing are firstly calculated as the total number of households which are identified as inadequate by the definitions presented in Table 6.1. The SDI is utilized to quantify improvements to overall basic needs, as defined in previous chapters, shown formally in *equations 1* and *2*.

$$X_i = \sqrt[n]{\prod_{j=1}^{n} X_i^j} \qquad [1]$$

Where the index, X_i, is formulated by aggregating n dimensions, for area i. The index considers the non-weighted average achievement of the normalised dimensions (176) resulting the final index given *in equation 2*.

$$X_i = \sqrt[5]{X_i^{water} X_i^{water\ location} X_i^{housing} X_i^{sanitation} X_i^{electricity}} \qquad [2]$$

Absolute improvements to overall basic needs outcomes are calculated based on the achievement of universal housing provisioning such that $X_i^{housing} = 1$, and thus calculate absolute improvements to basic needs outcomes as in *equation 3*.

$$X_{i,improved} = X_{i,new} - X_{i,original} \qquad [3]$$

Table 6.1: Definition of inadequate housing used to calculate the deficits in housing provision across three different scenarios. Note that all scenarios are compared at the nationally aggregated scale to facilitate comparison to existing literature, however only scenario 1 is related to changes in basic needs outcomes sub-nationally.

Scenario	Definition of inadequate housing	Notes
1	Inadequate housing defined as those households which are not non-permanent.	Definition used to define inadequate housing (4,6,219).
2	Inadequate housing defined as those households which are not constructed from: 1) Brick walls and concrete roofs, or 2) Concrete walls and concrete roofs.	The results of Chapter 4 quantify current trends within India revealing that a greater composition of such households across urban areas is associated with greater basic needs outcomes.
3	Inadequate housing defined as those households which are not constructed from brick walls or concrete roofs.	

6.2.2 The provision of material stocks to upgrade inadequate housing

The MS required per household based on the residential building MS of Chandigarh is calculated and therefore a single adequate urban housing archetype is considered. Residential buildings within Chandigarh are shown to be constructed primarily using burnt brick for walls and concrete for floors and roofs, with Chandigarh achieving high a provision of adequate housing to urban dwellers. This housing composition also accounts for 45% of the urban households nationally based on the census of India (173). Households of the same composition and number of stories as in Chandigarh are also studied within Delhi (86), and Vijayawada (192) with four story households of the same composition also documented in other regions of India (190,191). Additionally, a study has found a strong correlation between households constructed of burnt brick walls and permanent housing provision among India's districts (120). The adopted urban housing archetype to define MS requirements for adequate housing may therefore provide a representative estimation of the required MS for adequate housing within India based on current trends. The housing archetype also satisfies the DLS criteria outlined in previous studies (8,117,118). The considered archetype provides an average floor area of 26m^2/person and 112m^2/household across Chandigarh. Economically weaker-sections and low-income groups are stated to require a minimum of 28m^2 and 60m^2 per household respectively (4). Alternatively, the minimum floor area is defined as 35m^2 per household for a household size of four (4). The theoretical household size would therefore need to exceed approximately twelve persons to be deemed inadequate in this case. This is unlikely given the mean household size in India is approximately five persons with only 0.02% of the total number of urban households exceeding eleven persons based on the census of India (173). The archetype adopted here is therefore based on existing examples of adequate housing provisioning, i.e., those of Chandigarh examined in the previous chapter, which achieve the minimum floor space and material construction requirements as per the DLS literature. Specifically, the study assesses the material requirements for upgrading inadequate housing nationally via MS provisioning at the same intensity per household as provided within Chandigarh. This may therefore offer improved insight into actual future MS requirements for housing provision across India based on existing trends.

Given the available inventory data pertaining to inadequate housing, i.e., number of *households* provided within the census, it is possible to calculate a scaling coefficient based on the results of Chandigarh. This is achieved by quantifying the total MS of residential buildings at the city-level, as outlined in the previous chapter and shown in *equation 4* below:

$$MS_m = \sum_i MS_{m,i} = \sum INV_{i,t} \; x \; MIC_{m,i} \qquad [4]$$

Where the total city-level MS of Chandigarh is calculated as the total mass of material or component, m, of type, i, in the reference year, t. The inventory of items of type, i, within the wards, for the reference year, t, is then multiplied by the MIC, in mass per gross floor area, to calculate the total mass of each material in each item type which is summed over all wards within the city. The MS per household is ten calculated as shown in equation 5 below:

$$MS_m^{household} = \frac{MS_m}{N} \qquad [5]$$

Where the total MS for material, m, is divided by the total number of households, N, considering only the number of wards for which MS is calculated due to data availability. The corresponding embodied carbon (EC) and embodied energy (EE) are also assessed to shed light on the relative contribution of materials to overall environmental impacts, shown to be relevant in the previous chapter. Upper and lower bounds of MS are also assessed by calculating the total MS provided in Chandigarh based on the maximum and minimum values for each building archetype, corresponding to the values used to assess uncertainty in Figure 5.4.

6.2.3 Summary of methods

1. Scenario 1 - Using the census of India 2011 amenities and assets dataset, quantifying the number of households with inadequate housing as those which are of non-permanent construction for all towns and cities, subdistricts, districts and states.
2. Scenario 2 - Using the census of India 2011 dataset recording the count of household by the predominant material of wall and roof, define inadequate housing as those which are non-Chandigarh housing, i.e., non-brick wall and concrete roof construction (BCHH).
3. Scenario 3 - Using the census of India 2011 dataset recording the count of household by the predominant material of wall and roof, define inadequate housing as those which do not follow the trends identified in Chapter 4, i.e., non-BCHH or concrete wall and concrete roof construction (CCHH).
4. Scaling coefficient - Quantify the material requirements per households, kg / household, of each material required for adequate housing provision based on the city-level archetype in Chapter 5, i.e., the total city-wide material in residential buildings divided by the total number of urban households.
5. Quantify the material stock required to upgrade inadequate housing based on the household gaps for each scenario, i.e., the number of inadequate households identified in steps 1-3, by multiplying the required material mass per household by the number of inadequate households.
6. Quantify error bars for each scenario by quantifying the total MS of residential budlings at the city-level in Chandigarh as per the maximum and minimum required MS from the building samples and divide this by the total number of urban households to calculate the scaling coefficient. Follow step 5 for the maximum and minimum MS required.

6.3 Results and discussion

6.3.1 Material requirements for inadequate housing

The results firstly show that the required MS for adequate housing provision is approximately 216 tons/household, equivalent to 370 GJ/household and 52 tonsCO2e/household. These values are extrapolated over the existing deficits in housing provision based on the scenarios defined in Table 6.1 and presented as nationally aggregated estimates in Figure 6.1 For scenario 1, it is estimated that a little over 10 million households are identified as inadequate, requiring approximately 2.2 Gt of material to ensure universally adequate housing. This is equivalent to around 80 times the total residential building MS of Chandigarh. The equivalent EC and EE are approximately 0.54 Gt of CO2e, and 3.8 EJ respectively. In scenario 2, it is estimated that 21.1 million households are inadequate requiring 167 times the existing residential building MS provision of Chandigarh. Scenario 3, i.e., homogenising the total housing stock to that of Chandigarh, results in 190 times the residential building MS of Chandigarh, with approximately 24.5 million households requiring upgrades.

Assuming that all households are provided with housing to the same standard as that of Chandigarh, the national SDI increases from 0.79 to 0.81. The results therefore show that adequate housing provision requires a substantial quantity of material for minimal changes to overall basic needs outcomes. The sub-national distribution of MS among towns and cities as well as states in relation to the improvements in overall basic needs outcomes and the total size of the area is shown in Figure 6.2. Figure 6.3 shows the same relationship but in terms of the required per capita MS. The results together reveal that larger urban areas, i.e., larger data points, require a significantly larger provision of MS, and significantly lower MS per capita, to upgrade inadequate housing whilst achieving relatively low improvements to overall basic needs outcomes compared to smaller urban areas. Smaller urban areas generally require significantly lower total MS, but much larger MS per capita, to upgrade inadequate housing with relatively high improvement to overall basic needs outcomes compared to larger urban areas. The results therefore reveal a general trend, that larger urban areas tend to require more overall and experience minimal improvements to basic needs outcomes, whilst smaller urban areas tend to require less overall and experience greater improvements. However, there is variation in this relationship, with some smaller urban areas requiring a substantial amount MS per capita for marginal improvement to overall basic needs outcomes. Note here that the provision of MS for adequate housing only indicates potential improvements to basic needs outcomes as per the definitions of adequate housing given that we assume housing is provided to the same standard and thus MS per household as that of Chandigarh. The housing of Chandigarh is found in previous chapters to meet adequate housing definitions due to its permanent construction, but also meets minimum floor area per household as discussed previously. As such, the results do not explicitly state or imply that there is a causal relationship here between improved basic needs outcomes and the associated provision of MS. It is also important to note that the observations of significant required MS per capita with low improvements to overall basic needs outcomes in smaller urban areas is generally an artifact of the scale of existing housing deprivations, which are found to be lower in larger urban areas and generally higher in smaller urban areas, see Chapter 3.

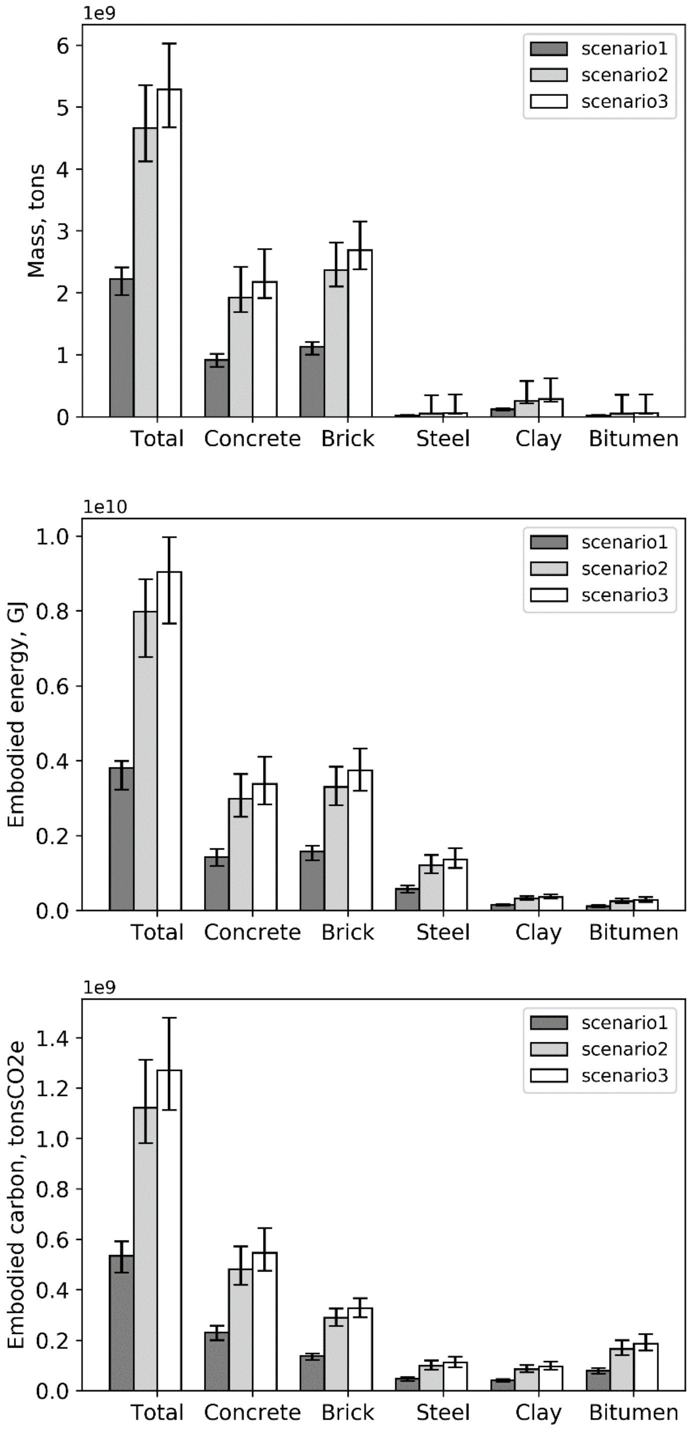


Figure 6.1: National (top) material, (middle) embodied energy, and (bottom) embodied carbon requirements for each scenario. Note that error bars are calculated by adopting the minimum and maximum MS values from the city-level Chandigarh residential building archetype to calculate minimum and maximum scaling coefficients, MS / household.

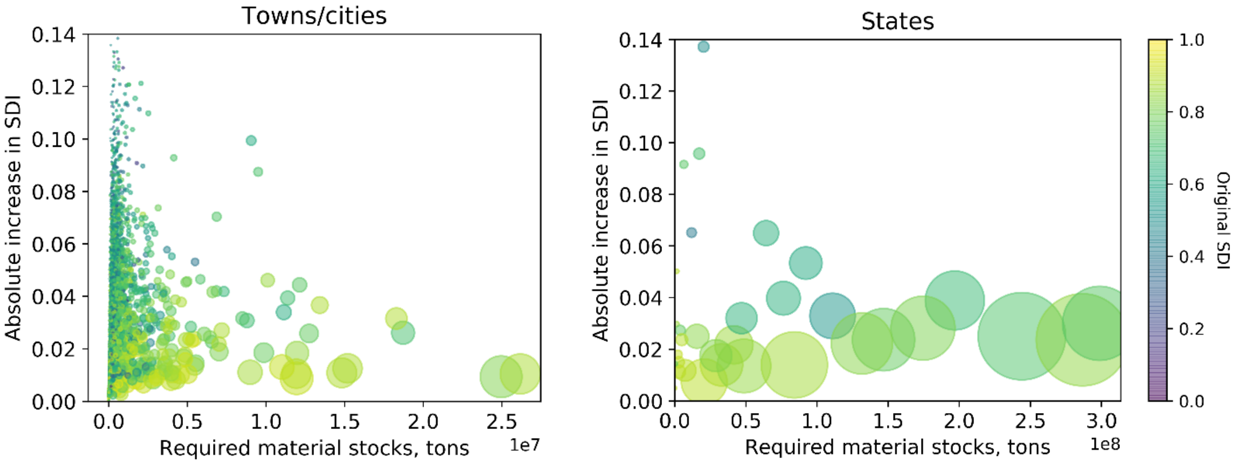


Figure 6.2: Total material stock required versus absolute increase in the SDI, $X_{i,improved}$. The colour of the data point corresponds to the original SDI values, and the size of the circle indicates the total number of households.

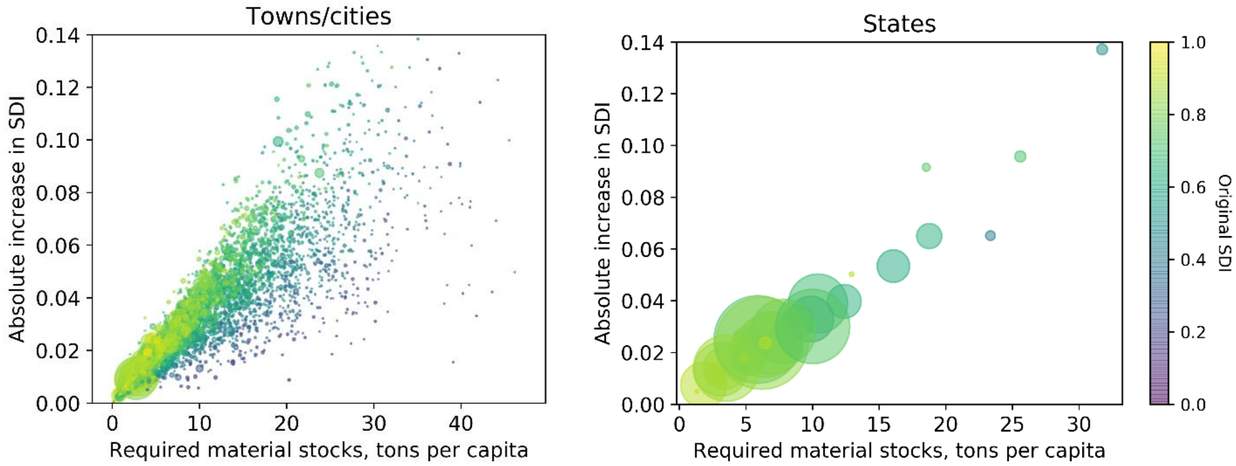


Figure 6.3: Required material stocks per capita versus absolute increase in SDI, $X_{i,improved}$. The colour of the data point corresponds to the original SDI values, and the size of the circle indicates the total number of households.

6.3.2 Implications for housing provision based on minimum benchmarks and existing in-use stocks

We now turn to a comparison of these results to those studies addressing deficits in DLS outcomes to understand the extent to which the provision of housing to minimum benchmarks, i.e., in terms of DLS, reduces energy requirements compared to the existing trends assessed here. However, existing studies, due to their high spatial aggregation and consideration of numerous dimensions, do not provide adequately disaggregated information regarding material or energy requirements for housing within India. Despite this, a comparison can be drawn between DLS material and energy requirements at regional and city-levels and the total MS requirements estimated here. For example, a study has estimated that approximately 145 EJ of energy are required to upgrade substandard housing globally via the definitions of DLS, with 63 EJ required in South Asia (8). The findings here indicate that between 3.8 EJ and 9.0 EJ may be consumed in India alone based on scenarios 1 and 3 respectively. While the aggregation of nations into global regions precludes any satisfactory direct comparison to India, the results suggest that between around 3% and 6% of global DLS requirements may be accounted for via the provision of adequate housing within India following existing trends. At the city-level, a study has quantified the total material requirements of 1.0 Mt and 11.5 Mt for upgrading structurally inadequate housing in Chandigarh and Delhi respectively by providing only the minimum requirements for floor space (4). The findings here reveal that 2.8 Mt and 19.2 Mt are required for Chandigarh and Delhi respectively as per scenario 1, and a maximum of 10.0 Mt and 181.2 Mt are required as per scenario 3. More realistic estimations are associated with improvements to non-permanent housing, i.e., scenario 1, as opposed to the homogenization of the total housing stock, i.e., scenario 3, however the results highlight the potentially significant variation in total requirements for the upgrade of housing to improve basic needs outcomes. The comparison of results therefore shows that savings of approximately 64% and 40% may be made by upgrading inadequate urban housing to minimum size requirements of households for Chandigarh and Delhi respectively, as opposed to continuing with existing trends to upgrade non-permanent housing. Providing a minimum floor area per household based on the household size therefore has the potential to significantly reduce the provision of MS to ensure adequate housing compared to existing trends in India.

Upgrades to inadequate housing are expected to be net additions to stocks, i.e., through the provision of new housing units with or without demolition of existing stocks, given that retention of unsuitable material within structural elements is undesirable and generally unfeasible. This holds implications for the per capita in-use stock of residential buildings within India. The net additions to stock resulting from non-permanent housing upgrades found here, i.e., scenario 1, are in the range of 6.2 to 7.6 tons/capita nationally with an average of 7.0 tons/capita based on the uncertainty in values for MS required per HH. This is equivalent to approximately 30% of China’s per capita in-use stock of residential buildings in 2008 (220). Alternatively, upgrading all housing to the same standard as Chandigarh, i.e., scenario 3, results in a required 21 tons/capita which is equivalent to approximately 66% of

China's per capita in-use stock of residential buildings in 2008 (220). Generally, per capita levels of MS are higher in developed countries than in developing countries which may be explained by differences in socioeconomic development (52). In this case, the driver of this in-use stock is the provision of basic needs to the current population, with results highlighting that existing deficits in living standards are a significant driver of MS within India. However, other studies have highlighted population and economic growth as important drivers, such as within Japan (98). The pursuit of economic growth is also generally considered a main driver for floor space growth (221), and is part of India's 'inclusive growth' strategy which outlines the goals of increased GDP and reductions to urban poverty in terms of basic service access (222). Further, India is expected to increase the population of middle-class households by 22 million in the coming years (217) which is likely to result in an increase in the average floor space provided per household given the minimum benchmarks corresponding to different income classes in India outlined in section 6.2.2 (4). This suggest that India may begin to follow similar trends of in-use stock accumulation as that of developed nations such as the U.S. if current trends continue, i.e., total floor space and in-use stocks per capita growing in conjunction with GDP per capita (221,223). This highlights the importance of minimum service provision given the city-level savings discussed previously, which may ensure resource efficient provision of material by limiting the overconsumption associated with increases to the floor area provision per capita. However, the widespread provision of MS to upgrade inadequate housing coupled with minimal improvements to overall basic needs found here underlines the need to further evaluate strategies for equitable and efficient MS provision within India. This is particularly important given the unprecedented rates of urbanization and population growth expected in coming decades (5,172), as well as the significant increase to housing and urban infrastructure provision expected in the coming years (24).

The required MS per capita may reduce based on the way in which housing is provided. For example, higher-rise construction than that of Chandigarh is likely to result in a lower material intensity, kg/m^2, as shown in Rio de Janeiro (67). This means that, given the same floor area provision on average per household, the MS required per capita to upgrade all housing would reduce. These savings may be compounded by integrating minimum floor area provision and low-energy technologies as assessed within the DLS literature (117). Another factor to consider is the dentification of urban areas. The provision of housing as quantified here would likely result in a sprawled urban development, similar to that of

Chandigarh as discussed in the previous chapter. Higher-rise construction may enable more dense urban areas which could reduce the demand on urban infrastructure and ensure greater material efficiencies across urban areas, as highlighted within Chapter 2 section 2.1. Future work should therefore seek to address the provision of higher-rise construction, such as residential buildings up to 16-stories as in Rio de Janeiro (67), as well as the implications of the spatial distribution of this provision on urban infrastructure to evaluate effective pathways to reduce future MS requirements per capita.

6.3.3 Urban infrastructure service provision and the achievement of interconnected SDGs

The significant resource provisioning for adequate housing is found to achieve minimal improvements to basic needs outcomes for many cities and states, as shown in Figure 6.2. The results highlight that the provision of MS based on current trends in India aimed at achieving SDG 11.1.1, i.e., adequate housing, are associated with significant trade-offs for SDG 12, and which provide only minimal improvements to the achievement of SDG 1.4.1. In Chapter 3 we have seen significant deficits in urban infrastructure provision. Studies have also highlighted the significantly lower material requirements for waste water and water supply pipes (53) as well as the energy requirements associated with the operation of such services within India (4). Thus, significantly greater improvements to overall basic needs outcomes are expected to be possible for lower per capita material requirements. Improvements to SDG 6.1.1, 6.2.1 and 1.4.1 may therefore be maximized with minimal impacts to SDG 12 in comparison to the pursuit of SDG 11.1.1 based on current practice. This underlines the crucial role of minimum service provision, particularly for housing, where material use is limited as per DLS requirements and which we have seen has the potential to decouple trends of MS provision and improving standards of living. It further highlights the need to rollout energy-saving DLS scenarios for housing construction and to ensure better harmonization of material and energy savings scenarios with assessments of existing trends for nations to develop a quantified understanding of the potential for decoupling. It also highlights the opportunity for significant increases to minimum standards of living resulting from the provisioning of urban infrastructure based on current practice. Future work should therefore seek to assess such material requirements to quantify the relative scale of improvements associated with urban infrastructure in comparison to housing provision. In addition, high-rise construction is shown to be more materially efficient in terms of the mass per unit floor area in some contexts (67) but has shown to be less so in some cases within India (191). Higher-rise constructions may benefit urban areas due to increased densification and thus result in additional efficiencies regarding urban infrastructure through a greater per capita utilization of stocks. Future work should therefore seek to evaluate the rollout of existing higher-rise constructions in comparison to the present study to assess the potential for improved energy efficiency based on current practice.

6.4 Limitations and concluding remarks

The presented study has addressed the provision of adequate housing based on the existing material requirements per household in-line with current trends of MS use within India. The provision of adequate housing results in minimal improvements to overall basic needs nationally, and across many towns, cities, and states. The results have revealed a general relationship, that smaller urban areas tend to do better with less in terms of the total mass of MS but require a significantly greater per capita stock provision than larger urban areas. This is generally a result of the existing trends of deprivation in basic services, however it provides a quantified understanding as to the magnitude of the required MS provision and increases to basic needs outcomes to reveal national trends for towns and cities as well as states. It also enables a comparison to existing studies assessing minimum material requirements to ensure DLS. This has revealed that housing provided to minimum floor space requirements per household may significantly reduce total MS requirements compared to current practice. However, given the relatively low overall improvements to basic needs nationally and sub-nationally for high per capita stock requirements, energy-saving alternatives incorporating low-carbon materials are crucial to sustainable development in India in the coming decades.

Finally, it is important to note some shortcomings of the current analysis. The study does not evaluate the ventilation strategies of the existing adequate housing archetype and thus whether the archetype meets household operational requirements for DLS. However, given the high living standards of the case study area it is expected that this would be the case. Further, inadequate housing based on overcrowding is not considered and therefore the actual values may be larger than estimated here. Additionally, regional variations in the mass of residential buildings are shown to exist within India despite a very similar construction (191). Future work should therefore seek to offer a more comprehensive baseline assessment of housing upgrades based on regional variations in material use.

7 Discussion and conclusions

In Chapters 1 and 2 we note that the Global South will need to increase net resource consumption to build, maintain and upgrade built environment services in an effort to improve living standards. However, with the currently limited studies addressing the deficits in living standards associated with built environment services and their relationship to material use in many developing and rapidly urbanising countries, there remains a lack of evidence to support policy making attempting to simultaneously achieve key interconnected SDGs. Further, there is now a clear need to provide such evidence at sub-national scales, with increasing attention on cities to achieve many SDGs. The presented studies from Chapters 3 - 6 form a narrative to investigate these challenges and provide evidence to support policy making. Ultimately, the results of Chapters 3-6 taken together points the policy lens towards nucleating solutions within urban areas such that basic needs, material efficiency and thus interconnected SDGs are all achieved through coordinated and targeted urban planning policy.

7.1 A general discussion on the future urban development of India

We have seen that basic needs outcomes associated with the provision of non-mobile built environment MS remain a widespread challenge to living standards within India. The multiscale assessment places national trends at key administrative levels and may therefore be used to coordinate planning between administrative bodies. This is important within India given the discrete urban planning levels that have been defined during the recent reforms to urban planning capacity (175). The results of Chapter 3 indicate that access to basic services is more-so a regional challenge which requires comprehensive planning to address the widespread regional roll-out of basic services such that national inequality is reduced. In the current framework of urban planning, this may be coordinated by national and state level planning bodies which are responsible for the master planning of essential urban infrastructure with consideration of the basic needs of the poor (175). However, the provision of these services will need to be achieved through detailed city-level planning which emphasises the need to align national- and state-level master plans with more detailed planning within cities.

Importantly, the results have underlined the need for complementary assessments, providing empirical evidence in the direction of such existing guidance within literature identified in Chapter 2. This has shown that a one-size-fits-all approach may not be appropriate and result in regressive policy by overlooking those most deprived households. This is highlighted through the complex characteristics of service-specific provisioning within Chapter 3 implying that policy makers should assess national trends complemented with detailed understandings within urban areas. However, it further highlights the need for SEM research focussed on the SFS-nexus to provide complementary understandings of the same problem, particularly in the context of living standards. Future work should consider developing complementary assessments of societal service provision and human wellbeing to adequately capture development outcomes in other contexts. This is particularly important for developed nations, as studies in these areas often rely on existing metrics such as the HDI or GDP which are difficult to disaggregate to cities and overlook many key dimensions of living standards. We have seen that the monitoring of multidimensional deprivation to complement average assessments is valuable for policymaking to ensure equitable development. By addressing the intra-urban distribution of service access among households, policy can complement widespread service provision assessments with an understanding of the distribution of service access among the population. This means that extreme multidimensional deprivation within urban areas is identified, which has been shown to be overlooked by averages in many cases in Chapter 3. Thus, policymakers may become better placed to ensure that those experiencing the most significant deprivation are not overlooked within master plans. This is in-keeping with the UN's pledge of "leaving no-one behind" (155) and highlights the value of integrating SDGs within future urban development policy.

We have also seen that basic needs outcomes have grown in conjunction with the provision of carbon intensive MS in Chapter 4, both of which are likely a result of the policy choices in how urban housing and infrastructure services have been provided. As such, it is important for policymakers to consider tendering projects which limit overconsumption of materials, e.g., through adopting DLS requirements for housing, or through Government investments in low-carbon materials such as "hollow cement concrete blocks" which have significantly lower embodied energy than fired clay bricks and cement, as quantified in a study within India (86). Further, the UN needs greater consideration of the relationship between basic needs and resource use and thus develop improved SDG indicators to capture these trade-offs within urban planning. This specifically relates to SDG 12.2 which addresses material consumption in absolute terms or relative to GDP to achieve “the efficient use of natural resources” (155). SDG 12.2 may be more appropriately captured in this context via a “material stock per capita per service outcome” indicator in relation to each key service which has its own SDG indicator.

While current recommendations are to focus SDG achievements within cities, this will, as we have seen in Chapter 3, overlook significant deprivation in many smaller urban areas such as towns. Further, in Chapter 5 we have seen the importance of instilling material efficiency strategies early in the development of urban areas to ensure that lock-in effects are avoided and circular economy strategies are introduced early to limit primary material consumption in future urban development. Therefore, focussing in deprived and smaller towns and cities may enable large-scale master planning that enables the successful achievement of interconnected SDGs now and in the future. This is particularly poignant within India given the GoI now acknowledges the benefits of, and intends to implement, master plans in the future, seeing them as critical for managing urbanisation and accommodating the basic needs of the population. The results of Chapter 5 are therefore of relevance to future urban master plans, noting the successful achievement of basic needs outcomes in Chandigarh but the shortcomings of this master plan in terms of efficient material use.

Overall, the results of Chapters 3-5 points the policy lens towards nucleating solutions within urban areas. Complementary, multiscale assessments of Chapter 3 have provided the benefit of additional granularity of basic needs outcomes among households, which has followed into a quantified assessment of the coupling of basic needs outcomes with carbon intensive materials in Chapter 4. Chapter 5 has also exemplified the potential for master planned cities to achieve high basic needs outcomes, but without adequate planning may result in significant overconsumption during early stage and future development. Specifically, this points towards dense urban areas, increasing the utilization of transport and building MS within a given area by limiting urban sprawl. It also exemplifies that master planning can lead to positive development outcomes for many decades and supports the GoI’s initiative to master plan areas. However, it highlights the need for policy makers to integrate material stock thinking into policy with the aim to ensure reduced MS requirements per capita for basic services over the lifetime of the built environment stock. This may be achieved either through targeted MS assessments at city- and sub-city level, or through appreciation of the principles of secondary resource use and lock-in effects. Ultimately, developing an understanding of the balance between the provision of living standards and the consumption of resources for continued service provision within existing and future urban areas is crucial to simultaneously achieve interconnected SDGs.

7.1.1 A brief discussion on the global implications

We have seen in Chapter 6 that India may be expected to require between 0.5 and 1.3 $GtCO_2e$ to upgrade all inadequate housing. This equates to 0.2% and 0.5% of the remaining Global carbon budget based on recent estimates to limit warming to 1.5 degrees Celsius (224). While this seems like an insignificant percentage, current estimates suggest that global greenhouse gas emissions need to be reduced by 1.4 $GtCO_2e$ each year to meet this warming target by 2050 (224). Thus, upgrading all housing may result in an increase in emissions equivalent to the annual global carbon emissions reduction aim. If India builds in resource efficiency strategies, as discussed extensively in Chapters 5 and 6, this may reduce both the upfront and future resource requirements and thus create a greater carbon budget for other nations. However, this highlights significant tensions between balancing consumption in the Global North and Global South.

Global trends indicate that in-use stock provision may increase significantly in both developed and developing countries, despite many nations of the Global North already achieving near universal access to basic services (46). As such, many SDGs related to basic service access are achieved in the Global North. Controversially however, this has restricted the available budget of resources for less developed countries to achieve a minimum living standard. Is it therefore appropriate for developed countries, such as many in the Global North, to adopt the same living standards metrics as the Global South such that net increases to resource consumption are providing *only basic* capabilities? For example, EU countries may adopt DLS requirements to quantify living standards as with the DLSI in Chapter 3, and benchmark resource requirements within carbon budgets, therefore only targeting deprived or underserved populations when considering net increases to in-use stocks of non-mobile built environment services.

Achieving the SDGs is a Global Agenda and therefore a Global responsibility. There is therefore a clear need for consensus on what constitutes a “minimum standard of living”, circling back to the contrasting viewpoints of the *eudaimonic* and *hedonic* perspectives discussed in Chapter 2. Future work is therefore critically needed in many other nations to accurately understand the extent to which resources which achieve key SDGs expand basic capabilities in the Global South. Future work should also aim to understand the processes resulting in increased in-use stock growth beyond universally high HDI levels in the Global North. It is then crucial to understand whether the relative environmental impacts imply potentially limiting continued consumption beyond basic capabilities in the Global North, or the urgent need for urban development in the Global South to instil extreme material efficiency strategies to ensure basic living conditions within carbon budgets.

7.2 Uncertainty and confidence in data

The uncertainty in model estimates is presented and discussed in each of the Chapters 3 – 6. However, the below discusses key considerations to uncertainty in results and the confidence in data, specifically further discussing considerations for Chapters 3 and 5 and the implications on their findings.

The sensitivity analysis of Chapter 3 is presented in Appendix A. We find that the results of the inter-urban inequality, or basic needs profile, remain robust for different definitions of the selected cities. Reducing the number of wards that comprise cities introduces significantly more urban areas to the study but is shown to increase the scale dependence of results only marginally. The inequality index found for different definitions does not change the perceived distribution of outcomes, i.e., they are distributed in a way that is closer to an equal distribution of limited outcomes, $b < 0.5$ as opposed to distributed closer to an all-or-nothing case, $b > 0.5$. Further, the results presented in Appendix A Table A.8 reveal that redefining towns or cities by their overlapping administrative divisions yields the same scale dependence between towns/cities and states, and only reduces the overall inter-urban inequality of towns and cities marginally. However, changes to the inter-urban inequality at each scale are statistically indistinguishable and thus, while the changes in the average inter-urban inequality index are shown to more significant for alternative city definitions by the number of wards as opposed to by overlapping administrative divisions, the resulting conclusions remain robust. Appendix A also presents alternative assessments of the SDI calculated using the arithmetic mean. The results show that the arithmetic mean overlooks significant deficits in standards of living at each scale and significantly reduces the estimated inter-urban inequality. This formulation of the average index generally estimates a higher mean achievement of dimensions and lower dispersion. This means that the line of best fit and thus the observed average inequality is significantly reduced. The analysis therefore supports the use of the geometric mean as a more appropriate approach for capturing deprivation and reflecting inequality in achievement of dimensions between urban areas. It further highlights that the choice of metric in this case has a larger impact on the observed outcomes than the definition of city by either the number of wards or by their overlapping administrative divisions. This points towards the careful consideration of metrics and also the use of alternative and complementary metrics to capture uncertainty and validate findings – as we have demonstrated in Chapter 3.

The uncertainty of results for residential building and road MS calculations within Chapter 5 are reflected as error bars within Figure 5.6. For residential buildings, the bottom-up approach goes further than traditional bottom-up approaches by archetyping by the city-specific plot-size or construction phase as per the masterplan, therefore capturing inter-plot variations in MS provision. However, uncertainty is further captured by quantifying the maximum and minimum MS for each plot type and calculating the total MS for each ward. As such, intra-plot variation is also captured. The material intensities found are also within the range expected for the region of India in which Chandigarh is constructed, as discussed in Chapter 5. While plot sizes do vary across Chandigarh, and the MS requirements for some plots can not be calculated due to data availability, plots are standardized from the architectural control and the material intensity per plot does not vary significantly as shown in Figure 5.3. Thus, the city is much more homogenous in its composition than many other cities for which MS assessments have been completed. However, it is important to note that the *actual* number of plots and the *actual* final construction of plots cannot be computed. Thus, it is difficult to validate the inventory and material intensity of plots and therefore whether the architectural control was itself constructed as designed in the plans. However, records demonstrate that the masterplan of Chandigarh has been implemented over multiple decades (209), with no changes to the boundaries of the district and with continued urban growth experienced to the periphery of the city (200), i.e., outside of the 26 wards considered in the study. Given that sectors are of fixed size and bound by the road network, with little-to-no room for densification as per the layout plans, it reasonable to assume that the total number of plots has remained unchanged since completion. Further, Google Earth imagery shows that the layout of the city and the story height of buildings is the same as provided on the architectural control. Note that the uncertainty for road MS is calculated and discussed at length in Chapter 5.

7.3 Recommendations for further work

Recommendations for further work are presented throughout Chapters 3-6, particularly in relation to the shortcomings of the respective studies and the questions raised based on the insights provided by the results. However, the body of work taken together raises four key questions for future research to develop a deeper understanding of the relationship between built environment MS and minimum standards of living: 1) to what extent are urban infrastructure MS coupled with basic needs outcomes?, 2) what are the spatiotemporal trends of the relationship between built environment MS and minimum standards of living?, 3) how does the relationship between built environment MS and minimum standards of living compare across different nations?, and 4) to what is the relative contribution of material stocks and material and energy flows over the lifespan of the service?

The results of Chapter 3 have highlighted the significant deficits in urban infrastructure service provision within India. It is therefore important for future work to understand the coupling of such service provision with the accumulation of urban infrastructure MS to better understand the relative scale of challenges between housing and urban infrastructure on basic needs outcomes. By integrating MSA of housing and urban infrastructure with assessments of living standards, future work may reveal synergistic urban planning strategies to ensure equitable and resource efficient development. For example, by better understanding the implications of the distribution of services on the accumulation of housing and infrastructure MS with the aim to address multiple deprivations identified through multidimensional poverty assessments within case study areas. Synergistic strategies may also be identified by integrating such MSA within methodologies which aim to evaluate improvements to the connectivity of deprived areas. The optimal reblocking methodology (214) may be particularly appropriate here which, in combination with MSA, may enable the optimization of MS, improvements to basic needs outcomes, as well as the existing parameters within the methodology such as disruption and cost. Such analysis, particularly when combined with multidimensional poverty metrics which capture the intra-urban distribution of service access rates, would ensure that policy is better equipped to achieve interconnected SDGs.

Future work should also seek to develop an understanding of the spatiotemporal trends of the coupling of MS and basic needs outcomes. This would lead to an improved understanding of how the observed coupling has evolved through space and time, for example by identifying how concentrations of deprivation and MS have evolved within and across urban areas through time. Inconsistencies in reporting between the 1991, 2001 and 2011 Indian censuses regarding the definition of administrative scales and the dimensions used to quantify basic needs outcomes currently limit this analysis. However, census data recording has become incrementally more detailed over previous decades. Therefore, it is expected that such an assessment may be feasible once the delayed census data of 2021 is released.

Future work should also aim to synthesize the monitoring of living standards with built environment MS assessments within other contexts to develop an understanding of this coupling in other nations. This, particularly in combination with spatiotemporal assessments, would offer an improved understanding as to the relative challenges within and between different nations and the potential pathways towards decoupling which is important given the global trends discussed in section 2.3.1. African nations are of importance given their expected urbanization rates, with Nigeria set to experience the third largest increase in urban population globally in the coming decades (5). Further, there remains limited MS assessments within these nations and there is therefore a clear need to address this relationship here. Further, existing basic needs assessments in Brazil and South Africa (6) reveal significant deprivation in urban infrastructure and housing across urban areas. Further work may therefore seek to integrate built environment MS assessments within such nations, particularly to quantify the potential coupling and reveal context-specific challenges and opportunities to decoupling nations from the observed global trends.

Finally, the study presented here has related characteristics of *material stocks* to basic needs outcomes at different scales. However, the operational energy, or energy flows, should be quantified for adequate housing and urban infrastructure over their expected lifespan to understand the relative carbon impact of energy flows and material stocks needed to operate and construct housing and infrastructure. This will expand the analysis further within SFS-nexus research by quantifying the material stocks, locked-in energy flows, and the societal benefit of the services. This is important for designing urban planning policy aimed at sustainable development, considering planning strategies to ensure low whole life carbon (WLC) development of infrastructure. Further, quantifying material flows for maintenance, not just upgrading inadequate services, is important to complete the SFS-nexus analysis, providing a comprehensive understanding of the WLC of built environment services and their benefits on society. Importantly, this may shed light on appropriate approaches to provide services that are able adapt to changing conditions in the future resulting from climate change, thus reducing the flow of waste materials and demand for new materials whilst ensuring adequate service provision. Therefore, policy may be able to inform design decisions to overcome lock-in effects, not only because of the provision of MS, e.g., the low per capita utilization of MS, but also the energy infrastructure, e.g., overheating buildings or undersized pipelines.

7.4 Summary of key findings and contributions to knowledge

Research question #1: **To what extent do households in India experience deficits in basic needs relating to non-mobile built environment material stocks?**

- The above research question seeks to address the lack of comprehensive assessments of the national trends of living standards relating to the provision of such stocks among many nations of the Global South.
- The research question is answered in Chapter 3 and is achieved by identifying dimensions of non-mobile built environment MS in the context of basic human needs and formalizing these within complementary metrics across scales of analysis.
- The results provide a comprehensive account of such basic needs outcomes, and contribute to the current literature two-fold: 1) the quantification of the extent to which minimum standards of living associated with the provision of built

environment MS are achieved, revealing novel insight into the national trends for India, and 2) the quantification of such trends by considering current recommendations within literature regarding the statistical limitations associated with monitoring development outcomes and the associated SDGs, thus enhancing the understanding of national trends and consequent policy implications.

Research question #2: **Does a relationship exist between the composition of non-mobile built environment MS and basic needs?**

- The above research question seeks to address the lack of a quantified understanding of the relationship between built environment MS and living standards, particularly at national and sub-national scales.
- The research question is answered in Chapter 4 and is achieved by developing a statistical model to quantify the relationship between deficits in basic needs outcomes and the composition of built environment MS, specifically in terms of the construction materials used for residential buildings, across scales of analysis.
- The cross-sectional trends show that concrete and brick materials stocked in residential buildings have grown in conjunction with basic needs outcomes. As such, the original contribution to existing literature is the quantification of the relationship between standards of living and material use, capturing variations across scales of analysis, for the first time. Specifically, the regression analysis results show that a unit increase (%) in the composition of urban areas in terms of BCHH and CCHH results in a 0.3% and 0.5% increase in basic needs outcomes on average measured by the SDI.

Research question #3: **What is the built environment material stock accumulation within a city with high basic needs outcomes in India?**

- The above research question seeks to address the lack of city and sub-city assessments of built environment MS accumulation in the Global South as well as the integration of living standards within such assessments to reveal the potential coupling within cities.

- The research question is answered in Chapter 5 and is achieved by quantifying the material stocked in residential buildings and roads at the city- and sub-city scale in Chandigarh, a rapidly developed city achieving high basic needs outcomes.
- The results show that the city has achieved high basic needs outcomes but with relatively high built environment MS which are provided in a way that limits future resource efficient urban development. This is largely explained by the unique urban form which prioritizes a low-rise and sprawled growth pattern resulting in a high per capita stock of roads compared to residential buildings in comparison to other cities. The results also show that the patterns of basic needs outcomes and MS provision are less clear among the local urban neighborhoods and points to the requirement for more comprehensive assessments of MS at this scale. The body of work therefore contributes to the current literature two-fold: 1) the quantification of in-use built environment MS at the city- and sub-city scale in India for the first time, and 2) the evaluation of the relationship between built environment MS and basic needs outcomes at the sub-city scale.

Research question #4: **What are the MS requirements and consequent impacts on basic needs resulting from the upgrade of inadequate housing nationally?**

- The above research question seeks to address the lack of a quantified understanding of the built environment MS requirements to ensure minimum standards of living following existing trends, particularly within India.
- The research question is answered in Chapter 6 and is achieved through the quantification of household MS requirements for adequate housing, which is based on India's existing trends identified in Chapters 4 and 5. This is then related to improvements in basic needs outcomes resulting from the universal provision of adequate housing.
- The findings indicate the significant material requirements for adequate housing provision if current trends continue, which result in minimal improvements to overall basic needs outcomes nationally. This is shown to be significantly higher compared to the provision of housing to minimum size requirements as evaluated in existing studies. The results also highlight that larger cities and states tend to require lower per capita MS and experience smaller improvements to overall basic needs

compared to smaller cities and states. As such, the study contributes to the existing body of research addressing the provision of material to achieve minimum living standards. Specifically, the original contribution is the quantification of national and sub-national material requirements based on existing adequate housing provision and its relation to improvements to overall basic needs outcomes.

7.5 Concluding remarks

Research to-date has fallen short of a quantified understanding of the relationship between standards of living and built environment MS. Such an understanding is needed to improve policy associated with the efficient and equitable provision of MS and thus the simultaneous achievement of interconnected SDGs. The body of work here seeks to address this gap by aiming to *understand the relationship between the provision of built environment MS and minimum standards of living*. This is achieved by enhancing and integrating the monitoring of development outcomes within MS assessments, using India as an important testbed to address the research aim in-place, which has revealed the quantitative coupling of living standards and built environment MS. Multiscale observations have revealed that widespread challenges exist regarding the coupling of living standards and the provision of built environment MS. The quantification of existing national trends across scales reveals that carbon intensive MS have grown with minimum standards of living and that substantial MS are required to address deficits in living standards in India if current trends are to continue. The results have also revealed that a significant amount of built environment MS have accumulated within a city achieving high standards of living and that the ways in which MS are provided has a significant impact on the efficiency of future urban development. The main original contribution of this work is therefore the empirical understanding of the relationship between built environment MS and basic needs outcomes through the improved integration of societal service provision measures within MS assessments. As such, it highlights the clear need to integrate MS thinking and the monitoring of living standards into urban planning and policy to reduce tensions in achieving interconnected SDGs.

A - Chapter 3 Supporting Information

A.1 Introduction

The following provides information supporting the analyses carried out in Chapter 3. The selection of adequate water supply dimensions within the SDI is firstly presented. Following this, regression results required to estimate the average inequality index for each scale are presented. The sensitivity of the average inequality index to the assumptions made within the main text are then presented, including an assessment of the sensitivity of the results to the metric formulation.

A.2 Correlation of water dimensions

As noted in Table 3.1 in section 3.2.1 of the main text, the source and location of drinking water are recorded separately within census such that dimensions relating to the availability and location of water are included separately within the SDI. In an existing study within Brazil and South Africa (1), the dimensions are aggregated as the respective census datasets record these dimensions simultaneously, e.g., the index formulated for South Africa defines achievement in the dimension relating to *improved water source* as household access to piped water within the dwelling, a tap inside the yard, or via a community tap less than 200m away (1). The main source of drinking water used to define adequate water access from the census of India is broadly coherent with this definition as well as those within the SDGs (2), i.e., tap water from a treated source. The location of the water source is defined as either *within, near,* or *away* from the premises (3). Spearman and Pearson correlation is undertaken to assess whether these dimensions should be considered separately within the SDI, and if so, which dimensions are to be included. However, to be in-keeping with many definitions of adequate water access within existing literature (1,4,5) and with broader monitoring imperatives such as the MPI (6) and SDGs (2), the SDI developed here only considers water located *within* or *near* the premises.

The results presented in Table 0.1 show that the source and the location of drinking water have a weak correlation and are therefore included separately within the SDI to capture both crucial dimensions of water access. The results also reveal a strong negative correlation between the location of the water source *within* and *near* the premises. As such, the location of the water source *within* the premises is included separately, and the location of the water source *near* the premises is omitted.

Table 0.1: Spearman and Pearson correlation coefficients between water dimensions, presented as Spearman, Pearson, for which a significant correlation is found between all dimensions. The values in bold show those dimensions which are strongly correlated.

Spearman, Pearson correlation	Treated tap water	Water located within the premises	Water location near the premises
Treated tap water	-	0.27, 0.26	-0.18, -0.15
Water located within the premises	0.27, 0.26	-	**-0.90, -0.87**
Water location near the premises	-0.18, -0.15	**-0.90, -0.87**	-

A.3 Inequality index

In this section, the results of the regression analysis undertaken to calculate the average inequality index in the main text are firstly presented. From here a sensitivity analysis of the average inequality index estimation to the definition of city selection, as well as the formulation of the SDI by the arithmetic mean, is presented.

A.3.1 Regression results

As discussed briefly in the main text, population weighted least squares (WLS) is adopted over ordinary least squares (OLS) regression to account for heteroscedasticity, see Figure 0.1. Note that the same methodology is adopted to calculate the inequality index by dimension.

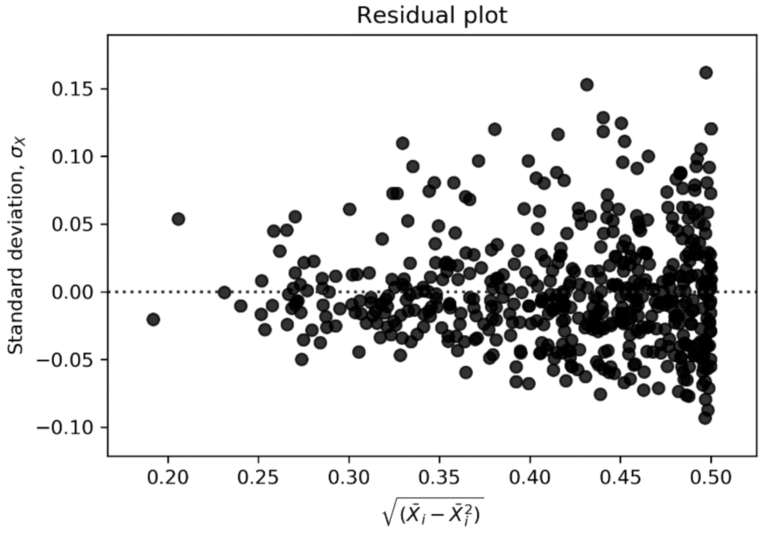


Figure 0.1: Heteroscedasticity of residuals when regressing $\sqrt{\bar{X}(1-\bar{X})}$ on $(\bar{X})$ adopting ordinary least squares regression.

A.3.1.1 Towns and cities

Table 0.2: Results for the regression of $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ at the town/city level.

Regression	**Inequality index, b**	**r²**	**95% CI**
WLS	0.324	0.91	[0.304, 0.345]
OLS	0.350	0.93	[0.341, 0.359]

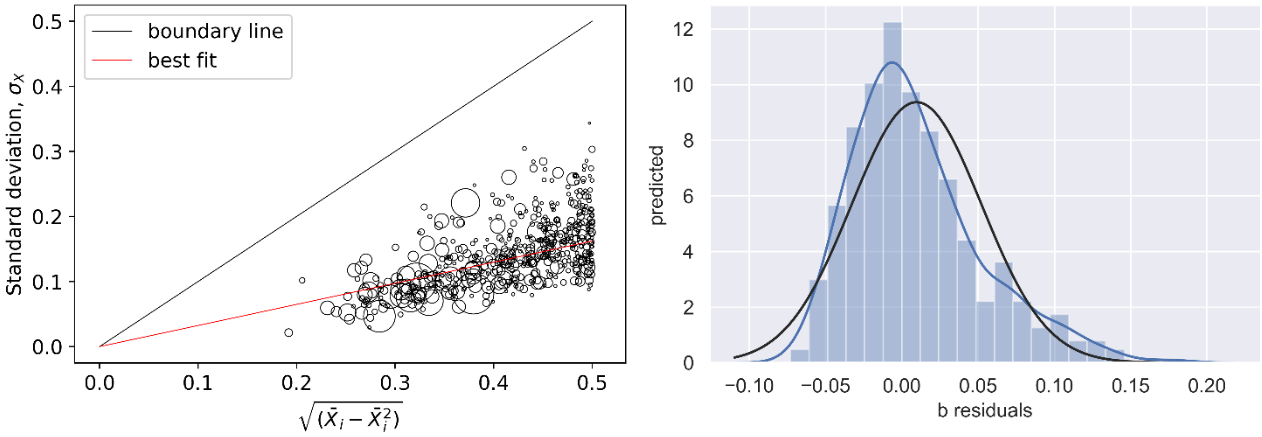


Figure 0.2: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for towns/cities using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.

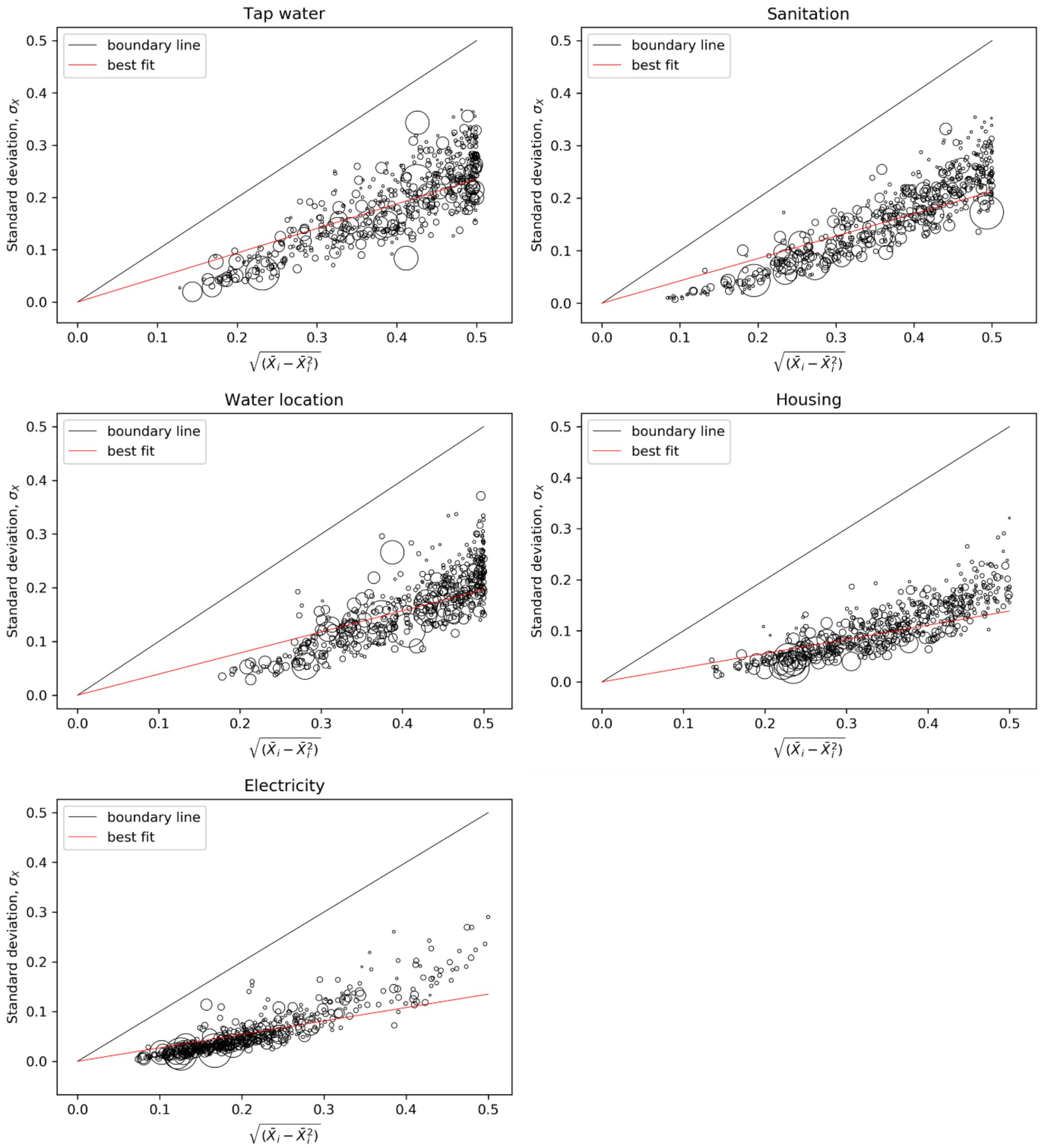


Figure 0.3: Relationship between σ($\bar{X}$) vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of towns/cities using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

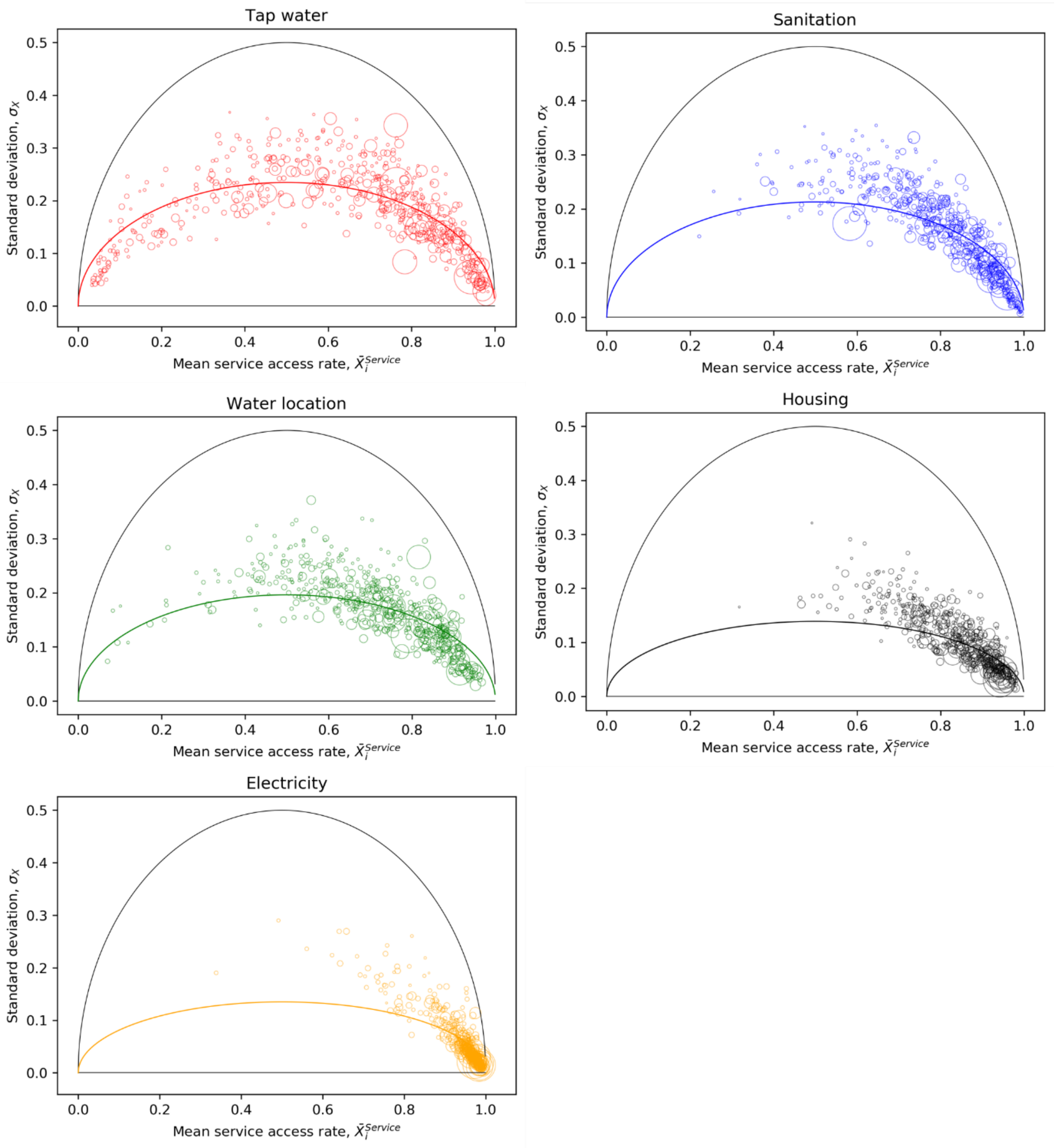


Figure 0.4: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the level of towns and cities. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.2 Subdistricts

Table 0.3: Results for the regression of $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ at the sub-district level.

Regression	**Inequality index, b**	**r^2**	**95% CI**
WLS	0.335	0.91	[0.312, 0.357]
OLS	0.356	0.93	[0.347, 0.365]

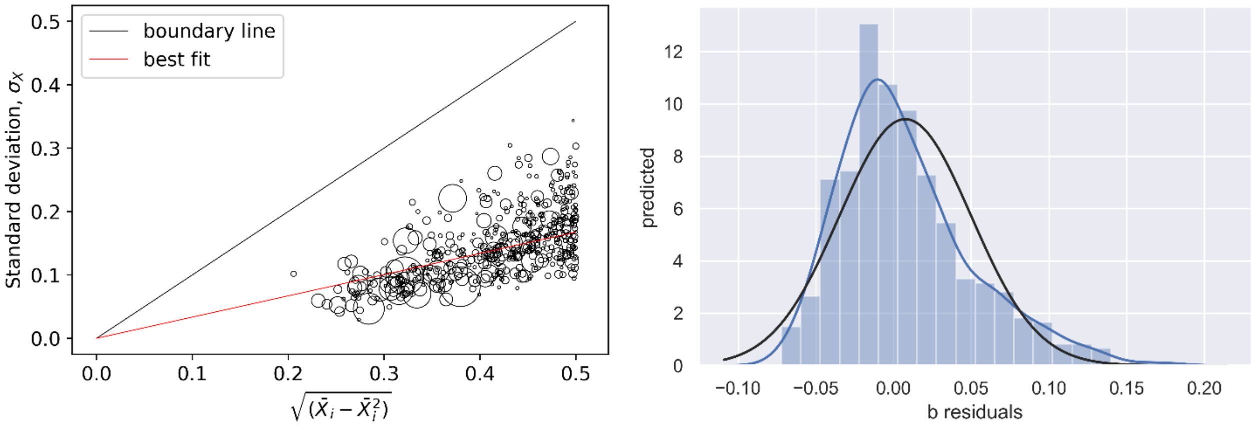


Figure 0.5: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for sub-districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.

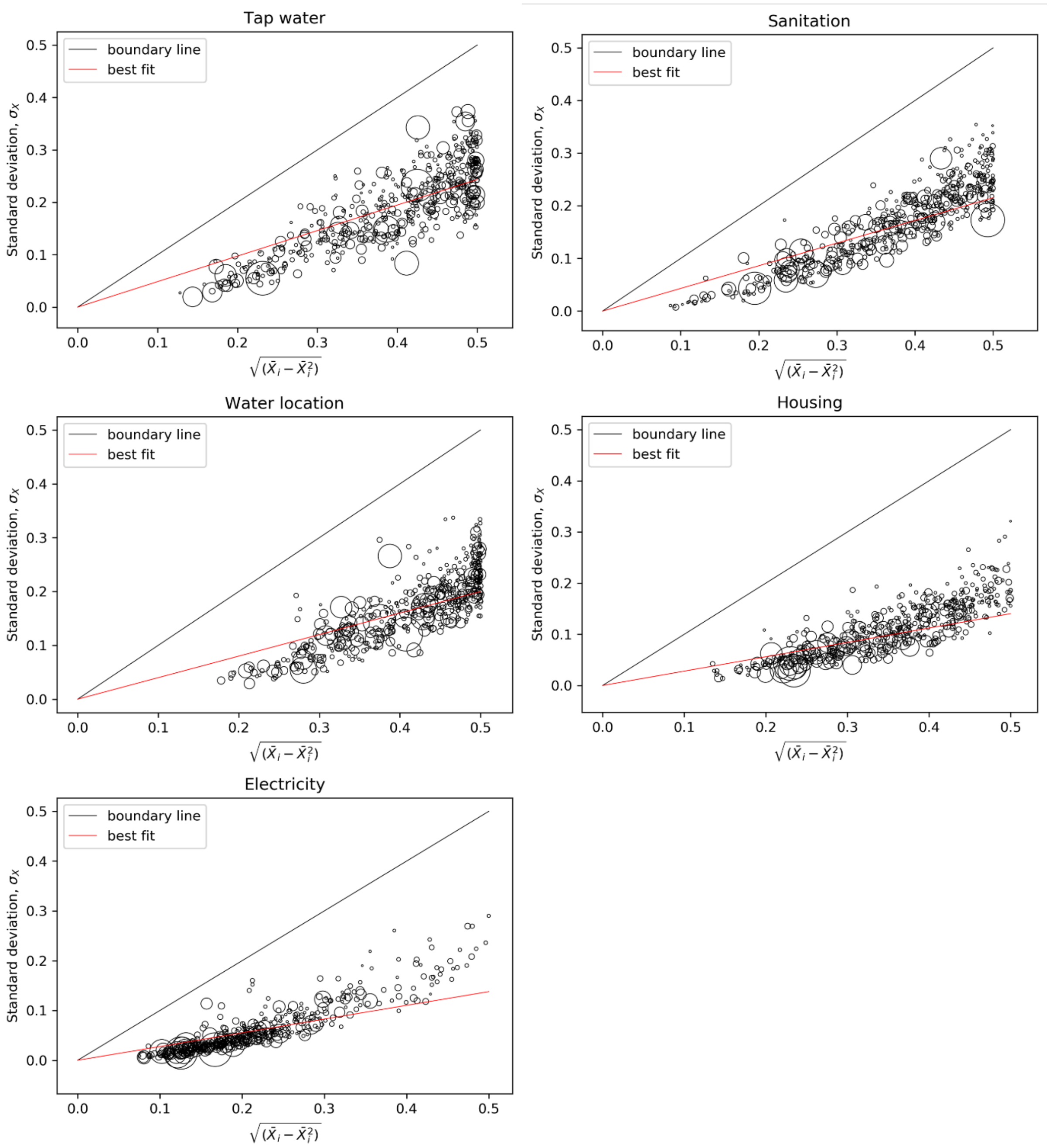


Figure 0.6: Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of subdistricts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

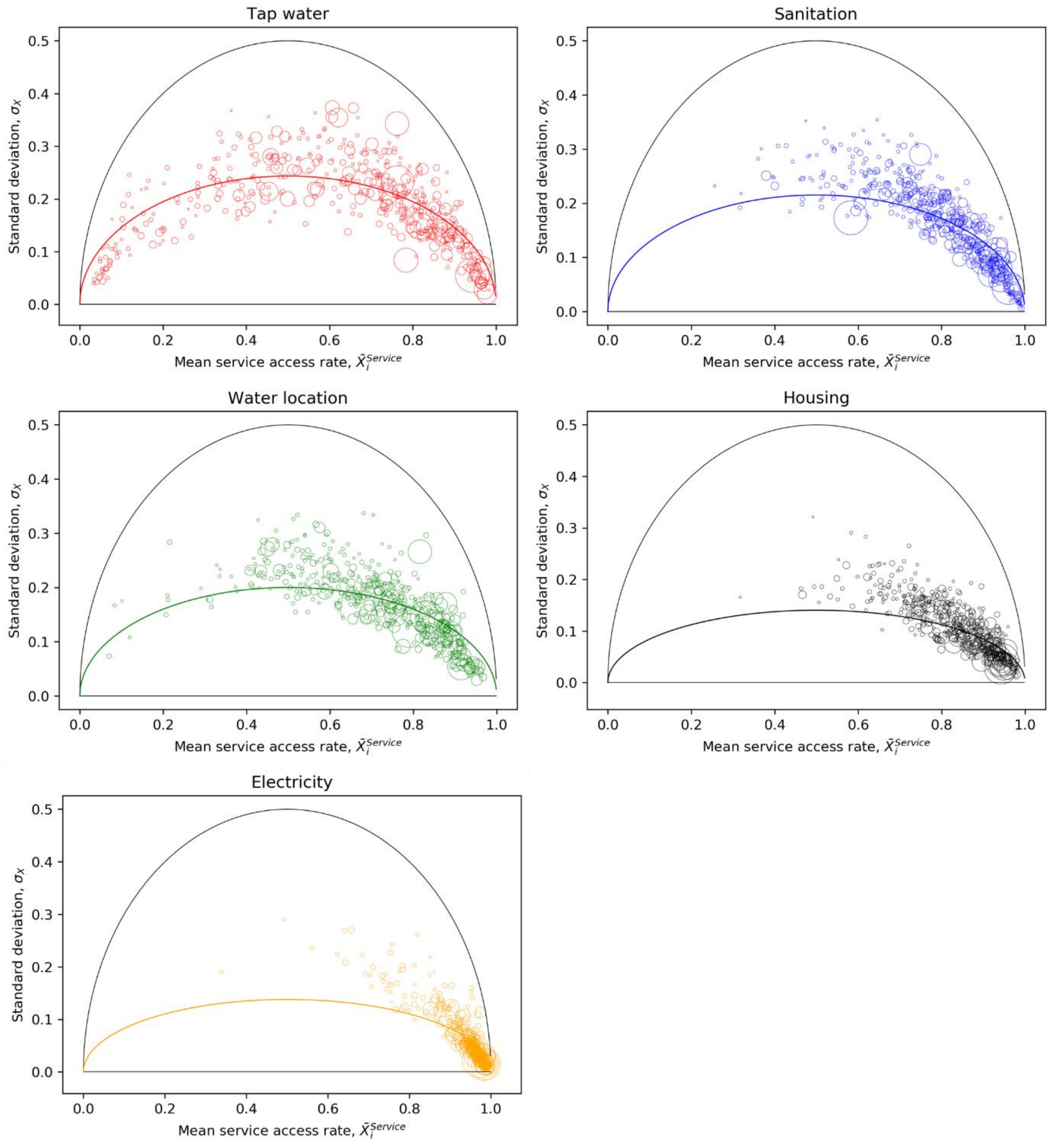


Figure 0.7: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the subdistrict level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.3 Districts

Table 0.4: Results for the regression of $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ at the district level.

Regression	Inequality index, b	r^2	95% CI
WLS	0.357	0.91	[0.333, 0.381]
OLS	0.372	0.93	[0.360, 0.384]

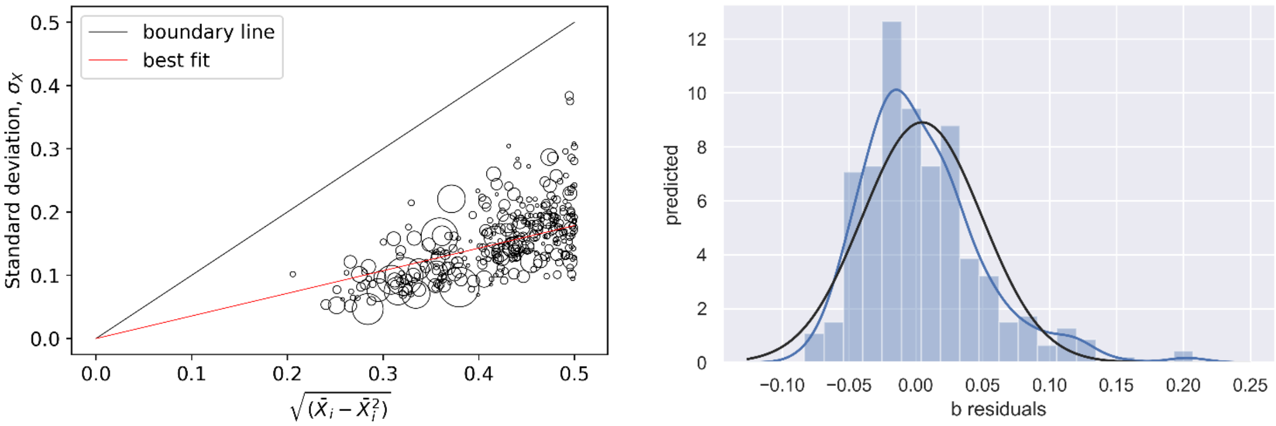


Figure 0.8: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.

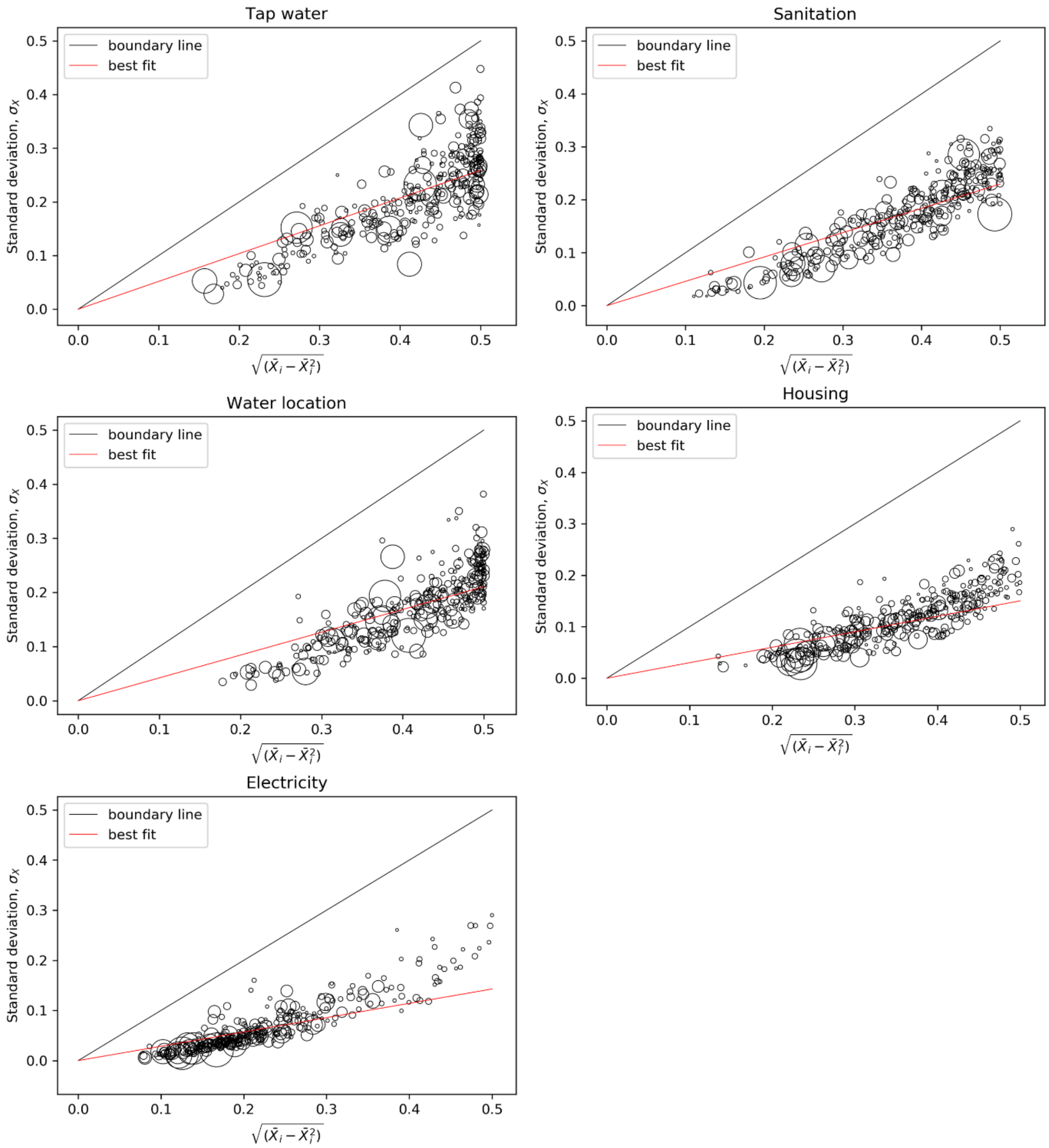


Figure 0.9: Relationship between σ($\bar{X}$) vs $\sqrt{\bar{X}(1-\ \bar{X})}$ used to compute the average inequality index for each dimension at the scale of districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

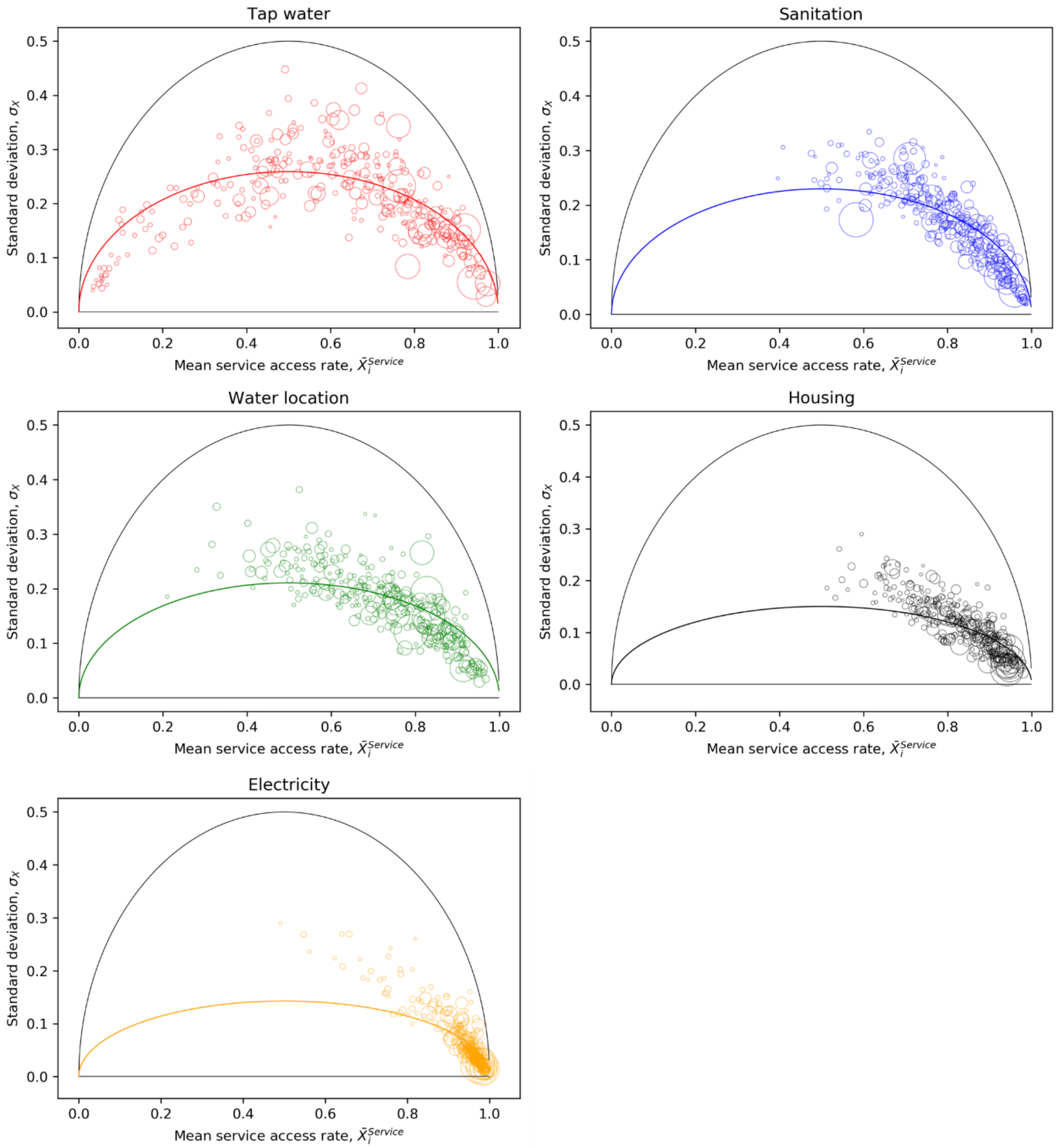


Figure 0.10: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the subdistrict level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.4 States

Table 0.5: Results for the regression of $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ at the state level.

Regression	**Inequality index, b**	**r^2**	**95% CI**
WLS	0.440	0.98	[0.414, 0.466]
OLS	0.451	0.96	[0.414, 0.488]

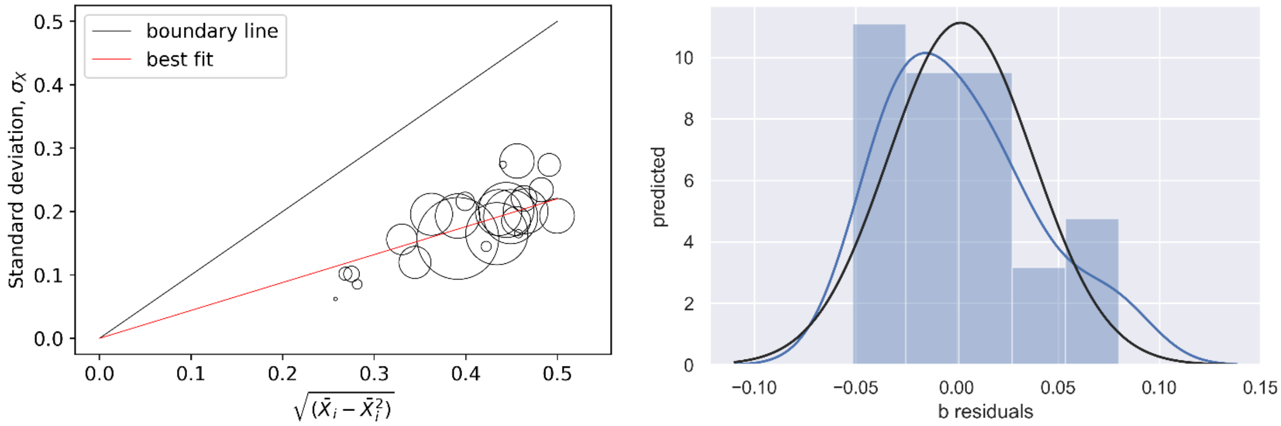


Figure 0.11: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean with minimal skew indicating that basic needs profiles are generally characterised by the inequality predicted on average.

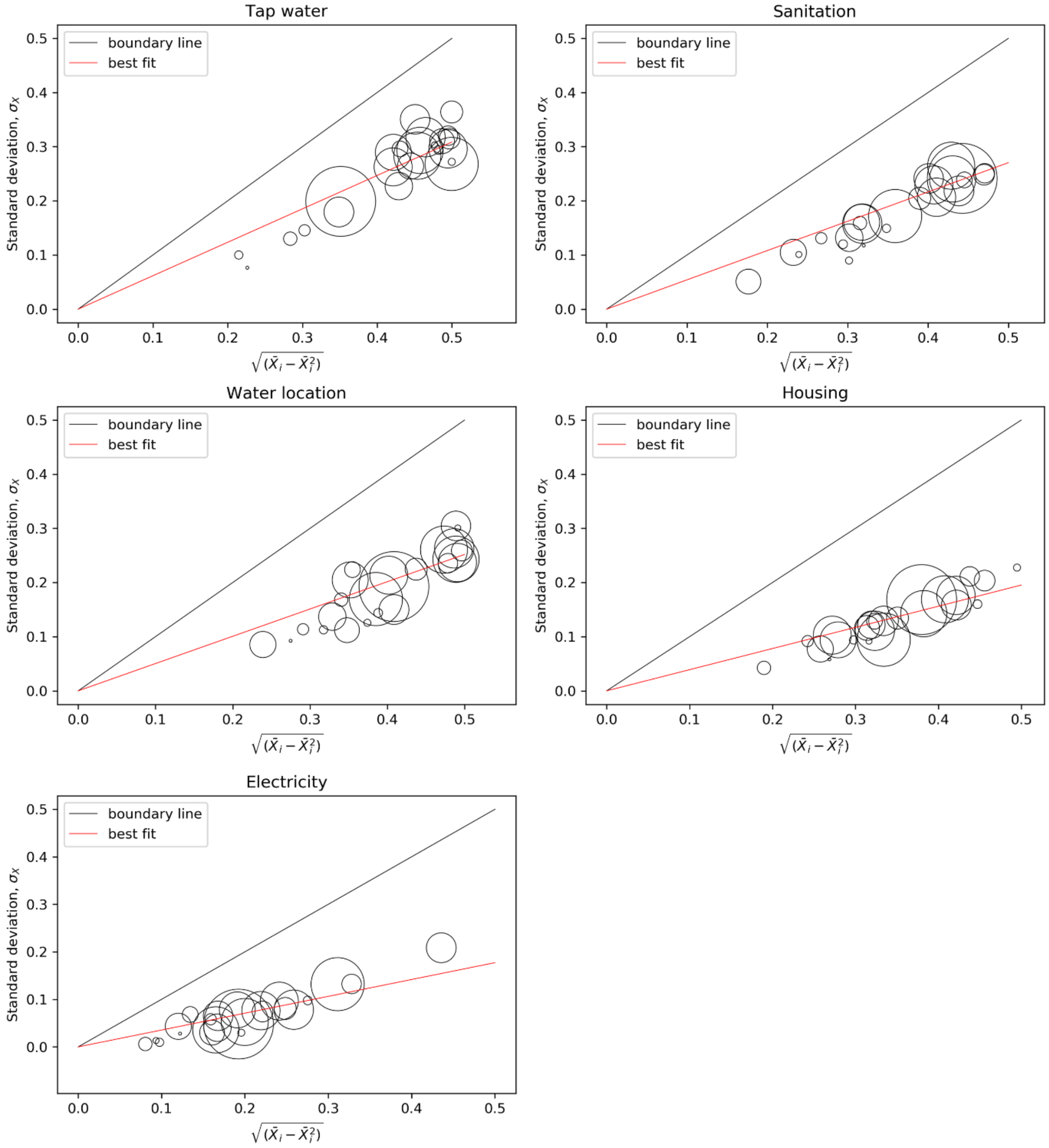
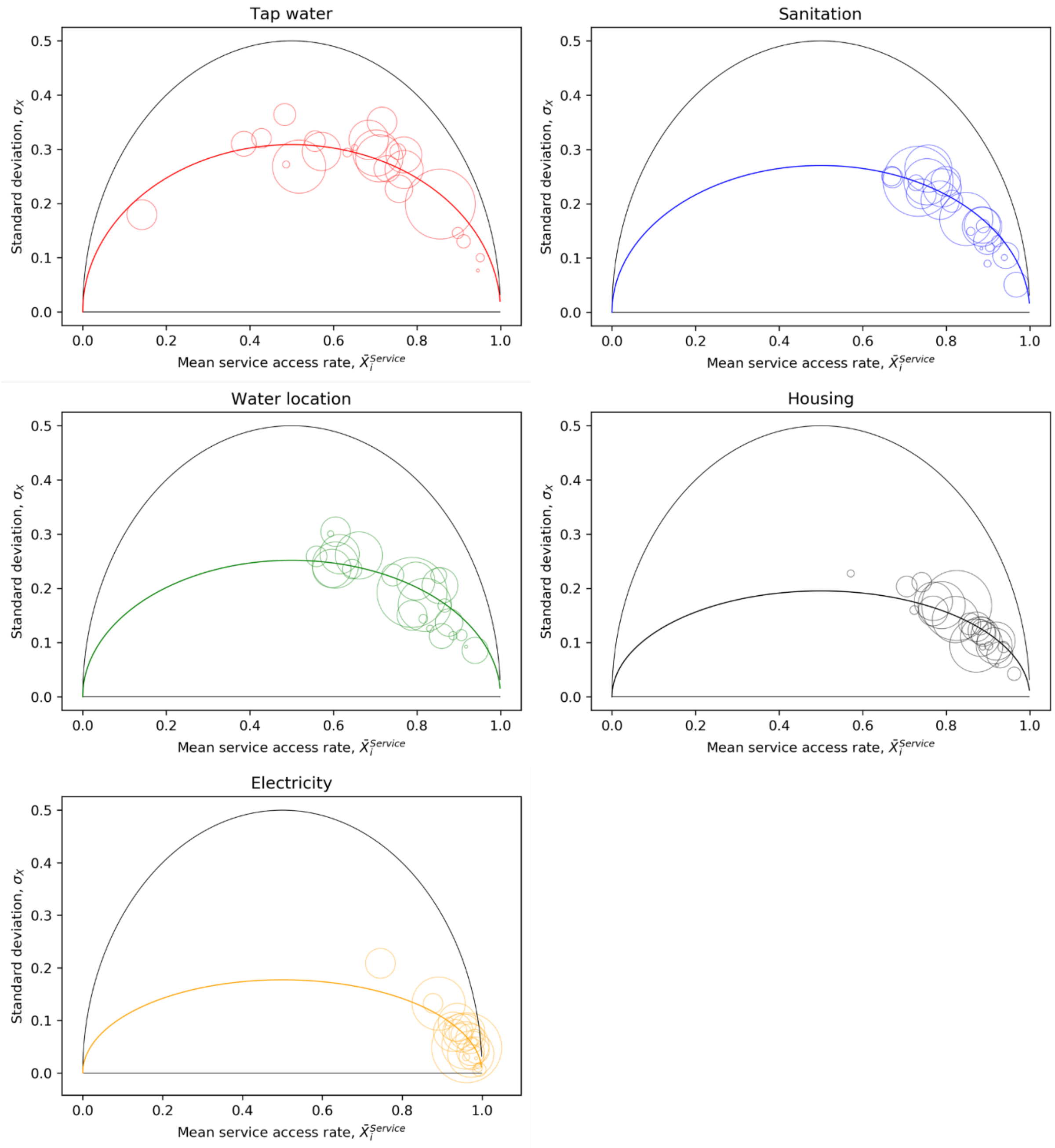


Figure 0.12: Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of states using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.


Tap water

Sanitation

Water location

Housing

Electricity

Figure 0.13: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the state level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.2 Sensitivity analysis

A.3.2.1 City definition

In Chapter 3, the selection of cities is defined as those containing at least 30 local administrative divisions, i.e., wards. This value is used as a rule of thumb to increase the confidence interval of the data when calculating the mean and standard deviation leading to the average inequality index. However, in doing so, the city sample size is reduced significantly, from 4027 towns and cities to 524. As a result, the number of states included is reduced from 33 to 24. As such, the following analysis estimates the sensitivity of the results to this rule of thumb, reducing the number of wards required to define a city from 30 to 15 in increments of 5.

The results are presented in Table 0.6 and indicate that, as more cities are included due to the decreasing requirement for the number of wards, the scale dependence of the inequality measure tends to increase slightly as well as the estimated magnitude of inequality, i.e., the b value increases marginally but with overlapping confidence intervals compared to other definitions in some cases such that there is no statistically observable change. The most significant observable changes in the average inequality are found for sub-districts and districts, however these changes remain marginal. The same results are observed for including cities which contain 25 wards as with including those with 30 wards. For the 20 ward definition, the results reveal that states are statistically distinguishable as with previous results, but that districts exhibit a scale dependence compared to sub-districts and districts, unlike with the 30 and 25 ward definition. Towns and cities remain statistically indistinguishable from sub-districts by this definition. These findings are coherent with the 20 ward definition. However, all scales are found to be statistically indistinguishable from each other when defining cities by those with 15 or more wards. This significantly increases the sample size such that all states within India are included. The scale dependence observed by this definition is likely a result of the administrative definitions of larger urban areas, as we have seen in Chapter 3. Larger cities tend to have significantly more local urban administrative areas than smaller cities, and these cities tend to be simultaneously under the administrative control of city, sub-district and district levels as defined by the census (3). As such, the overlapping definition generally results in the average inequality being statistically indistinguishable from each other across these scales, as seen in Chapter 3. However, including a significantly greater number of smaller towns and cities, which are generally only under town/city administration and therefore themselves belong to the broader administrative divisions of sub-districts and districts, results in the increased scale-dependent average inequality.

The sensitivity analysis therefore reveals that increasing the number of smaller towns and cities within the assessment tends to increase the observed scale dependence of national inequality characterized by the national basic needs profile. However, the average inequality predicted at this scale is statistically indistinguishable across each definition given the overlapping confidence interval, which is also the case for multiple definitions at other scales. Further, the results agree with findings in Chapter 3 that inequality between states is observed to a greater extent than towns and cities and that deficits in access to services are more widespread than concentrated within a selection of particularly deprived areas, i.e., the inequality in service access, estimated by the b-value, remains below 0.5 for all scales.

Table 0.6: Sensitivity of the average inequality index estimation, *b*, to the city selection defined by the number of wards, or local urban administrative areas, within each city, i.e., cities are included within the study if the number of wards is equal to or exceeds those stated in the table. Note that no. of wards = 30 is used to define city selection in the analysis within Chapter 3.

Scale	No. of wards	Sample size	Inequality index, b	95% CI	Fit, r^2
Towns/cities	30	524	0.324	[0.303, 0.344]	0.91
	25	895	0.330	[0.312, 0.348]	0.91
	20	1319	0.333	[0.317, 0.349]	0.91
	15	2762	0.340	[0.326, 0.354]	0.91
Sub-districts	30	486	0.3345	[0.312, 0.357]	0.908
	25	806	0.342	[0.322, 0.361]	0.91
	20	1126	0.352	[0.333, 0.370]	0.931
	15	1846	0.379	[0.363, 0.396]	0.913
Districts	30	321	0.357	[0.333, 0.381]	0.911
	25	405	0.382	[0.361, 0.403]	0.928
	20	462	0.411	[0.391, 0.430]	0.94
	15	526	0.443	[0.426, 0.461]	0.946
States	30	24	0.440	[0.407, 0.473]	0.982
	25	27	0.451	[0.424, 0.477]	0.989
	20	29	0.462	[0.434, 0.489]	0.989
	15	33	0.491	[0.462, 0.520]	0.988

A.3.2.2 Arithmetic versus geometric mean

The following illustrates the sensitivity of the results to the metric formation, specifically noting the progression of composite index formulations from the aggregation of dimensions via an arithmetic to a geometric mean, as with the HDI (7). The HDI evolved from the additive to multiplicative formulation of the composite index to better capture extremes within the population, emphasizing that the achievement of all dimensions is essential to achieve a minimum level of development and that these dimensions are not substitutional (1). The formula to calculate the geometric and arithmetic means are shown in equations 1 and 2 respectively.

$$X_i = \sqrt[n]{\prod_{j=1}^{n} X_i^j} \qquad [1]$$

$$X_i = \sum_{j=1}^{n} \frac{X_i^j}{n} \qquad [2]$$

The results show that the arithmetic mean overlooks significant deficits in standards of living at each scale. This formulation of the average index generally estimates a higher mean achievement of dimensions and lower dispersion, i.e., the arithmetic mean moves data points towards the bottom right of Figure 0.14. This means that the line of best fit and thus the observed average inequality is significantly reduced, indicated by a flatter line of best fit as in **Error! Not a valid bookmark self-reference.** and a significantly lower inequality index estimated in Table 0.7.

Table 0.7: Inequality index results for the geometric mean (main text) compared to the arithmetic mean formulation of the SDI.

Level	Mean	Inequality index, b	r^2	95% CI
Town/city	Geometric	0.324	0.91	[0.304, 0.345]
	Arithmetic	0.255	0.92	[0.250, 0.262]
Sub-district	Geometric	0.335	0.91	[0.312, 0.357]
	Arithmetic	0.261	0.93	[0.255, 0.268]
District	Geometric	0.357	0.91	[0.333, 0.381]
	Arithmetic	0.276	0.94	[0.268, 0.284]
State	Geometric	0.440	0.98	[0.414, 0.466]
	Arithmetic	0.338	0.99	[0.322, 0.355]

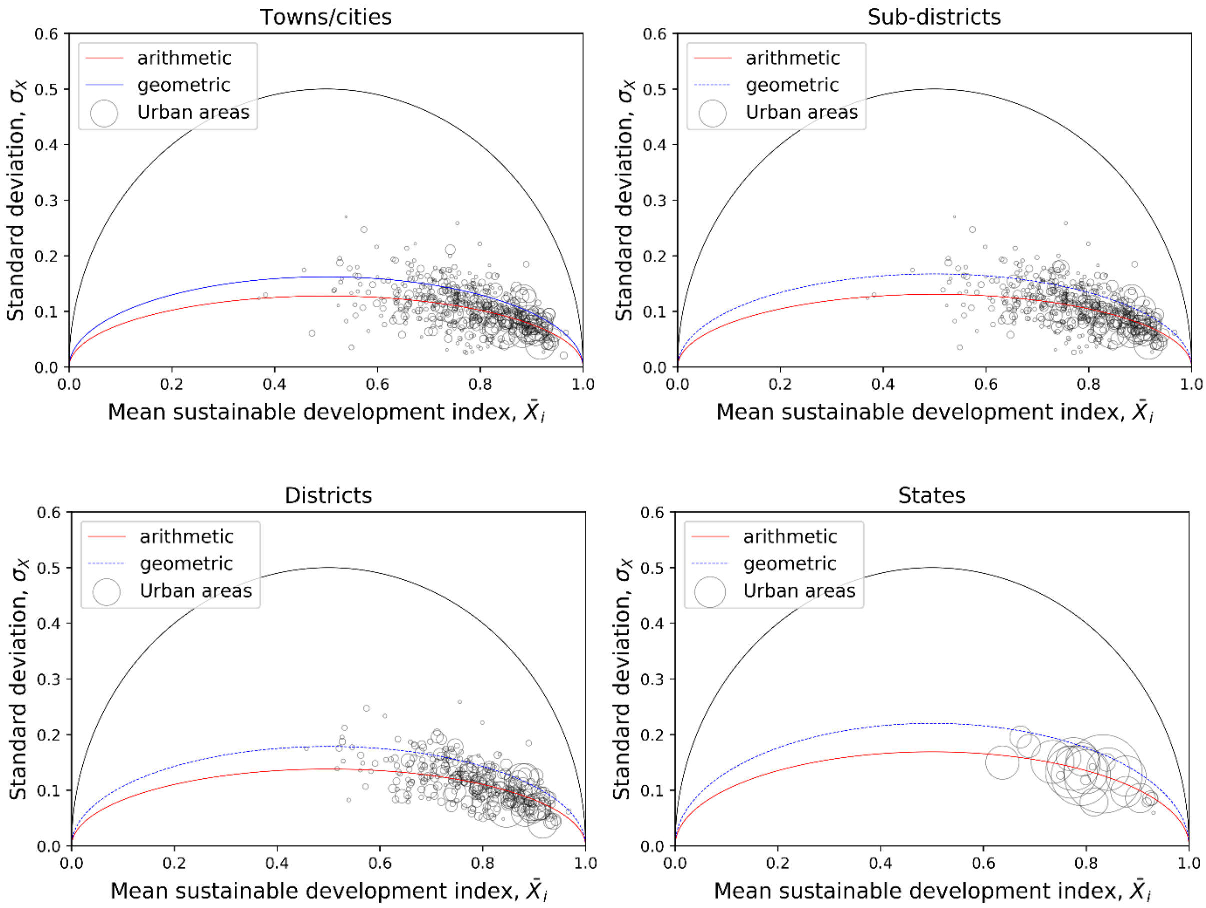


Figure 0.14: The relationship between the standard deviation of the SDI, σ_i, and the mean SDI, $\bar{X}_i$, for different administrative scales using the arithmetic mean method of aggregation. The profiles are calculated using SDI values for wards contained within each city as in the main text. The size of the circle is proportional to the total urban population. The upper black line is the boundary of maximum inequality, $b = 1$, and the lower black line, the x-axis, is the boundary of minimum inequality, $b = 0$.

The red line represents the line of best fit calculated by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ using population WLS regression and adopting the arithmetic mean formulation of the SDI. The blue line indicates the line of best fit as calculated by the geometric mean in the main text for reference.

A.3.2.3 Overlapping administrative divisions

Table 8: Results for the regression of $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ at the town/city level for those towns/cities which are simultaneously towns/cities, subdistricts, and districts, i.e., overlapping administrative divisions, in comparison to the original values.

Towns/cities	No. of data points	Inequality index, b	r^2	95% CI
Overlapping	204	0.318	0.89	[0.284, 0.352]
Non-overlapping	319	0.333	0.93	[0.318, 0.350]
Original	524	0.324	0.91	[0.304, 0.345]

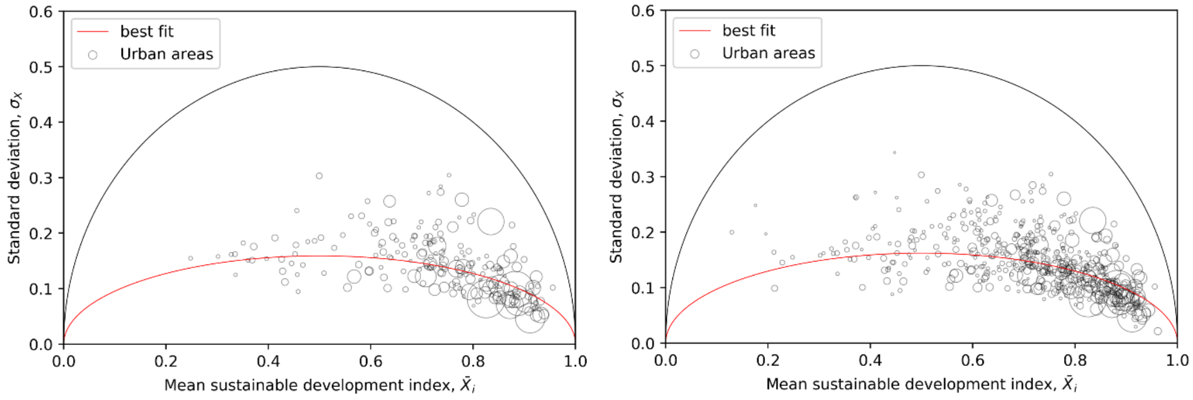


Figure 0.15: The relationship between the standard deviation of the SDI, σ_i, and the mean SDI, $\bar{X}_i$, at the town/city scale. (left) The relationship for those towns/cities which are simultaneously towns/cities, subdistricts, and districts, i.e., overlapping administrative divisions, in comparison to (right) the relationship for those towns/cities which are non-overlapping. The profiles are calculated using SDI values for wards contained within each city. The size of the circle is proportional to the total urban population. The upper black line is the boundary of maximum inequality, b = 1, and the lower black line, the x-axis, is the boundary of minimum inequality, b = 0. The red line represents the line of best fit calculated by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ using population WLS regression.

The results reveal minor changes to the average inequality index at the scale of towns/cities when redefining towns/cities as those which are simultaneously towns/cities, subdistricts, and districts. In total, 320 towns/cities are omitted from the analysis and the average inequality index changes from $b = 0.324$ to $b = 0.318$, values which are statistically indistinguishable from each other. Similarly, when assessing the average inequality index for those towns/cities which are non-overlapping the average inequality index changes from $b = 0.324$ to $b = 0.333$. Thus, while the overlapping administrative divisions are a driving factor for the scale independence at town/city, subdistrict, and district level, redefining towns/cities by their overlapping administrative divisions yields the same scale dependence between towns/cities and states, and only reduces the overall inter-urban inequality marginally. This, in combination with the sensitivity analysis on city definitions presented in section 0, suggests that the definition of town/city by the number of wards has a greater impact on the observed average inequality than the overlapping definition of administrative divisions. However, the results of the alternative aggregation approach shown in Table A.7 highlight that the choice of metric has a greater impact on the perceived outcomes than the definition of city. This points to the policy lens towards the careful consideration of metrics and also the use of alternative and complementary metrics to capture uncertainty and validate findings between metrics – as we have demonstrated in Chapter 3.

B - Chapter 4 Supporting Information

B.1 Regression model selection

B.1.1 Household composition variables

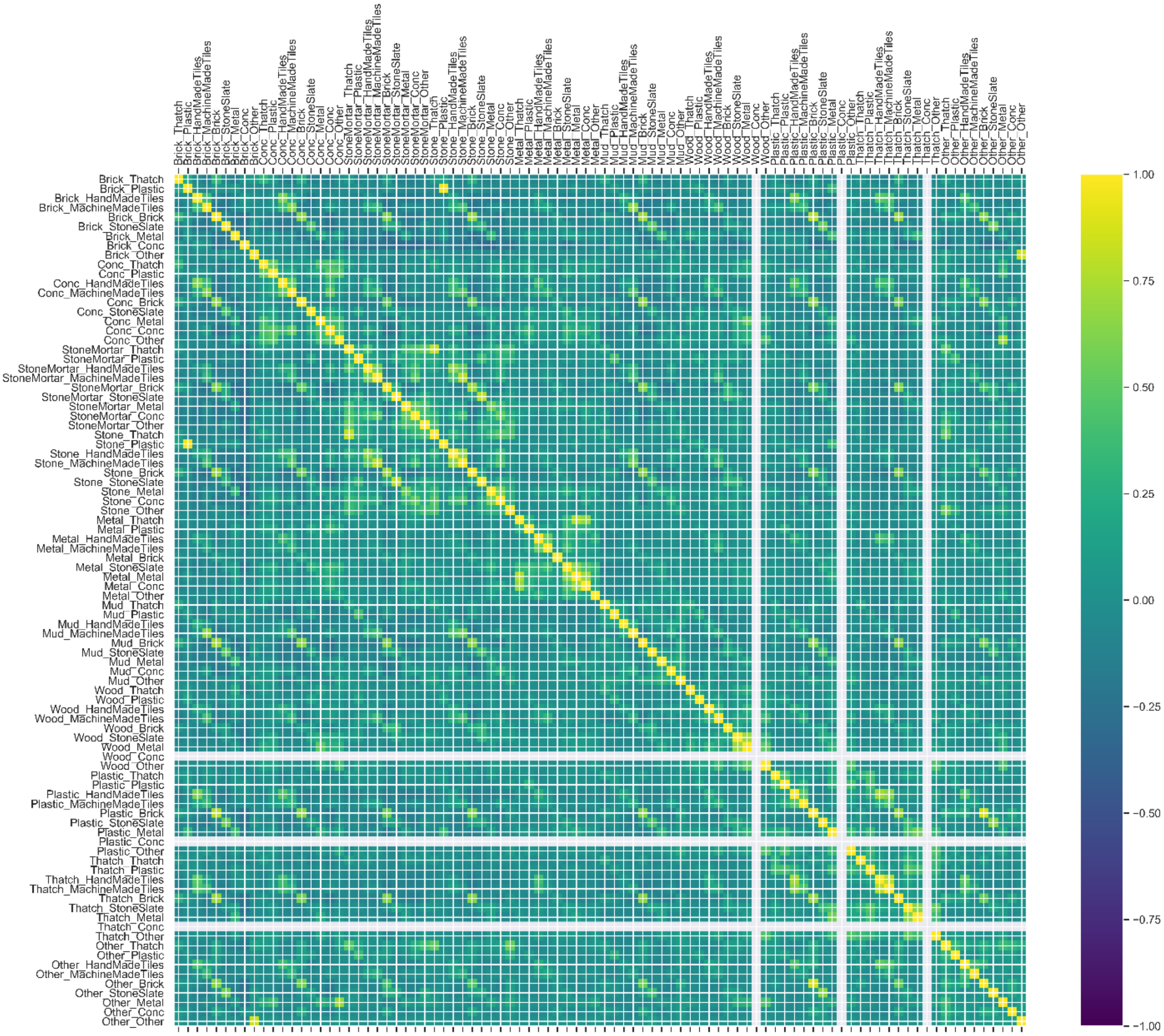


Figure 0.16: Co-linearity of variables relating to the composition of households by material used for walls and roofs, displayed as material of *Wall_Roof*. The white vertical and horizontal lines indicate variables which correspond to 0% of household compositions.

B.2 Univariate analysis

Table 0.9: Results of the univariate beta regression from regressing the listed variable, noted as material of *Wall_Roof* as in Figure 0.16, on the SDI. The mean composition refers to the average prevalence of households comprised of a unique combination of wall and roof materials among towns and cities, as shown in Chapter 4 Figure 4.1. Note that stone for wall materials refers to stone packed with mortar. Bold variables indicate those with a statistically significant relationship with basic needs outcomes, using a $pvalue < 0.05$.

Variable	Mean composition (%)	P-value
Brick_Conc	**41**	**0.00**
Brick_Metal	8	0.34
Brick_Stone/Slate	7	0.36
Brick_Brick	5.7	0.31
Stone_Conc	5.7	0.09
Conc_Conc	**4.4**	**0.00**
Brick_HandMadeTiles	**2.8**	**0.00***
Brick_MachineMadeTiles	2.4	0.64
Mud_HandMadeTiles	2.3	0.22
Stone_Stone/Slate	**2.2**	**0.00***
Mud_metal	**2.0**	**0.00***
Mud_Thatch	**1.5**	**0.00***
Stone_Metal	1.3	0.57
Total	**86.3%**	-

*refers to variables which are found to have a significant but negative relationship with basic needs outcomes.

The results of **Table 0.9** indicate that Brick_Conc and Conc_Conc variables have a statistically significant and positive relationship with basic needs outcomes for variables which account for more than 1% of the total household composition of towns and cities on average.

B.3 Link function

Table 0.10: Link function selection for multi-variable beta regression at the town and city level, adopting Brick_Conc and Conc_Conc as covariates based on the results of **Error! Reference source not found.**. The results indicate that the complementary log-log link function is most suitable for the final beta regression, with the lowest Bayesian Information Criteria (BIC) and log likelihood.

Link function	AIC	BIC	Log likelihood
Complementary log-log	-814	-797	411
Log-log	-810	-792	409
Logit	-811	-793	410
Probit	-812	-795	410

The application of logit or probit in this case is not appropriate given that they measure only binary outcomes, with the SDI found within a continuous range from 0 to 1. However, the absence of knowledge of the dynamics governing the process that are modelled means that it is appropriate to calculate regression coefficients based on statistical regression measures, i.e., the Bayesian information criteria and log-likelihood, to reason between adopting the complementary log-log or the log-log link function.

B.4 Material composition of areas achieving high basic needs outcomes

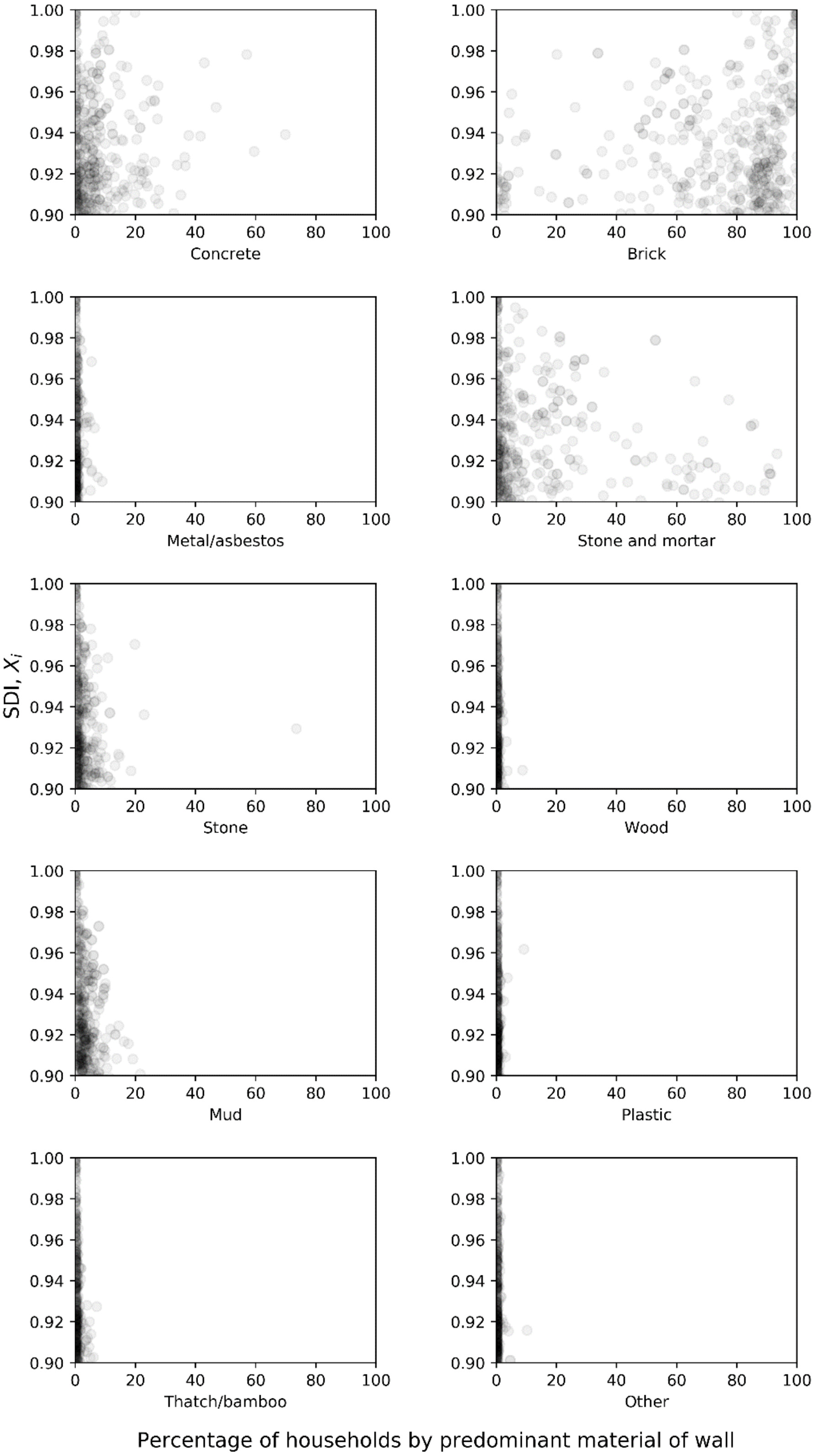


Figure 0.17: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of walls, for areas achieving an SDI > 0.9.

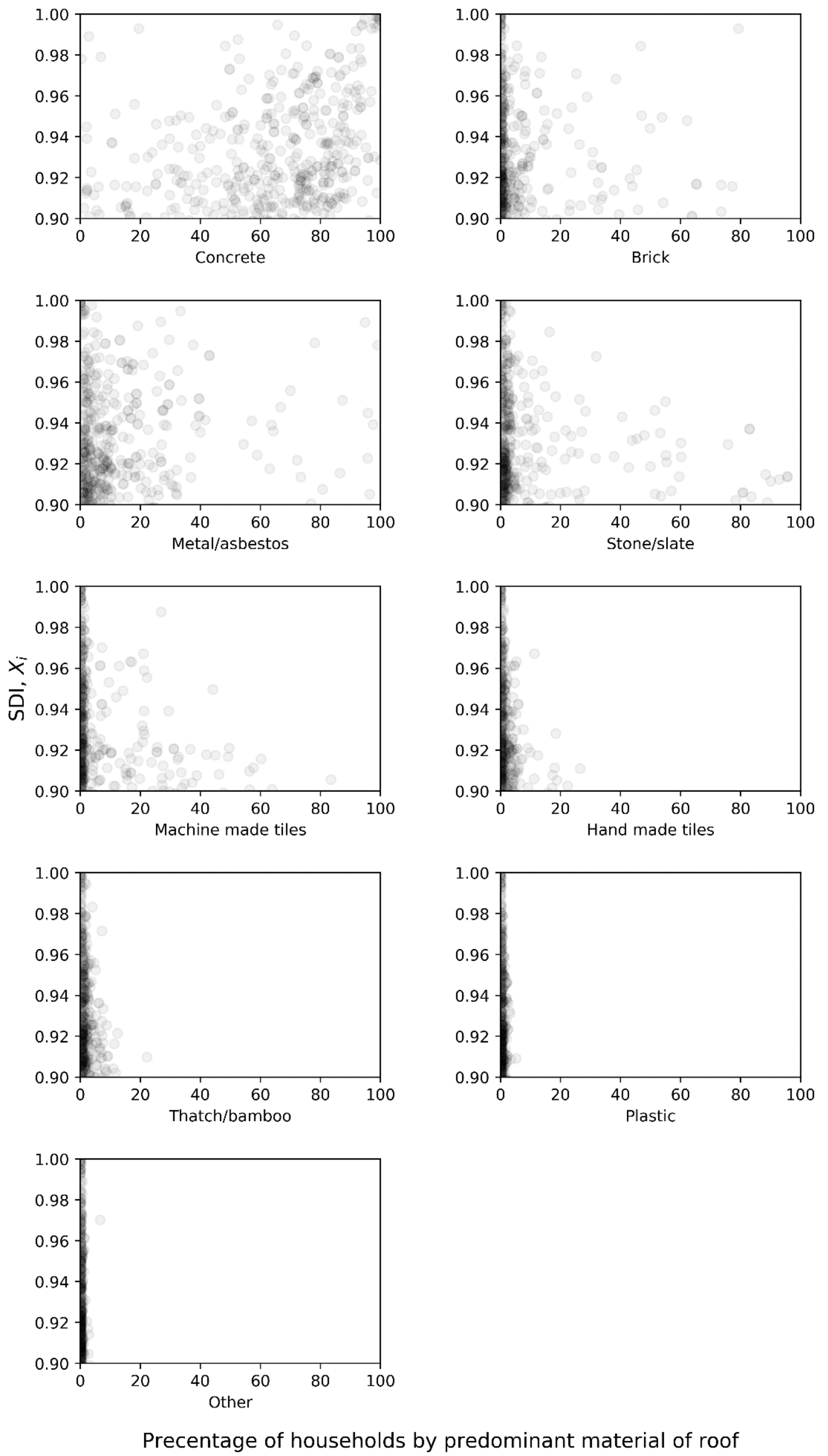


Figure 0.18: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of roofs, for areas achieving an SDI > 0.9.

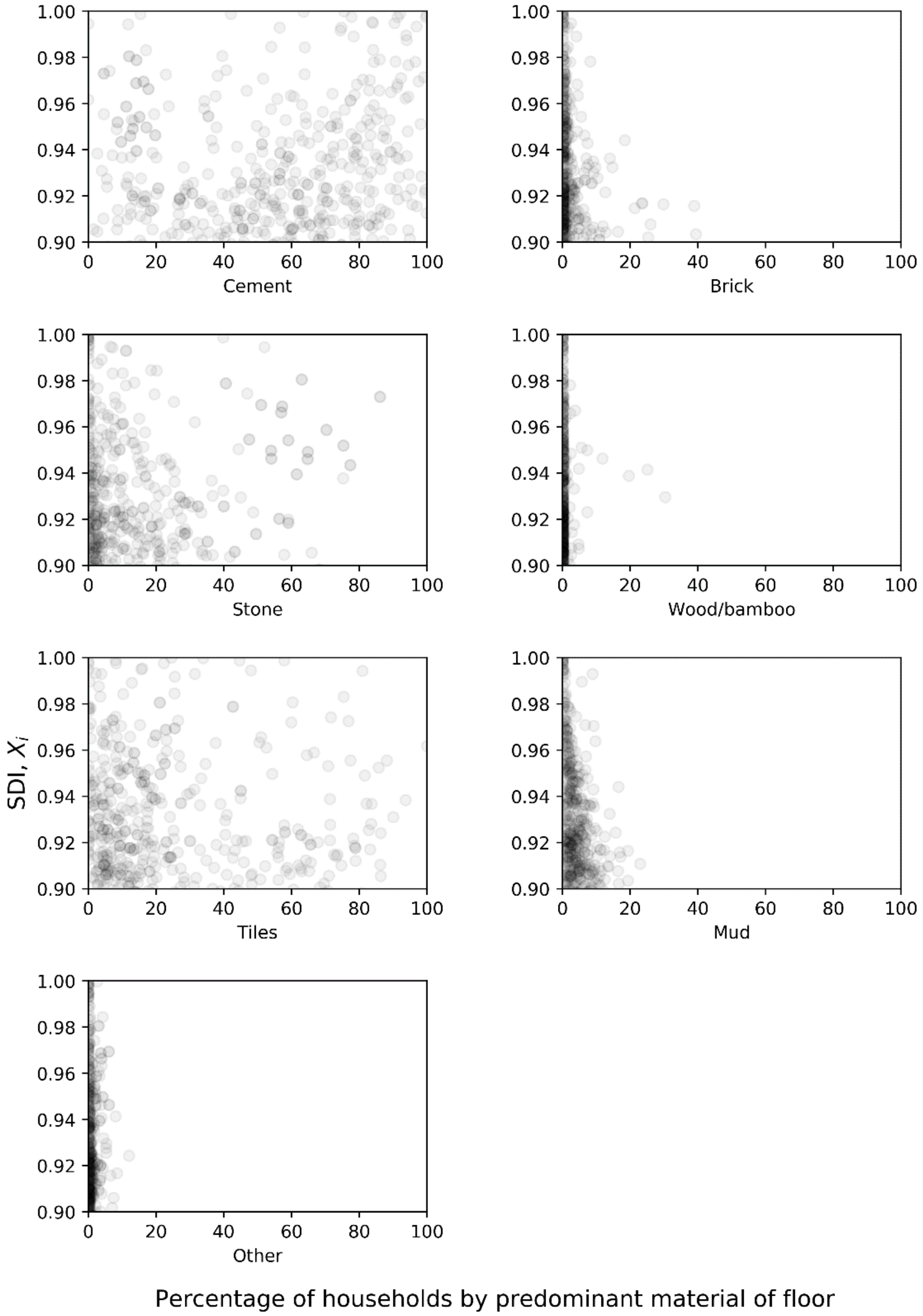


Figure 0.19: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of floors, for areas achieving an SDI > 0.9.

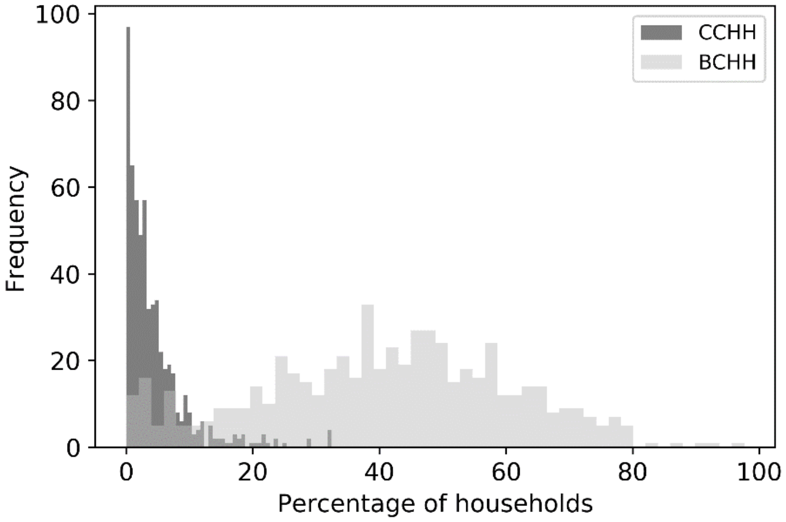


Figure 0.20: The frequency distribution of BCHH and CCHH across the towns and cities of urban India. The figure shows that BCHH is widely adopted and at a variety of rates, while CCHH is largely present in a small percentage of towns and cities and is mainly only responsible for a small percentage of the built environment in many areas.

C - Chapter 5 Supporting Information

C.1 Residential buildings

The uniform composition of housing is evident through the available architectural control building drawings and associated documentation provided by the Chandigarh Administration and the Directorate of Census Operation in Chandigarh (1–3). The uniform typology of buildings of Chandigarh is dictated by the architectural control due to the master planning of the city and means that a single city-level archetype is appropriate for comparison to other studies of building archetypes. However, due to data provided by the Chandigarh Administration (1) it is possible to further the archetype classification to create Chandigarh-specific archetypes. As a result, it is possible to map the material intensity coefficient (MIC) data more accurately to the inventory of items within each sector. Building sample drawings can be found following the link to the architectural control drawing repository on the Chandigarh Administration website within the citizen facilitation section (4).

C.1.1 Inventory of items

The process and data used to create the inventory of items for Chandigarh-specific archetype classifications, i.e., where we further homogenize building samples by plot type and government housing scheme is provided within the main text. The inventory of items, i.e., the number of different plot types or government housing schemes within a sector, are collected from layout plans. Figure 0.1 shows an example layout plan for sector 35. The inventory of items at the sector level are then aggregated to their respective wards as per the Census ward map (5), see Figure 0.1 of the main text, and combined with the MIC values shown in Figure 5.3 of main text. Inventory data pertaining to plot types and numbers within sectors can be found on the Chandigarh Administration website within the citizen facilitation section (6) or alternatively on the website for the Department of Urban Planning Chandigarh (7).

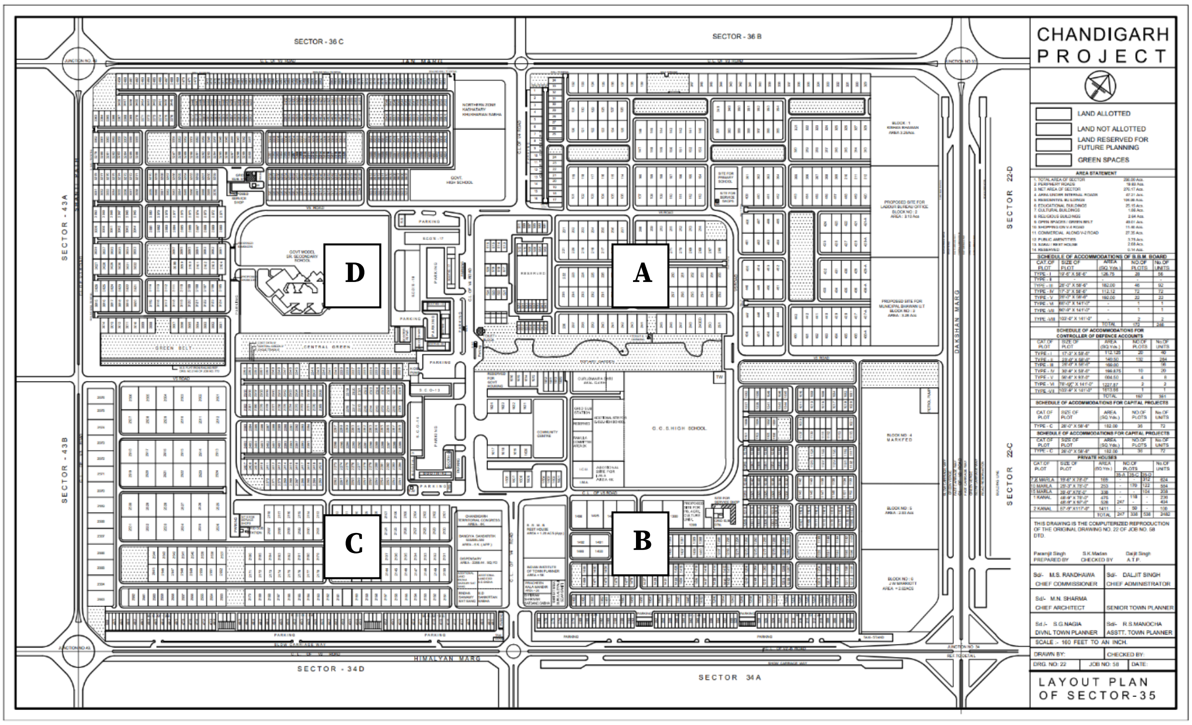


Figure 0.1: Example layout plan used to calculate the inventory of items at the sector-level. Each grid, e.g., a, b, c, and d, within sectors corresponds to a sub-sector, summing to 4 in total for each sector. The number of each plot type is summarized within the schedule of accommodation for different project types within the drawing notes. Where the schedule is not provided, and the plot types are labelled within each sub-sector, the plot types are counted manually and related to the construction phase of the sector.

C.1.2 Material and embodied energy intensity coefficients

Building samples are collected through the Chandigarh Administration Citizens Facilitation which stores architectural control drawings for various plot types and government housing schemes. The maximum available number of building drawings relating to the inventory of items are used to calculate MIC values per archetype. In total, 12 building samples are collected for superstructure MIC calculation and 2 building samples collected from the Chandigarh Housing Board (8) to calculate substructure MICs due to the greater detail of foundations provided in comparison with architectural control drawings. An example architectural control drawing is shown in **Figure 0.2. Table 0.1** contains the material property data used to calculate the total mass and embodied energy of materials and components for all building samples. **Figure 0.4:** Total material stock by component across the wards of the Municipal Corporation of Chandigarh.**Figure 0.4** shows the MIC for each archetype disaggregated by building component.

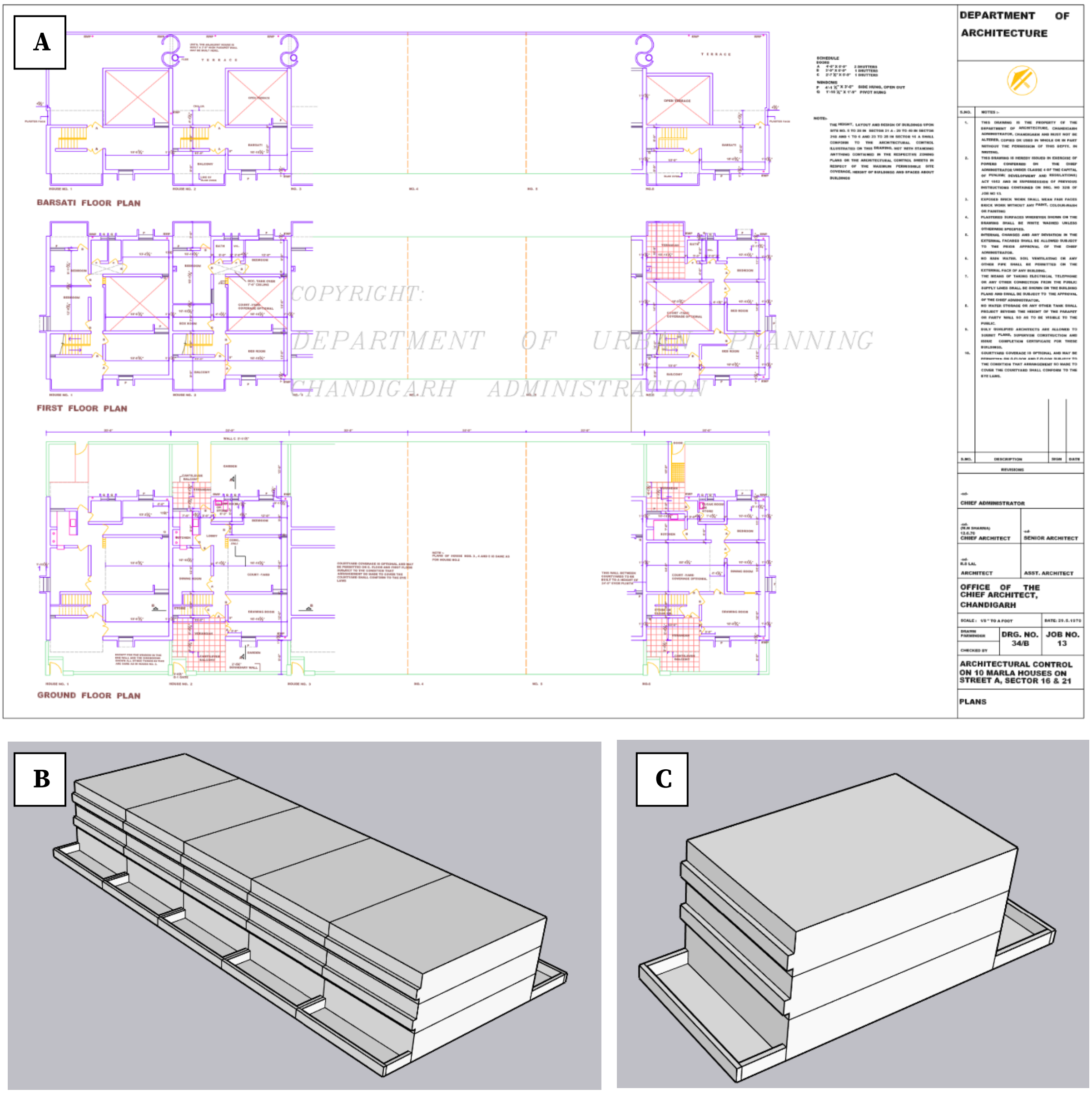


Figure 0.2: (A) Example architectural control drawing showing the plan view for a 10 marla housing plot type (4). (B) Simple 3D model of a row of 10 marla housing (authors own) and (C) a simple 3D model of a single 10 marla plot (authors own), where the plot size includes the footprint of the building and the two external areas.

Table 0.1: Material properties used to calculate the total mass and embodied energy of residential buildings, raw values are provided by (9)

Material	Density (kg/m^3)	Embodied energy (GJ/unit)	EC (kgCO2/ton)
Reinforced concrete slab (1% steel)	2300	3.65 (m^3)	0.067
Reinforced concrete foundation (0.5% steel)	2300	2.56 (m^3)	0.122
Brick	1800	2.41 (m^3)	1.82
Steel	7800	20.62 (ton)	2.98
Clay tiles	2300	3.33 (ton)	0.334
Bitumen membrane	1100	2.98 (ton)	0.334

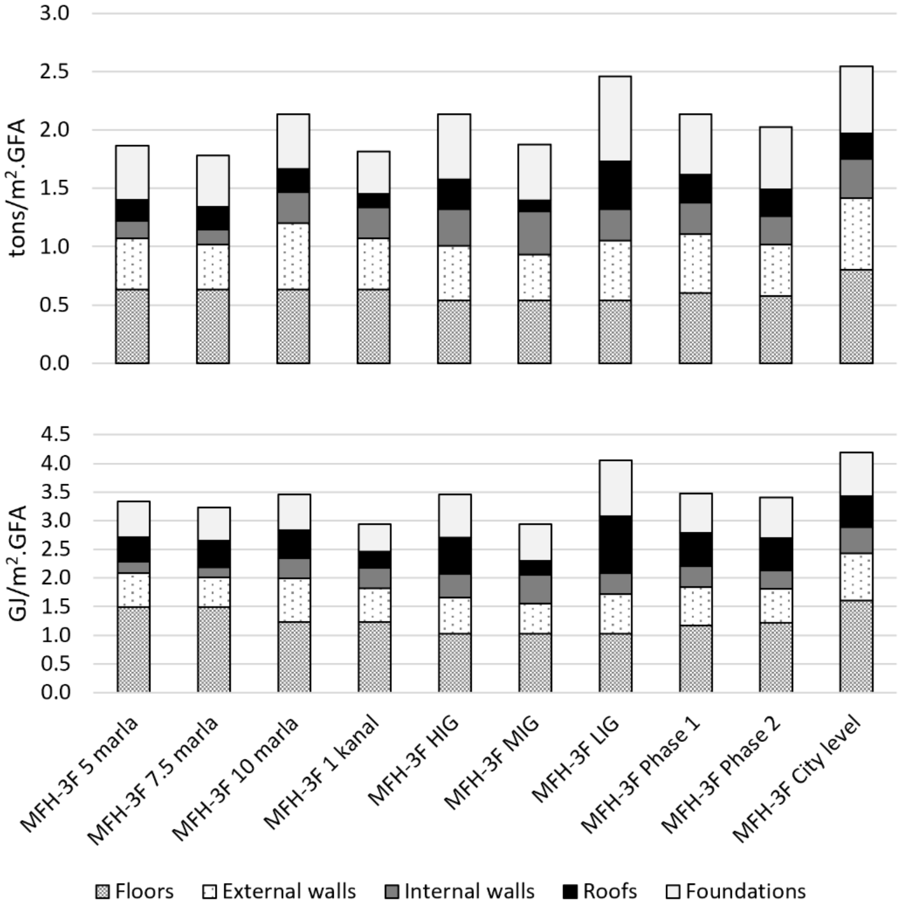


Figure 0.3: (Top) MIC disaggregated by materials, and (bottom) embodied energy intensity of materials for MFH-3F housing of brick walls and reinforced concrete floors and roofs. We use twelve building samples corresponding to various plot sizes, m^2, and government housing schemes which includes high-, 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.

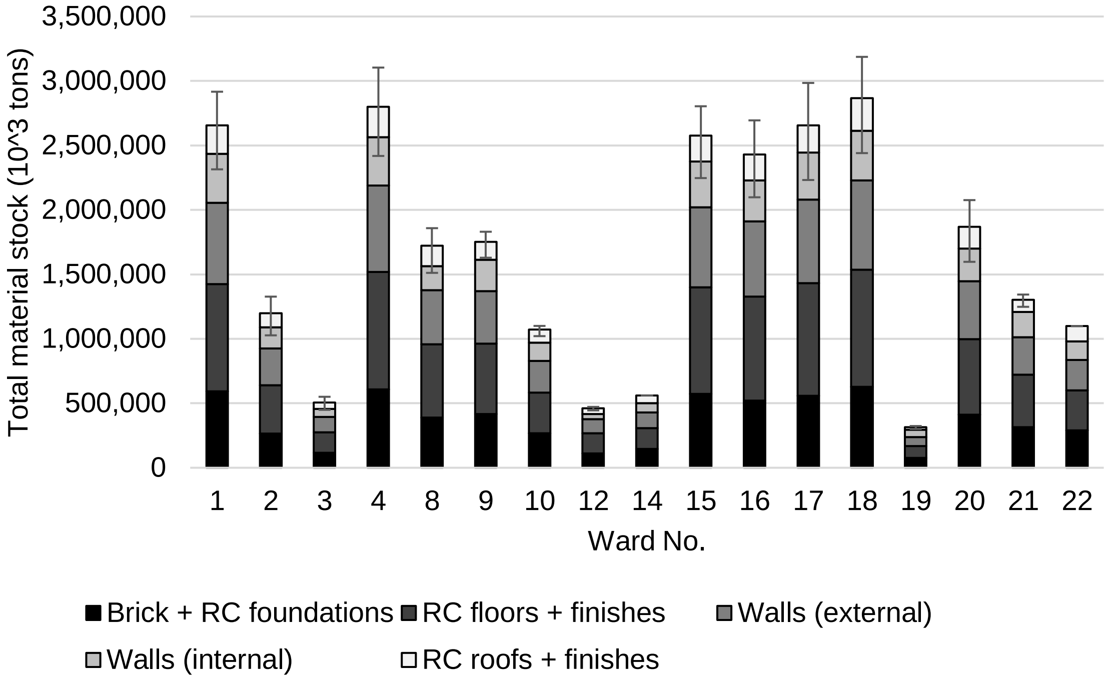


Figure 0.4: Total material stock by component across the wards of the Municipal Corporation of Chandigarh.

C.1.3 Summary of key assumptions

While architectural control drawings show standard dimensions for the structural framing and floor and roof finishes, a number of assumptions are made to fill gaps in data per drawing and layout plan. We assume standard dimensions and detailing of buildings where data is not available as a result of the stringent architectural control. Architectural control drawings generally show the roof as half thickness of the floors. Most drawings show the roof as 4.5" RC slab with 1.5" clay tiles and 2 layers of bitumen. Where these details are not provided, we assume these specifications in line with the architectural control. Where the thickness of concrete is not specified for roofs, we calculate the thickness by the difference between the overall specified thickness and roof finishes as per the assumptions or the specifications on drawings. The thickness of bitumen is not specified explicitly and we therefore assume the thickness is 5mm as per (9). Most drawings show floors with 1.5" ceramic tiles for finishes and we assume this specification in line with the architectural control where details are not provided. Structural drawings specifying foundation details show that foundation thicknesses are related to the thickness of the wall. Walls are shown to be either 9" (internal walls) or 13.5” (external walls). Thus, we assume foundation (strip footings) correspond to the wall thickness for all architectural control drawings. As discussed in the main body, the ground conditions of Chandigarh are uniform and the building typologies homogeneous, thus we assume that foundation design is the same across buildings (strip footings under load bearing walls constructed of concrete, RC and brick). Most drawings specify wall thicknesses for internal and external walls of 9” and 13.5” respectively. We assume this thickness for drawings where these are not specified. Brick jails (walls surrounding the roof terrace area) are constructed of brick of half story height and are therefore considered as external walls. For the 5 marla plot type (126m^2), the width of the building is not given. We assume the width is the same as the 7.5 marla plot and verify the overall plot size (130m^2). Plot types often correspond to particular sectors which belong to their own construction phase as per the masterplan. We therefore assume this architectural control is generalized as per the phase and create two building archetypes for phase 1 and 2 to account for unknown plot types within sectors. We assume that steel accounts for 1% of the total volume of concrete for which is used for reinforcing as per the data available from (9). This value corresponds to reinforced slabs which are used for the floor system of all buildings. The drawings show no reinforcement in beams or columns due to load-bearing brick and masonry walls on the interior and exterior of the building and reinforced slabs used for floor systems with no structural beams specified. We assume that construction methods leading to 2011 are the same as in the masterplan, with drawings showing no difference between original drawings (dating from 1956) to revised drawings (dating up to 2008).

C.2 Roads

C.2.1 Inventory of items

We use Geofabrik (https://download.geofabrik.de/asia/india.html) to obtain transport infrastructure data from openstreetmap (OSM). The road types are split into various categories such as residential, path, primary, and secondary etc. and are highlighted on the respective maps of Chandigarh in ArcMAP below. Residential categorizations of roads are most common, accounting for 54% of the total length of roads downloaded. We evaluate primary, residential, secondary, service, tertiary, and trunk road types including their respective *link* data where necessary (as these contain details such as roundabouts and are merged into a single road type). We therefore account for ~93% of the total length of road data available, omitting roads that are unclassified as well as those limited in coverage and thought to be unrepresentative of the total stock (e.g., cycleways and pedestrian/paths).

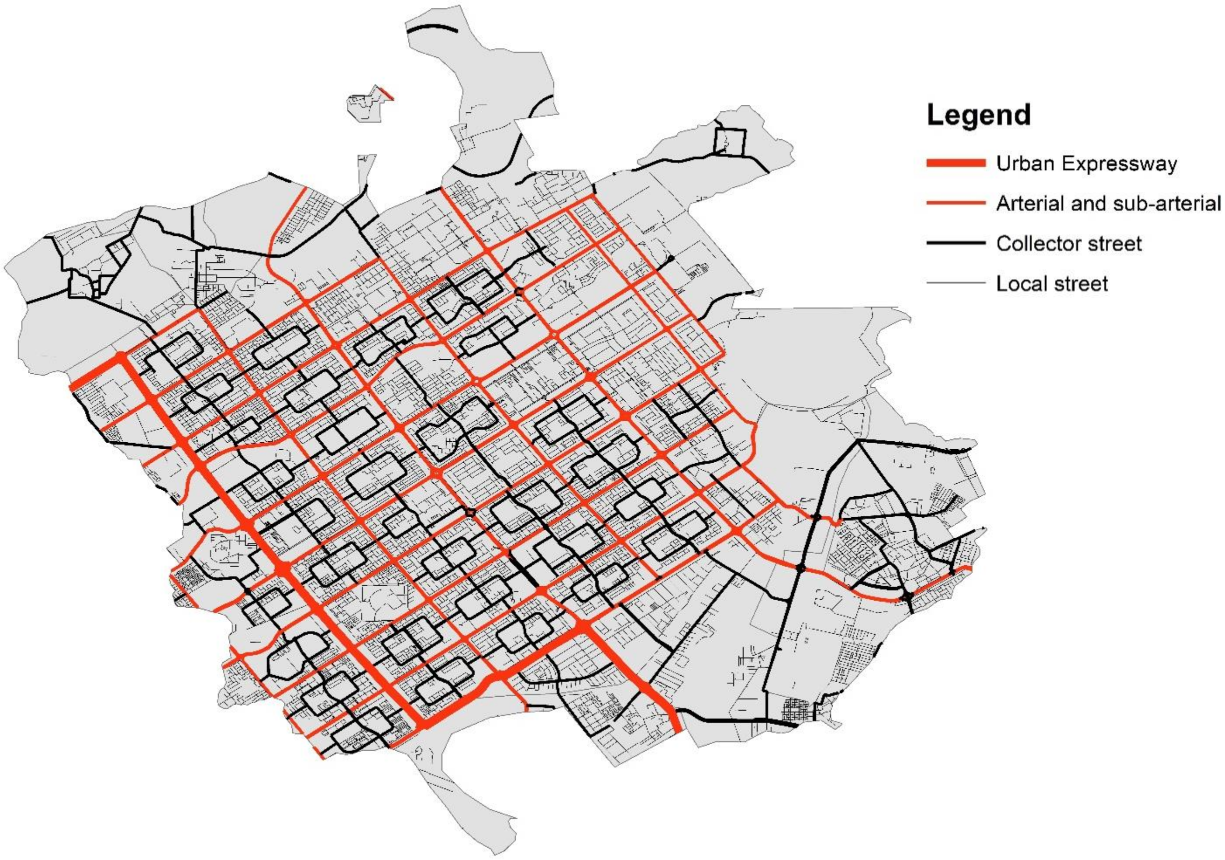


Figure 0.5: Map of the road network of Chandigarh adopting OSM data as per the wards of Chandigarh. The various road types of Chandigarh are aggregated into appropriate road archetypes as in **Table 0.2** to aid comparability between studies.

C.2.2 Material intensity coefficients

Table 0.2: The road types present within Chandigarh and their approximate width as estimated using Google Earth.

Road type	Road type as per Chandigarh's road system	Approximate width, m	Recommended lane widths for roads, m (10)*
Urban expressway	V1	50	40-75
Arterial and sub-arterial roads	V2-V3 (sector perimeter)	30	30-60
Collector street	V4 (entering sectors)	25	15-30
Local street	V5 (leading to residential buildings)	10	10-15

*recommended lane widths as per Table 4.1 URC Geometric Design Guidance.

C.2 Roads

Table 0.3: Material intensity of roads as per the national estimate for roads in Vietnam (11) which are used to calculate the total material stock of roads within Chapter 5.

				Material intensity, kg/m					
Road type	**Road composition**	**Material intensity, kg/m^2** (11)		Surface layer			Base layer		
		Surface layer	Base layer	Stone	Sand	Asphalt	Stone	Sand	Asphalt
Urban expressway	Asphalt	5.35	99.02	10515	0	268	0	76590	4951
	Sand	0	1531.8						
	Stone	210.3	0						
Arterial and sub-arterial roads	Asphalt	5.35	99.02	6309	0	161	0	45954	2971
	Sand	0	1531.8						
	Stone	210.3	0						
Collector street	Asphalt	5.35	99.02	5258	0	134	0	38295	2476
	Sand	0	1531.8						
	Stone	210.3	0						
Local street	Stone	331.2	1800	3312	409	0	18000	0	0
	Sand	40.9	0						

Table 0.4: Material intensity of roads as per the estimated values from an alternate study in Hanoi, Vietnam (12). The final material intensities of each road type within Chandigarh as per the studies are shown in the right-most columns. The lower material intensity values are used to calculate the sensitivity of the overall results in Chapter 5, which is briefly discussed in section 5.4.1.

	Material intensity, kg/m^2				**Study road type**	**Total material intensity, kg/m**	**Total material intensity, kg/m ***
Road type	Sand	Limestone/basalt	Cement	Asphalt binder			
Asphalt concrete, low class BTN	108	1142	0	8	Urban expressway	62,900	82,824
					Arterial and sub-arterial	37,740	55,395
					Collector street	31,450	46,163
Bitumen treated crushed stones	75	856	0	5	Local street	9,360	21,721

*total values from Table 0.4 from original study values.

C.2.3 Summary of key assumptions

Generally, assumptions are made by relating the raw data, i.e., location/type of road, and the measured road width within Google Earth, to the Chandigarh specific hierarchal road network, the recommended land widths for roads (10) and the road composition as per (11). We assume that all arterial and sub-arterial roads are of the same width, the majority of which are sub-arterial and measure 30m wide. We assume that V1-V4 roads are constructed the same as per the similar visual appearance. V5 roads are assumed to be constructed out of stone as opposed to asphalt and stone, owed to their significantly narrower construction compared to V1-V4 roads and that surface layer is a stone color as opposed to the darker asphalt surface layer from Google Earth imagery. We also assume that service roads are of the same construction as V5. We obtain data from literature for the material intensity of roads and thus assume that the road composition is similar to that in Vietnam as per the study from roads (11). We omit the use of cycleways, footways, living streets, paths, pedestrian, steps, track and unclassified road types which seem to be partially accounted for relative to the road types.

C.3 Comparison of city-level results

Table 0.5: Data used to calculate material stock coefficients for comparison to the values of Chandigarh calculated in Chapter 5. Unless referenced otherwise, all values are taken directly from, or calculated using values provided within, the respective study.

City, country, Year	*Population*	*Area, km²*	*Stock type*	*Total material stock, tons*	*Reference*
Jakarta, Indonesia, 2012	9,900,000	661.5 (13)	Residential buildings	299,700,000	(14)
Bandung, Indonesia, 2012	2,400,000	167.3 (15)	Residential buildings	94,000,000	
Rio de Janeiro, Brazil, 2010	6,318,960	1,200	Residential buildings	78,828,773	(16)
Beijing, China, 2013	21,150,000 (17)	667.2	Roads	159,000,000	(18)
Beijing, China, 2008	14,400,000	1310.9	Residential buildings	470,000,000	(19)
Chiclayo, Peru, 2007	*MS coefficients provided within the study*	*MS coefficients provided within the study*	Residential buildings	*MS coefficients provided within the study*	(20)
Singapore, 2016	5,600,000	716	Residential buildings	132,220,000	(21)
Esch-sur-Alzette, Luxembourg, 2010	32,600	14.35 (22)	Residential buildings	3,440,000	(23)
Manchester, England, 2004	30,232	8	Roads	650,000	(24)
	30,232	8	Buildings	2,250,000	
Wakayama, Japan, 2004	49,819	11	Roads	1,333,000	
	49,819	11	Buildings	10,000,000	

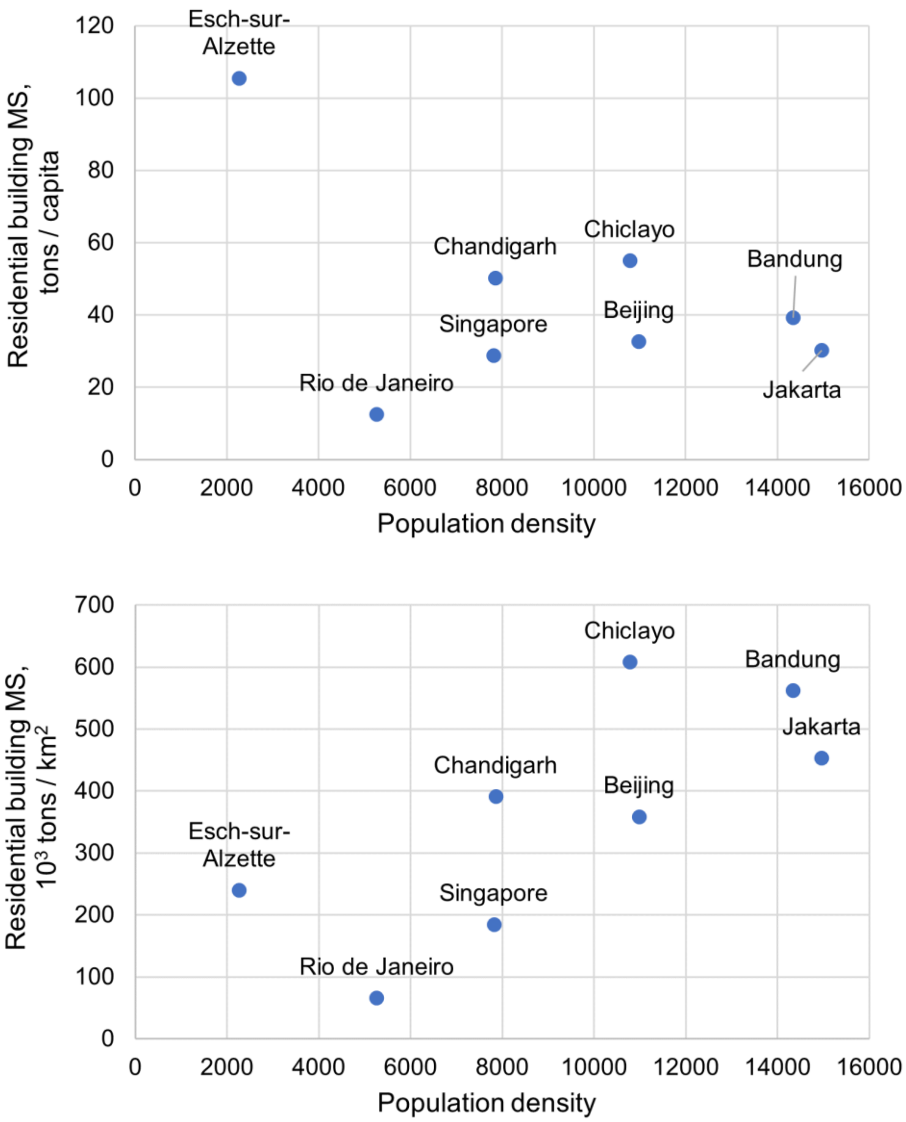


Figure 0.6: Relationship between the total MS of residential buildings and population density for (top) MS per capita, and (bottom) MS per km^2, for cities cited in Table 0.5.

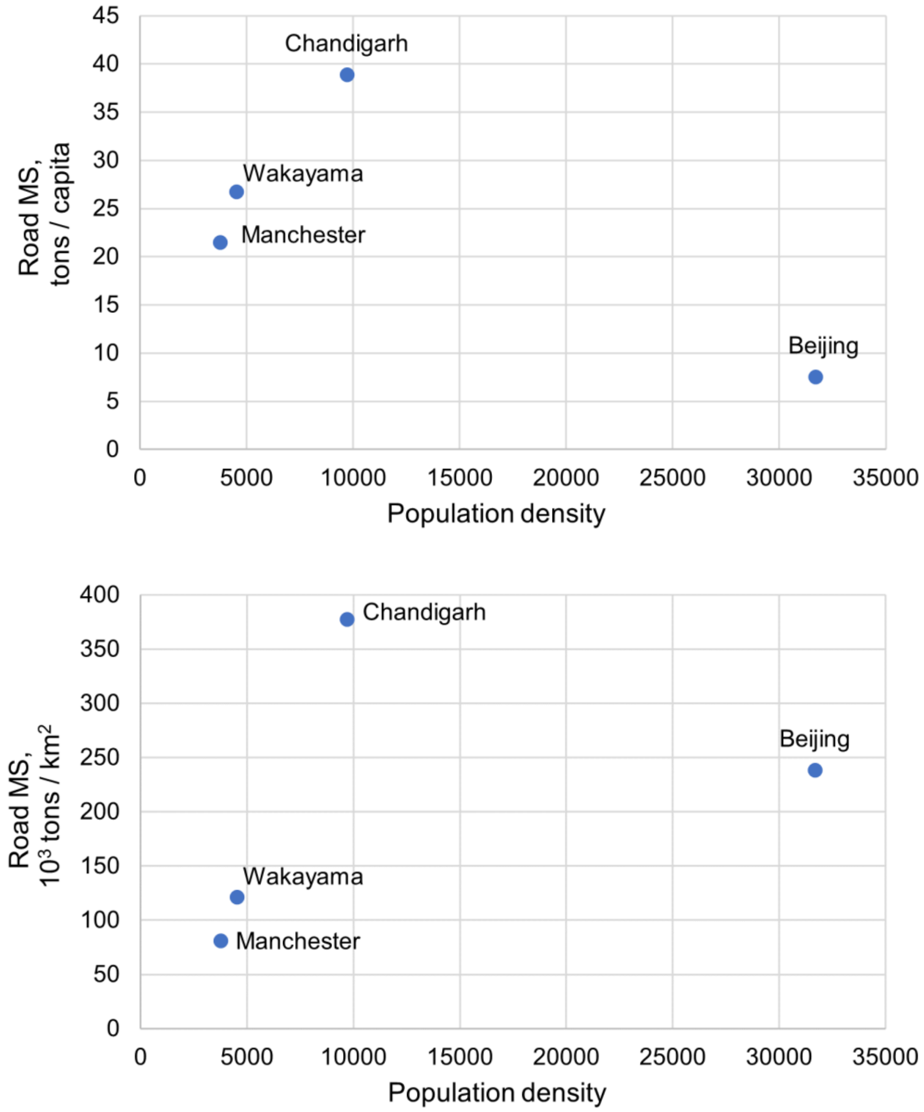


Figure 0.7: Relationship between the total MS of roads and population density for (top) MS per capita, and (bottom) MS per km^2, for cities cited in Table 0.5.

C.4 Chandigarh ward map

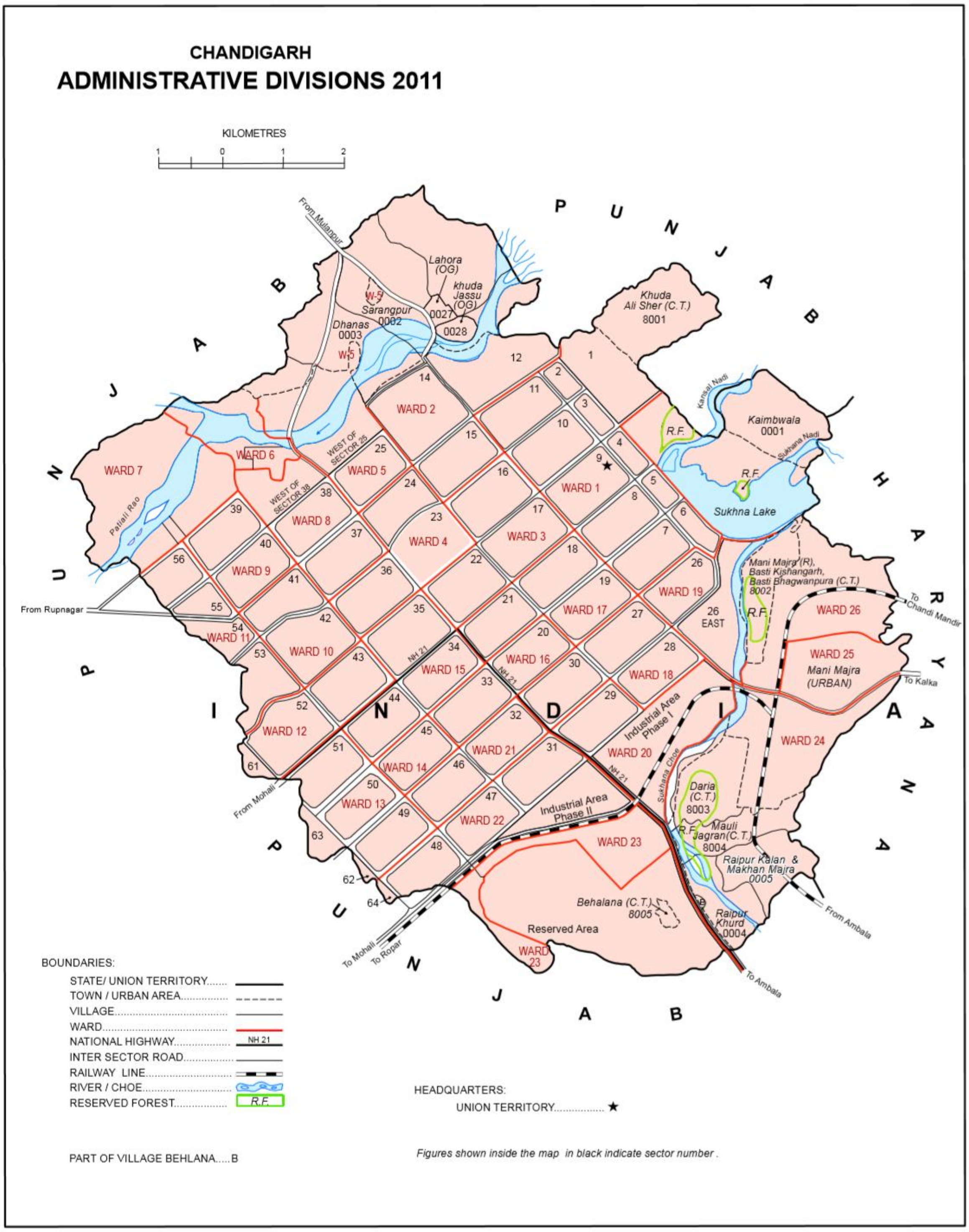


Figure 0.8: Map of the administrative divisions of Chandigarh as per the Census of India 2011 (5).

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A - Chapter 3 Supporting Information

A.1 Introduction

The following provides information supporting the analyses carried out in Chapter 3. The selection of adequate water supply dimensions within the SDI is firstly presented. Following this, regression results required to estimate the average inequality index for each scale are presented. The sensitivity of the average inequality index to the assumptions made within the main text are then presented, including an assessment of the sensitivity of the results to the metric formulation.

A.2 Correlation of water dimensions

As noted in Table 3.1 in section 3.2.1 of the main text, the source and location of drinking water are recorded separately within census such that dimensions relating to the availability and location of water are included separately within the SDI. In an existing study within Brazil and South Africa (1), the dimensions are aggregated as the respective census datasets record these dimensions simultaneously, e.g., the index formulated for South Africa defines achievement in the dimension relating to *improved water source* as household access to piped water within the dwelling, a tap inside the yard, or via a community tap less than 200m away (1). The main source of drinking water used to define adequate water access from the census of India is broadly coherent with this definition as well as those within the SDGs (2), i.e., tap water from a treated source. The location of the water source is defined as either *within, near,* or *away* from the premises (3). Spearman and Pearson correlation is undertaken to assess whether these dimensions should be considered separately within the SDI, and if so, which dimensions are to be included. However, to be in-keeping with many definitions of adequate water access within existing literature (1,4,5) and with broader monitoring imperatives such as the MPI (6) and SDGs (2), the SDI developed here only considers water located *within* or *near* the premises.

The results presented in Table A.1 show that the source and the location of drinking water have a weak correlation and are therefore included separately within the SDI to capture both crucial dimensions of water access. The results also reveal a strong negative correlation between the location of the water source *within* and *near* the premises. As such, the location of the water source *within* the premises is included separately, and the location of the water source *near* the premises is omitted.

Table A.1: Spearman and Pearson correlation coefficients between water dimensions, presented as Spearman, Pearson, for which a significant correlation is found between all dimensions. The values in bold show those dimensions which are strongly correlated.

Spearman, Pearson correlation	Treated tap water	Water located within the premises	Water location near the premises
Treated tap water	-	0.27, 0.26	-0.18, -0.15
Water located within the premises	0.27, 0.26	-	**-0.90, -0.87**
Water location near the premises	-0.18, -0.15	**-0.90, -0.87**	-

A.3 Inequality index

In this section, the results of the regression analysis undertaken to calculate the average inequality index in the main text are firstly presented. From here a sensitivity analysis of the average inequality index estimation to the definition of city selection, as well as the formulation of the SDI by the arithmetic mean, is presented.

A.3.1 Regression results

As discussed briefly in the main text, population weighted least squares (WLS) is adopted over ordinary least squares (OLS) regression to account for heteroscedasticity, see Figure A.1. Note that the same methodology is adopted to calculate the inequality index by dimension.

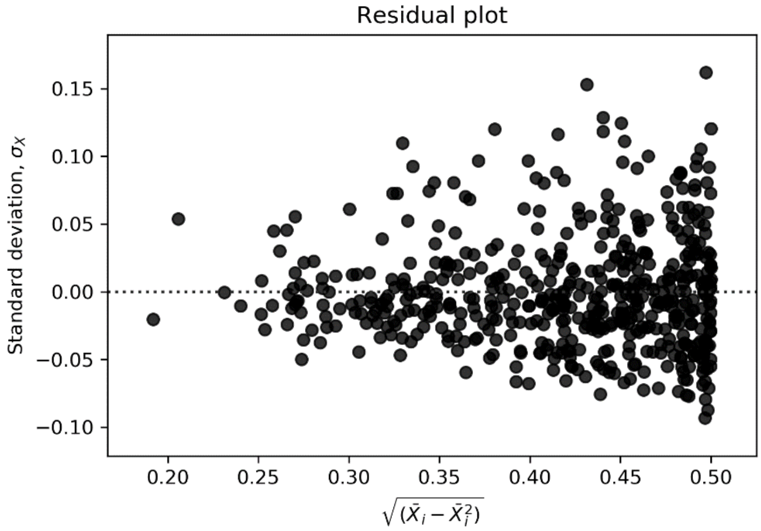


Figure A.1: Heteroscedasticity of residuals when regressing $\sqrt{\bar{X}(1-\ \bar{X})}$ on $(\bar{X})$ adopting ordinary least squares regression.

A.3.1.1 Towns and cities

Table A.2: Results for the regression of $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ at the town/city level.

Regression	Inequality index, b	r^2	95% CI
WLS	0.324	0.91	[0.304, 0.345]
OLS	0.350	0.93	[0.341, 0.359]

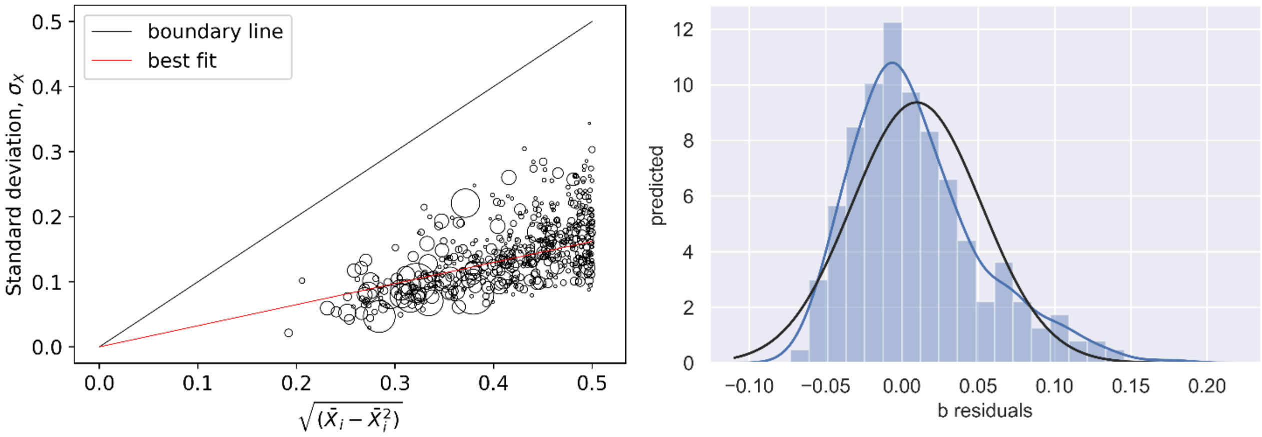


Figure A.2: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for towns/cities using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.

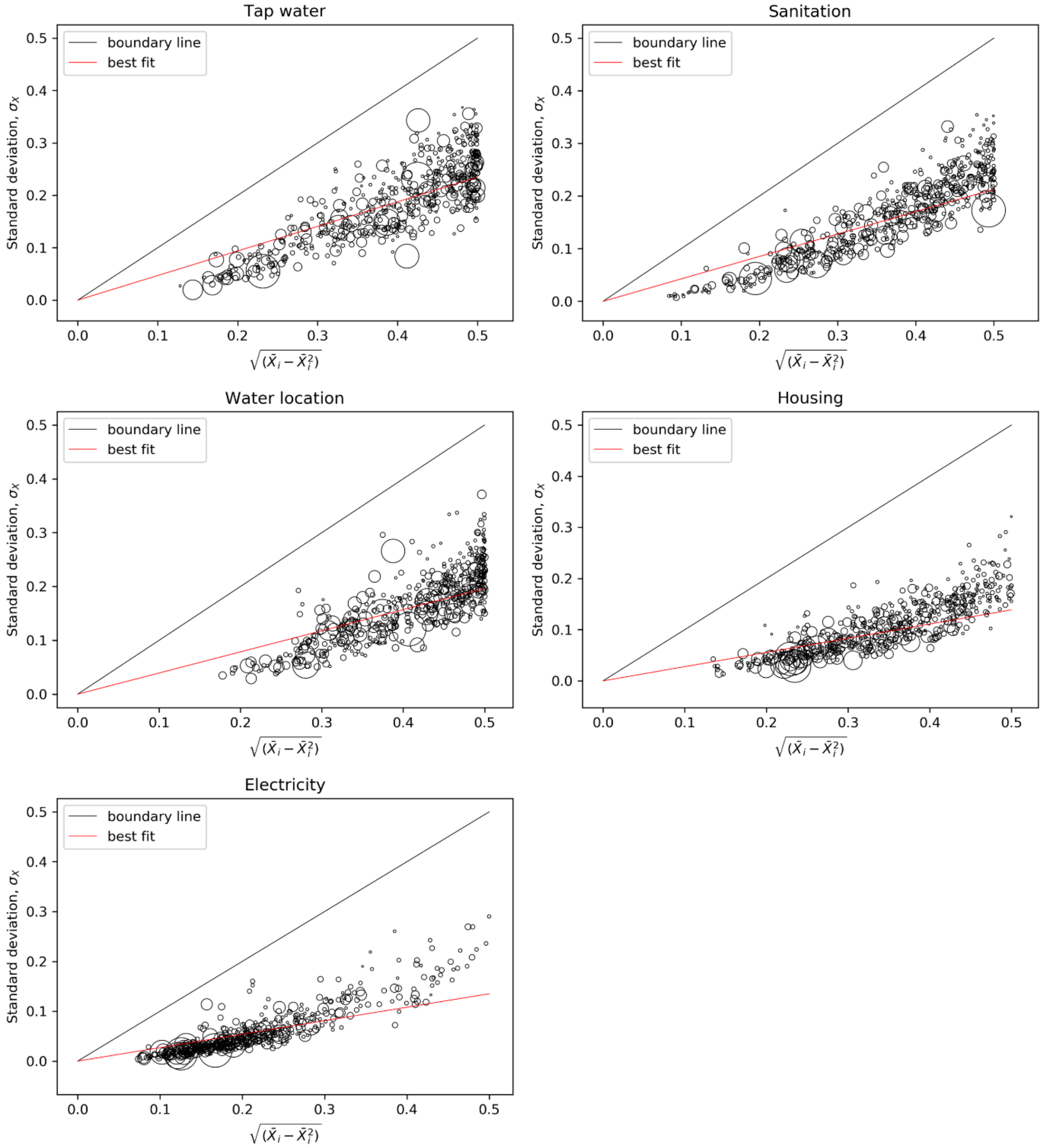


Figure A.3: Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of towns/cities using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

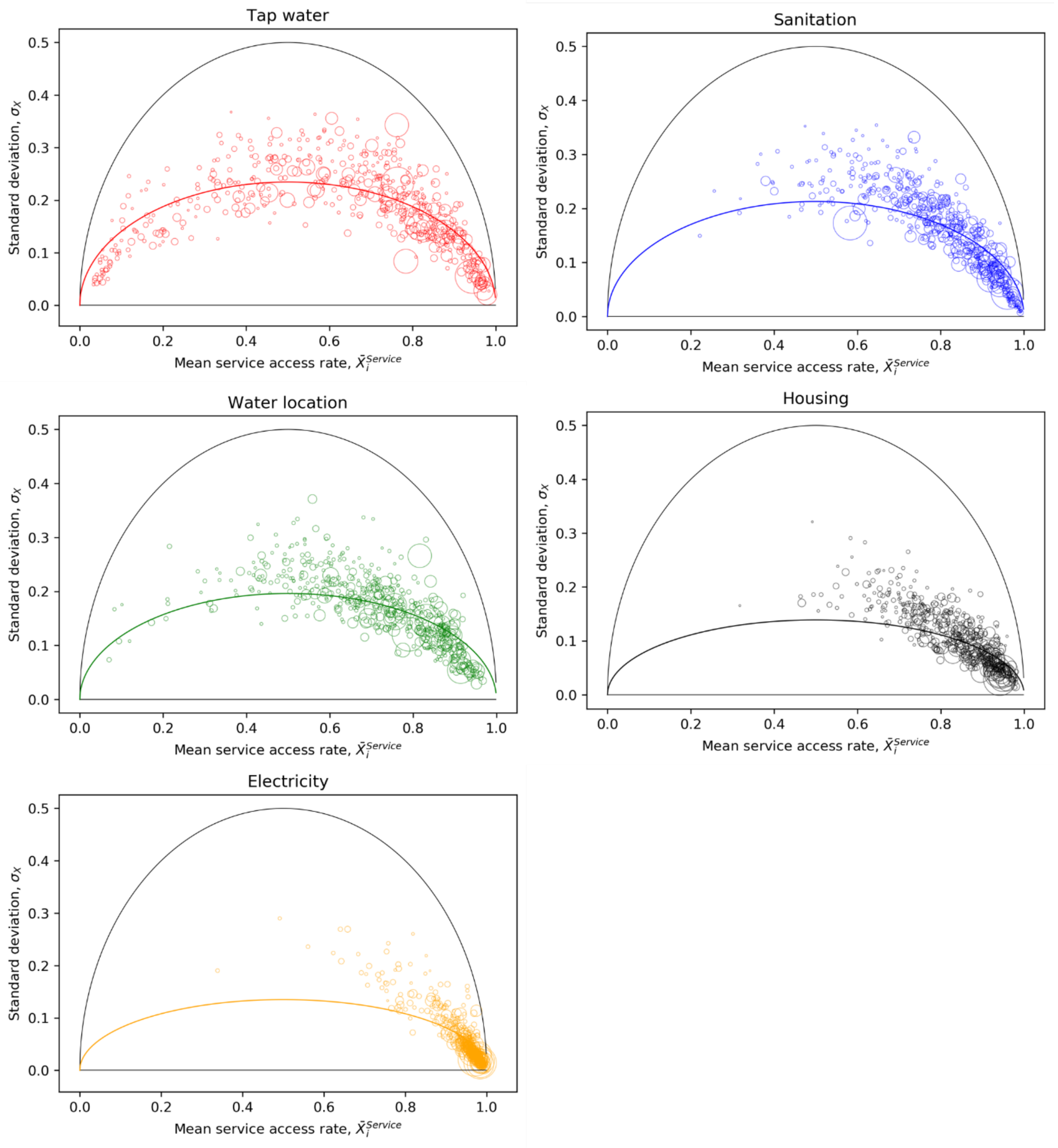


Figure A.4: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the level of towns and cities. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.2 Subdistricts

Table A.3: Results for the regression of $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ at the sub-district level.

Regression	**Inequality index, b**	**r²**	**95% CI**
WLS	0.335	0.91	[0.312, 0.357]
OLS	0.356	0.93	[0.347, 0.365]

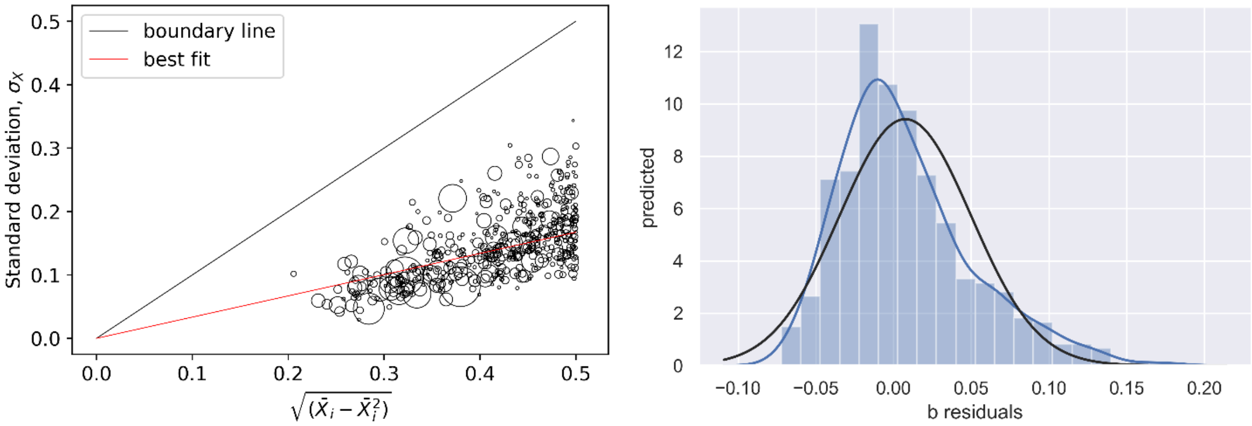


Figure A.5: (left) Relationship between $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ used to compute the average inequality index for sub-districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.

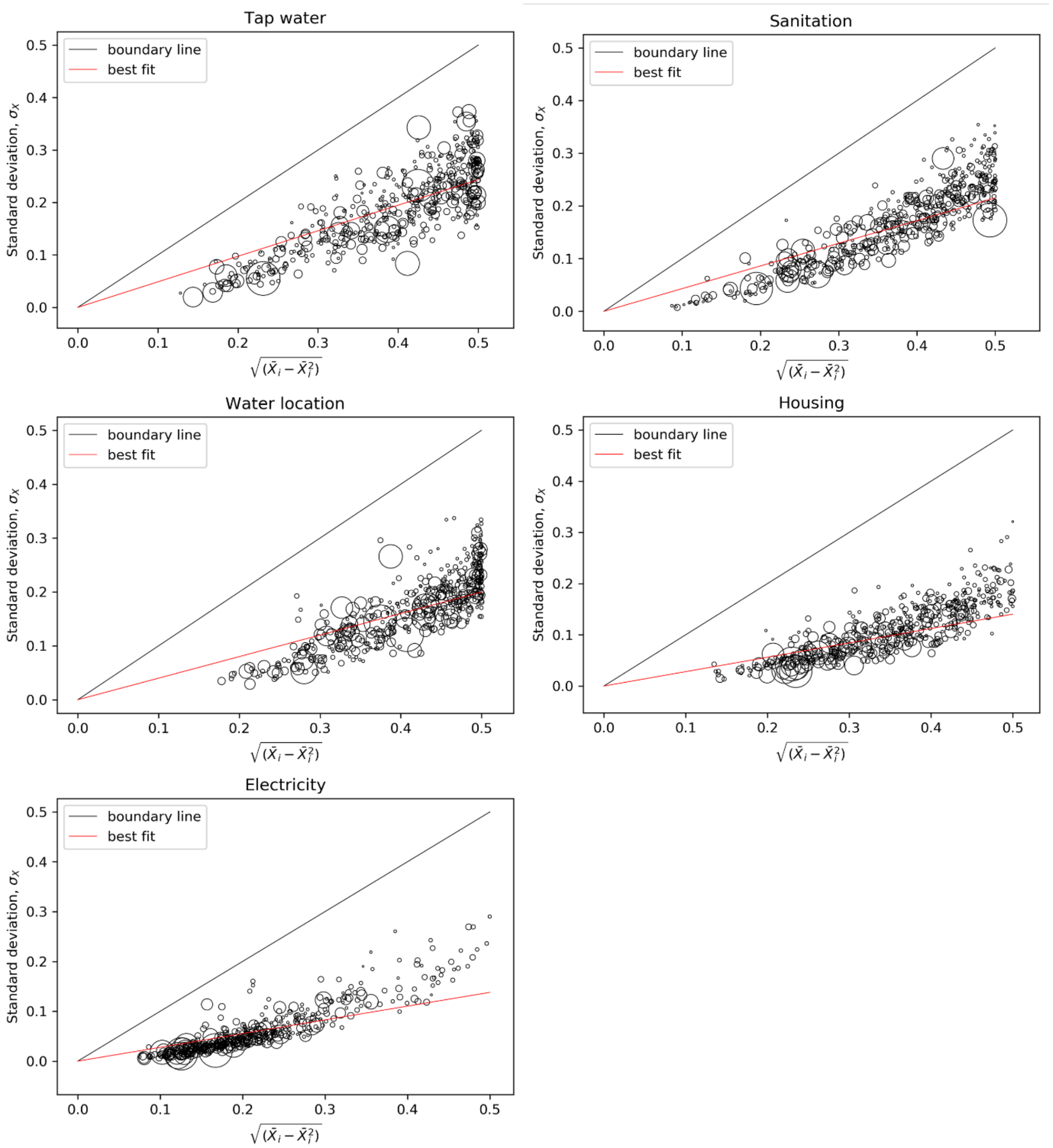


Figure A.6: Relationship between σ($\bar{X}$) vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of subdistricts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

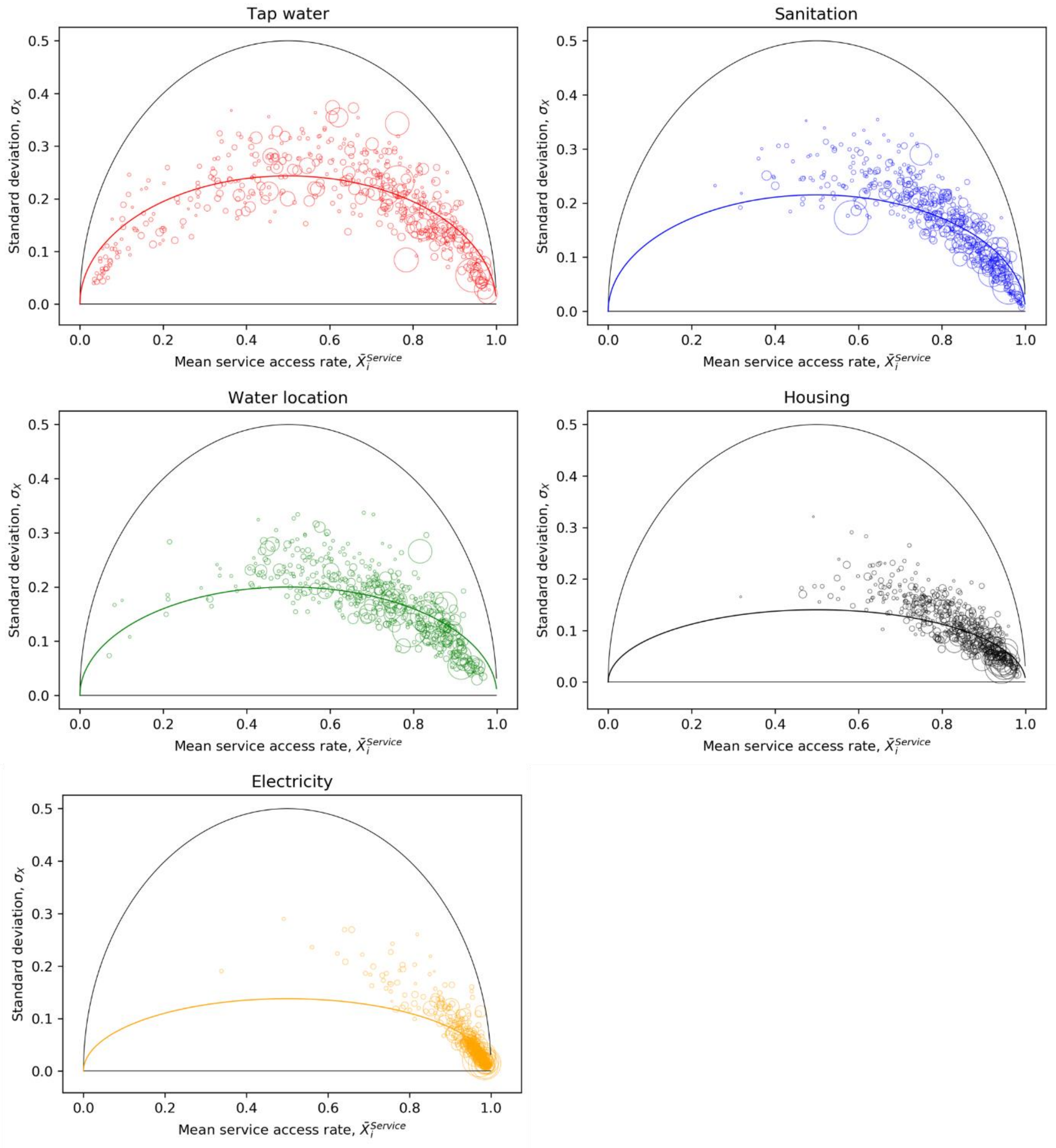


Figure A.7: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the subdistrict level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.3 Districts

Table A.4: Results for the regression of $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ at the district level.

Regression	**Inequality index, b**	**r^2**	**95% CI**
WLS	0.357	0.91	[0.333, 0.381]
OLS	0.372	0.93	[0.360, 0.384]

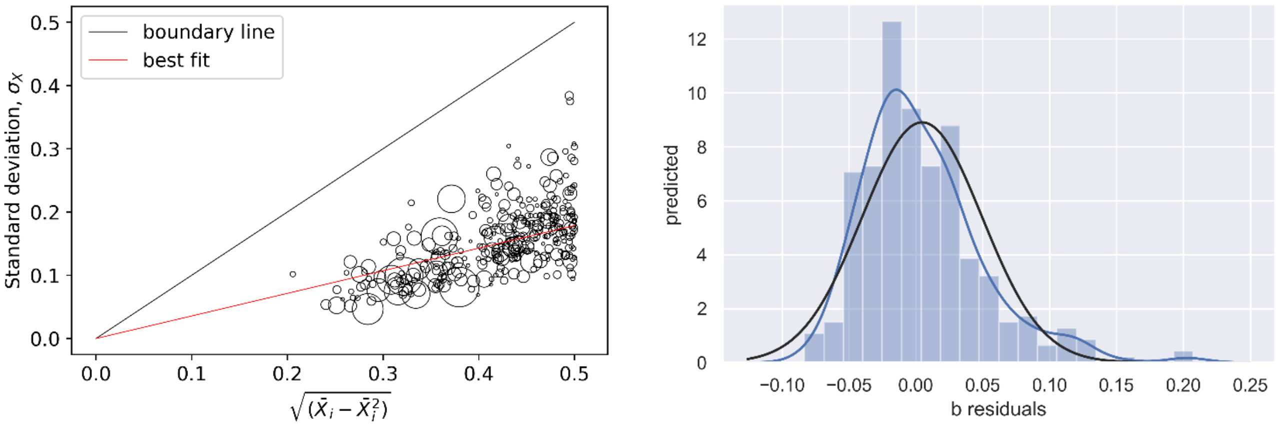
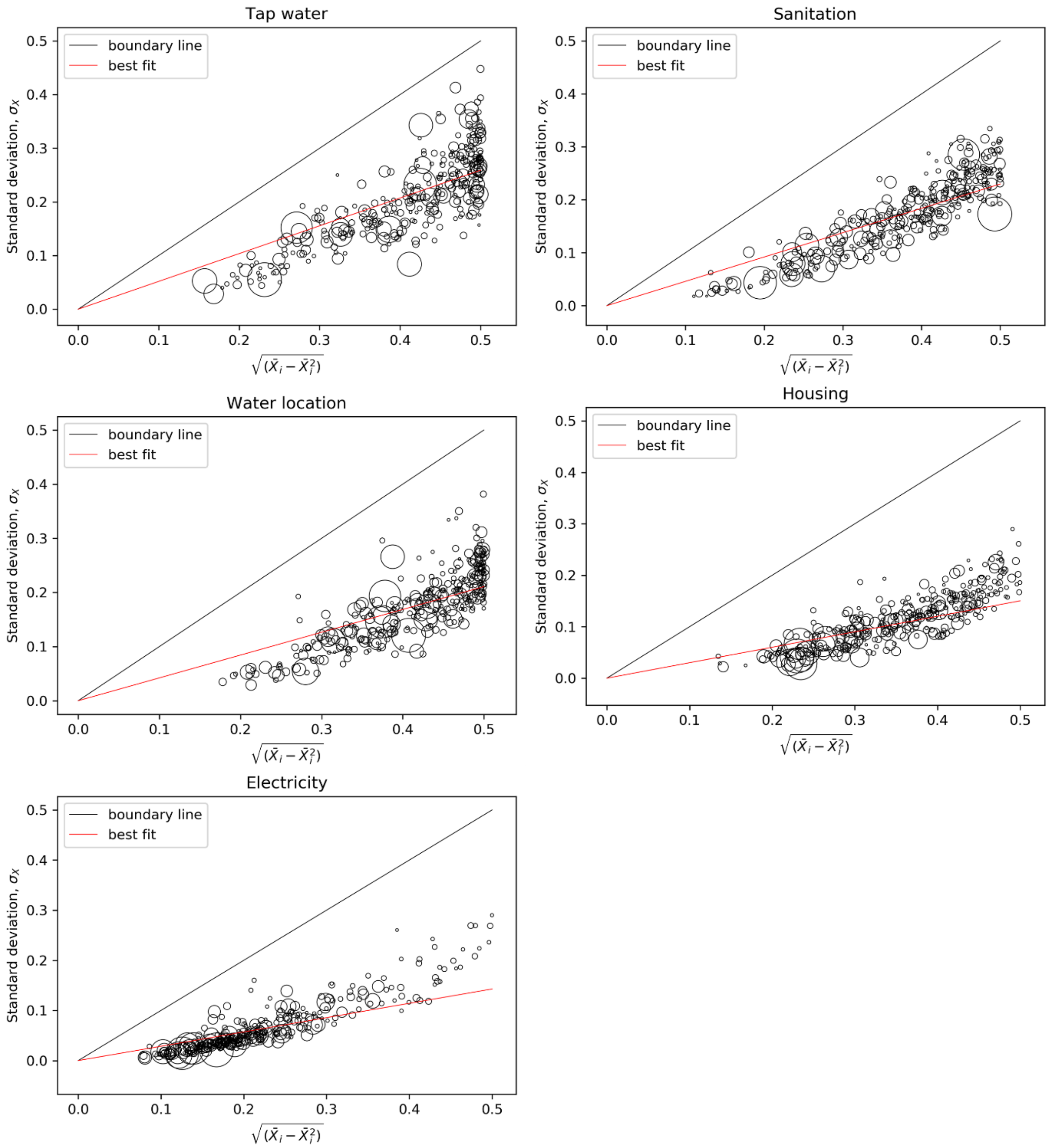


Figure A.8: (left) Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean and are right skewed indicating that basic needs profiles can be characterised by higher inequality than predicted on average.



Tap water

Sanitation

Water location

Housing

Electricity

Figure A.9: Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

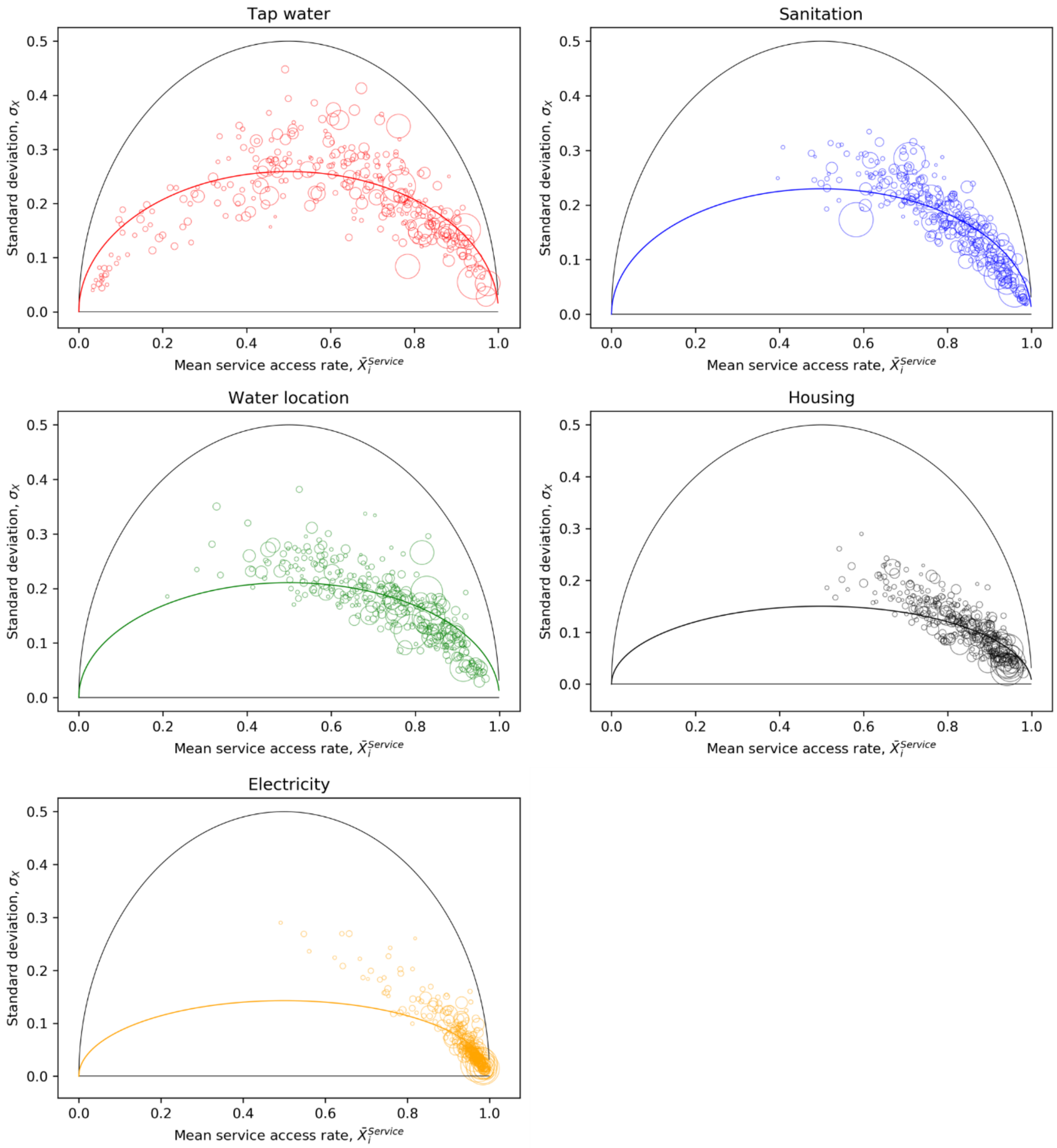


Figure A.10: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the subdistrict level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.1.4 States

Table A.5: Results for the regression of $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ at the state level.

Regression	**Inequality index, b**	**r^2**	**95% CI**
WLS	0.440	0.98	[0.414, 0.466]
OLS	0.451	0.96	[0.414, 0.488]

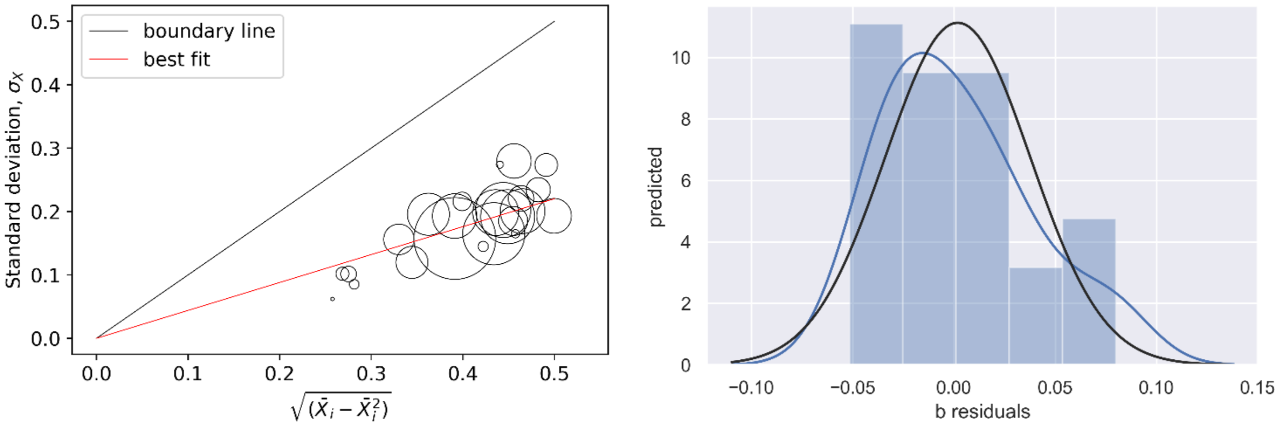


Figure A.11: (left) Relationship between $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ used to compute the average inequality index for districts using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity. (right) Residuals for the WLS showing the kernel density plot in blue and the best fit normal distribution in black. The residuals are generally clustered close the mean with minimal skew indicating that basic needs profiles are generally characterised by the inequality predicted on average.

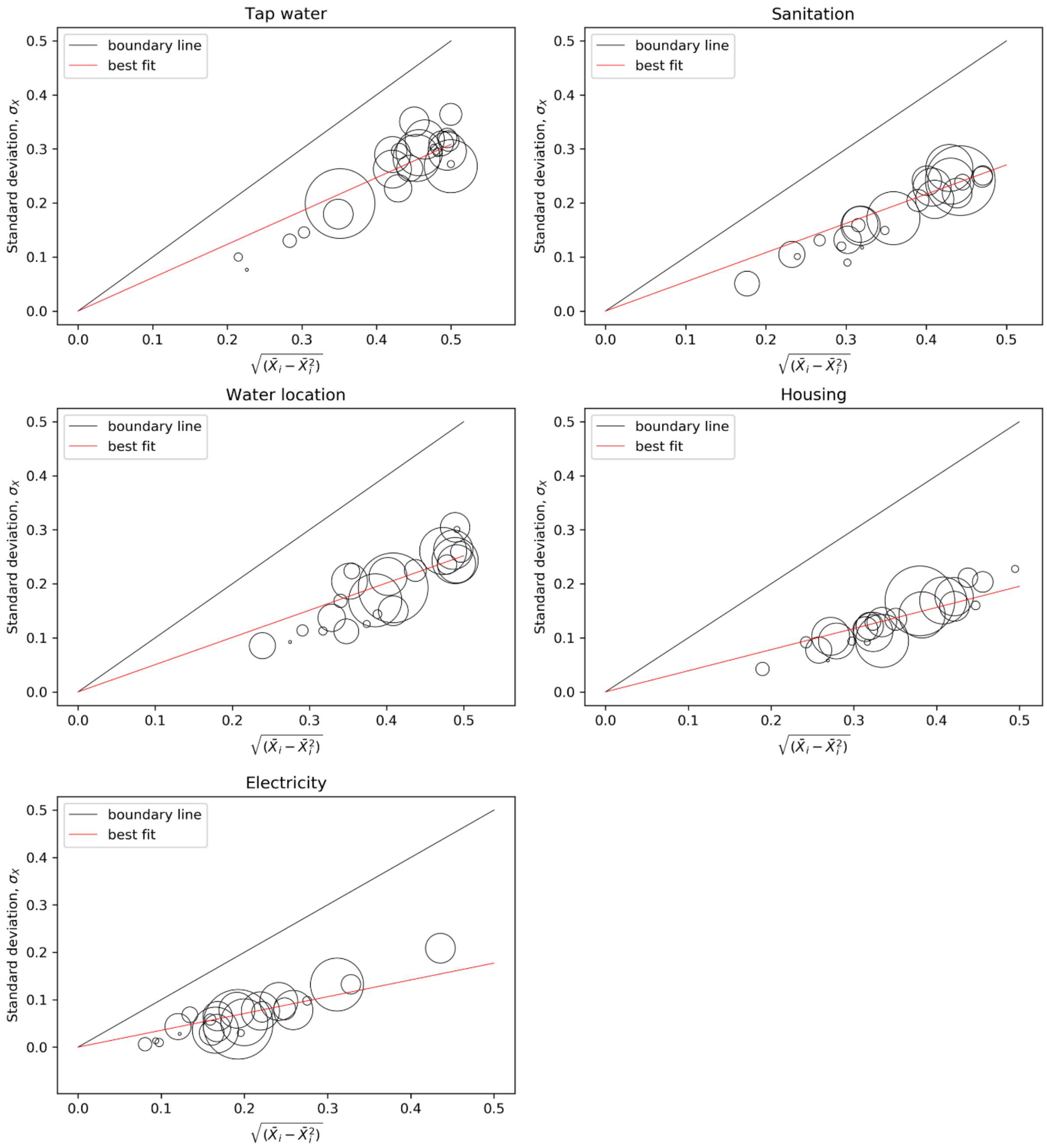


Figure A.12: Relationship between $\sigma(\bar{X})$ vs $\sqrt{\bar{X}(1-\bar{X})}$ used to compute the average inequality index for each dimension at the scale of states using population WLS and White-Huber-Eicker standard errors to account for heteroscedasticity.

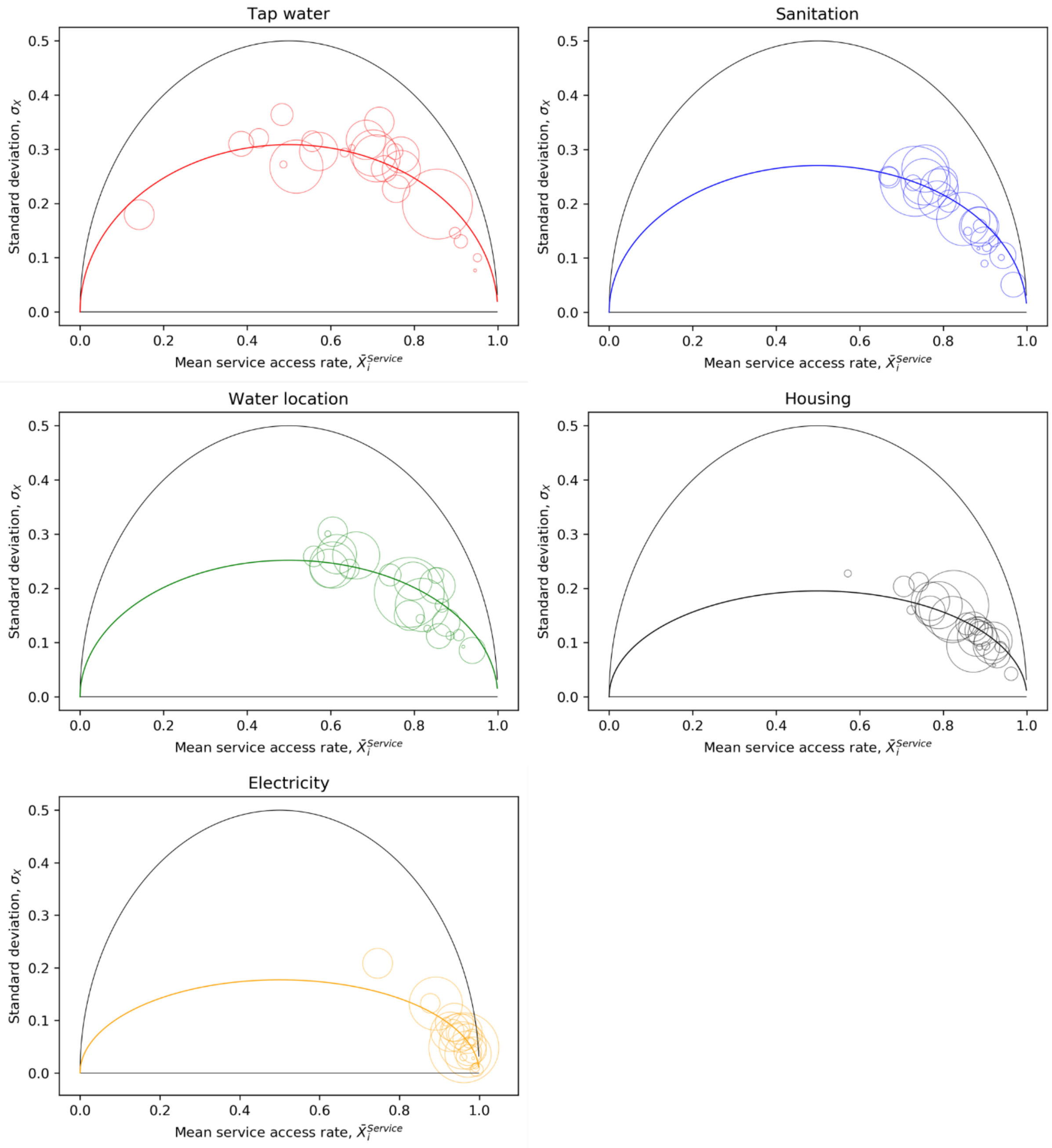


Figure A.13: The relationship between the standard deviation of the household access rate σ_i and the mean access rate, $\bar{X}_i$ for each dimension comprising the SDI at the state level. The size of the circle is proportional to the total urban population, with the upper and lower black line indicating maximum, b = 1, and minimum, b = 0, inequality respectively.

A.3.2 Sensitivity analysis

A.3.2.1 City definition

In Chapter 3, the selection of cities is defined as those containing at least 30 local administrative divisions, i.e., wards. This value is used as a rule of thumb to increase the confidence interval of the data when calculating the mean and standard deviation leading to the average inequality index. However, in doing so, the city sample size is reduced significantly, from 4027 towns and cities to 524. As a result, the number of states included is reduced from 33 to 24. As such, the following analysis estimates the sensitivity of the results to this rule of thumb, reducing the number of wards required to define a city from 30 to 15 in increments of 5.

The results are presented in Table A.6 and indicate that, as more cities are included due to the decreasing requirement for the number of wards, the scale dependence of the inequality measure tends to increase slightly as well as the estimated magnitude of inequality, i.e., the b value increases marginally but with overlapping confidence intervals compared to other definitions in some cases such that there is no statistically observable change. The most significant observable changes in the average inequality are found for sub-districts and districts, however these changes remain marginal. The same results are observed for including cities which contain 25 wards as with including those with 30 wards. For the 20 ward definition, the results reveal that states are statistically distinguishable as with previous results, but that districts exhibit a scale dependence compared to sub-districts and districts, unlike with the 30 and 25 ward definition. Towns and cities remain statistically indistinguishable from sub-districts by this definition. These findings are coherent with the 20 ward definition. However, all scales are found to be statistically indistinguishable from each other when defining cities by those with 15 or more wards. This significantly increases the sample size such that all states within India are included. The scale dependence observed by this definition is likely a result of the administrative definitions of larger urban areas, as we have seen in Chapter 3. Larger cities tend to have significantly more local urban administrative areas than smaller cities, and these cities tend to be simultaneously under the administrative control of city, sub-district and district levels as defined by the census (3). As such, the overlapping definition generally results in the average inequality being statistically indistinguishable from each other across these scales, as seen in Chapter 3. However, including a significantly greater number of smaller towns and cities, which are generally only under town/city administration and therefore themselves belong to the broader administrative divisions of sub-districts and districts, results in the increased scale-dependent average inequality.

The sensitivity analysis therefore reveals that increasing the number of smaller towns and cities within the assessment tends to increase the observed scale dependence of national inequality characterized by the national basic needs profile. However, the average inequality predicted at this scale is statistically indistinguishable across each definition given the overlapping confidence interval, which is also the case for multiple definitions at other scales. Further, the results agree with findings in Chapter 3 that inequality between states is observed to a greater extent than towns and cities and that deficits in access to services are more widespread than concentrated within a selection of particularly deprived areas, i.e., the inequality in service access, estimated by the b-value, remains below 0.5 for all scales.

Table A.6: Sensitivity of the average inequality index estimation, *b*, to the city selection defined by the number of wards, or local urban administrative areas, within each city, i.e., cities are included within the study if the number of wards is equal to or exceeds those stated in the table. Note that no. of wards = 30 is used to define city selection in the analysis within Chapter 3.

Scale	No. of wards	Sample size	Inequality index, b	95% CI	Fit, r^2
Towns/cities	30	524	0.324	[0.303, 0.344]	0.91
	25	895	0.330	[0.312, 0.348]	0.91
	20	1319	0.333	[0.317, 0.349]	0.91
	15	2762	0.340	[0.326, 0.354]	0.91
Sub-districts	30	486	0.3345	[0.312, 0.357]	0.908
	25	806	0.342	[0.322, 0.361]	0.91
	20	1126	0.352	[0.333, 0.370]	0.931
	15	1846	0.379	[0.363, 0.396]	0.913
Districts	30	321	0.357	[0.333, 0.381]	0.911
	25	405	0.382	[0.361, 0.403]	0.928
	20	462	0.411	[0.391, 0.430]	0.94
	15	526	0.443	[0.426, 0.461]	0.946
States	30	24	0.440	[0.407, 0.473]	0.982
	25	27	0.451	[0.424, 0.477]	0.989
	20	29	0.462	[0.434, 0.489]	0.989
	15	33	0.491	[0.462, 0.520]	0.988

A.3.2.2 Arithmetic versus geometric mean

The following illustrates the sensitivity of the results to the metric formation, specifically noting the progression of composite index formulations from the aggregation of dimensions via an arithmetic to a geometric mean, as with the HDI (7). The HDI evolved from the additive to multiplicative formulation of the composite index to better capture extremes within the population, emphasizing that the achievement of all dimensions is essential to achieve a minimum level of development and that these dimensions are not substitutional (1). The formula to calculate the geometric and arithmetic means are shown in equations 1 and 2 respectively.

$$X_i = \sqrt[n]{\prod_{j=1}^{n} X_i^j} \qquad [1]$$

$$X_i = \sum_{j=1}^{n} \frac{X_i^j}{n} \qquad [2]$$

The results show that the arithmetic mean overlooks significant deficits in standards of living at each scale. This formulation of the average index generally estimates a higher mean achievement of dimensions and lower dispersion, i.e., the arithmetic mean moves data points towards the bottom right of Figure A.14. This means that the line of best fit and thus the observed average inequality is significantly reduced, indicated by a flatter line of best fit and a significantly lower inequality index estimated in Table A.7.

Table A.7: Inequality index results for the geometric mean (main text) compared to the arithmetic mean formulation of the SDI.

Level	Mean	Inequality index, b	r^2	95% CI
Town/city	Geometric	0.324	0.91	[0.304, 0.345]
	Arithmetic	0.255	0.92	[0.250, 0.262]
Sub-district	Geometric	0.335	0.91	[0.312, 0.357]
	Arithmetic	0.261	0.93	[0.255, 0.268]
District	Geometric	0.357	0.91	[0.333, 0.381]
	Arithmetic	0.276	0.94	[0.268, 0.284]
State	Geometric	0.440	0.98	[0.414, 0.466]
	Arithmetic	0.338	0.99	[0.322, 0.355]

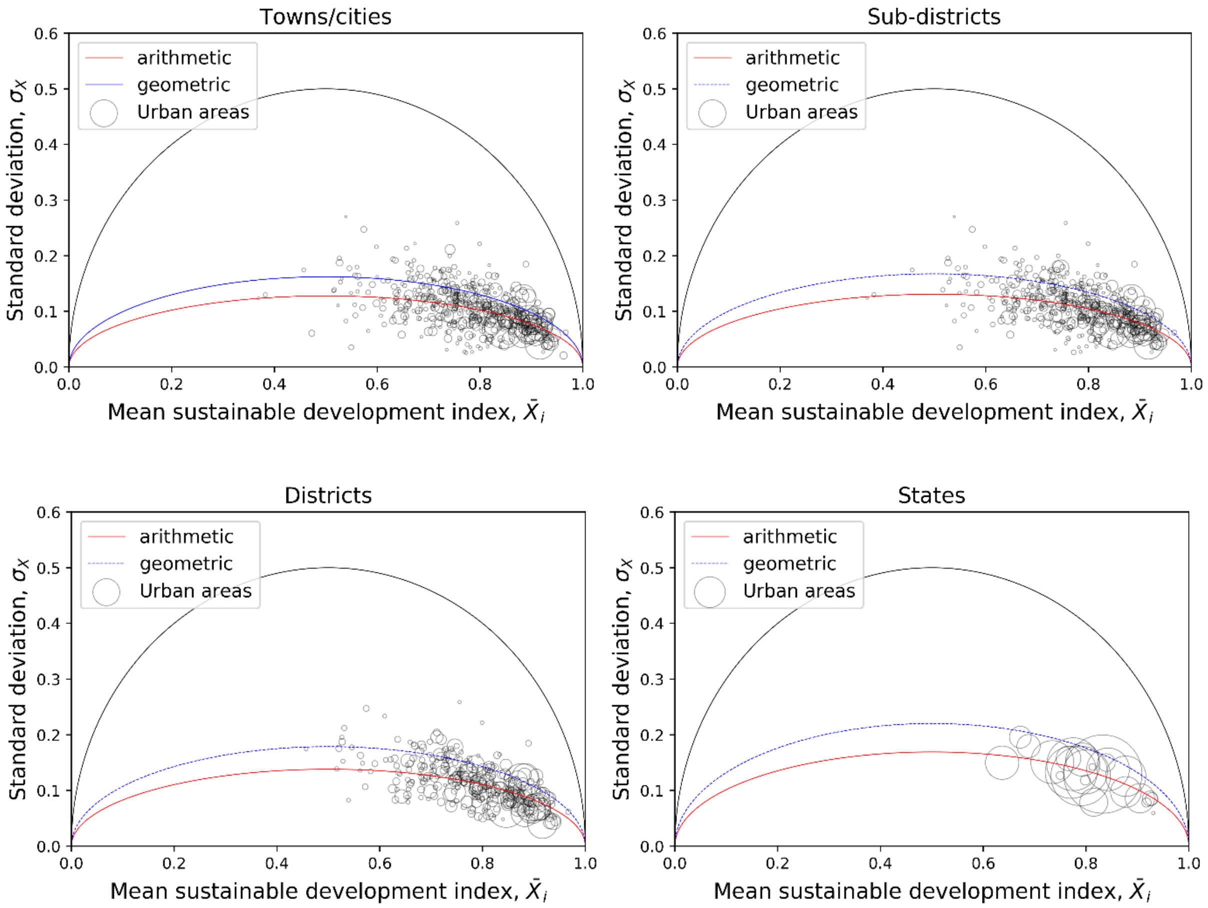


Figure A.14: The relationship between the standard deviation of the SDI, σ_i, and the mean SDI, $\bar{X}_i$, for different administrative scales using the arithmetic mean method of aggregation. The profiles are calculated using SDI values for wards contained within each city as in the main text. The size of the circle is proportional to the total urban population. The upper black line is the boundary of maximum inequality, b = 1, and the lower black line, the x-axis, is the boundary of minimum inequality, b = 0.

The red line represents the line of best fit calculated by regressing σ_i on $\sqrt{\bar{X}_i - \bar{X}_i^2}$ using population WLS regression and adopting the arithmetic mean formulation of the SDI. The blue line indicates the line of best fit as calculated by the geometric mean in the main text for reference.

A.3.2.3 Overlapping administrative divisions

Table 8: Results for the regression of $\sigma(\overline{X})$ vs $\sqrt{\overline{X}(1-\overline{X})}$ at the town/city level for those towns/cities which are simultaneously towns/cities, subdistricts, and districts, i.e., overlapping administrative divisions, in comparison to the original values.

Towns/cities	No. of data points	Inequality index, b	r^2	95% CI
Overlapping	204	0.318	0.89	[0.284, 0.352]
Non-overlapping	319	0.333	0.93	[0.318, 0.350]
Original	524	0.324	0.91	[0.304, 0.345]

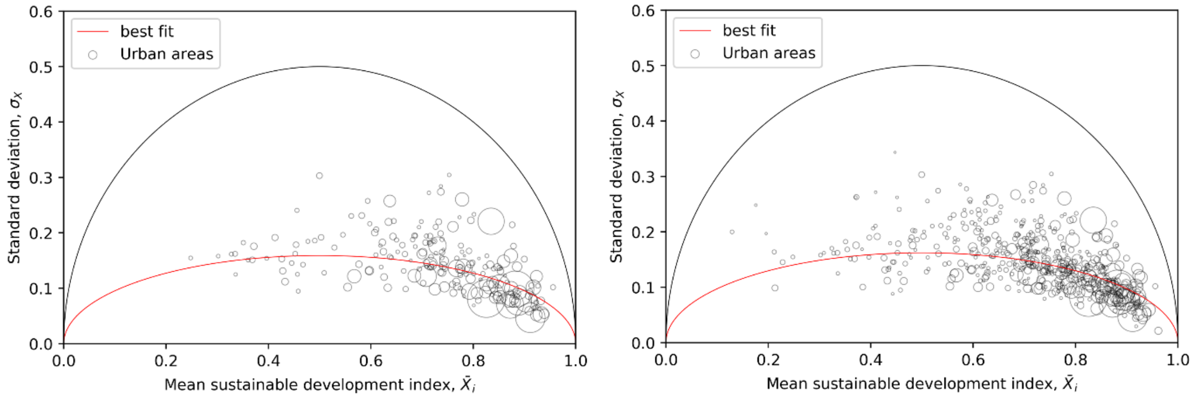


Figure A.15: The relationship between the standard deviation of the SDI, σ_i, and the mean SDI, $\overline{X}_i$, at the town/city scale. (left) The relationship for those towns/cities which are simultaneously towns/cities, subdistricts, and districts, i.e., overlapping administrative divisions, in comparison to (right) the relationship for those towns/cities which are non-overlapping. The profiles are calculated using SDI values for wards contained within each city. The size of the circle is proportional to the total urban population. The upper black line is the boundary of maximum inequality, b = 1, and the lower black line, the x-axis, is the boundary of minimum inequality, b = 0. The red line represents the line of best fit calculated by regressing σ_i on $\sqrt{\overline{X}_i - \overline{X}_i^{\,2}}$ using population WLS regression.

The results reveal minor changes to the average inequality index at the scale of towns/cities when redefining towns/cities as those which are simultaneously towns/cities, subdistricts, and districts. In total, 320 towns/cities are omitted from the analysis and the average inequality index changes from $b = 0.324$ to $b = 0.318$, values which are statistically indistinguishable from each other. Similarly, when assessing the average inequality index for those towns/cities which are non-overlapping the average inequality index changes from $b = 0.324$ to $b = 0.333$. Thus, while the overlapping administrative divisions are a driving factor for the scale independence at town/city, subdistrict, and district level, redefining towns/cities by their overlapping administrative divisions yields the same scale dependence between towns/cities and states, and only reduces the overall inter-urban inequality marginally. This, in combination with the sensitivity analysis on city definitions presented in section A.3.2.1, suggests that the definition of town/city by the number of wards has a greater impact on the observed average inequality than the overlapping definition of administrative divisions. However, the results of the alternative aggregation approach shown in Table A.7 highlight that the choice of metric has a greater impact on the perceived outcomes than the definition of city. This points to the policy lens towards the careful consideration of metrics and also the use of alternative and complementary metrics to capture uncertainty and validate findings between metrics – as we have demonstrated in Chapter 3.

B - Chapter 4 Supporting Information

B.1 Regression model selection

B.1.1 Household composition variables

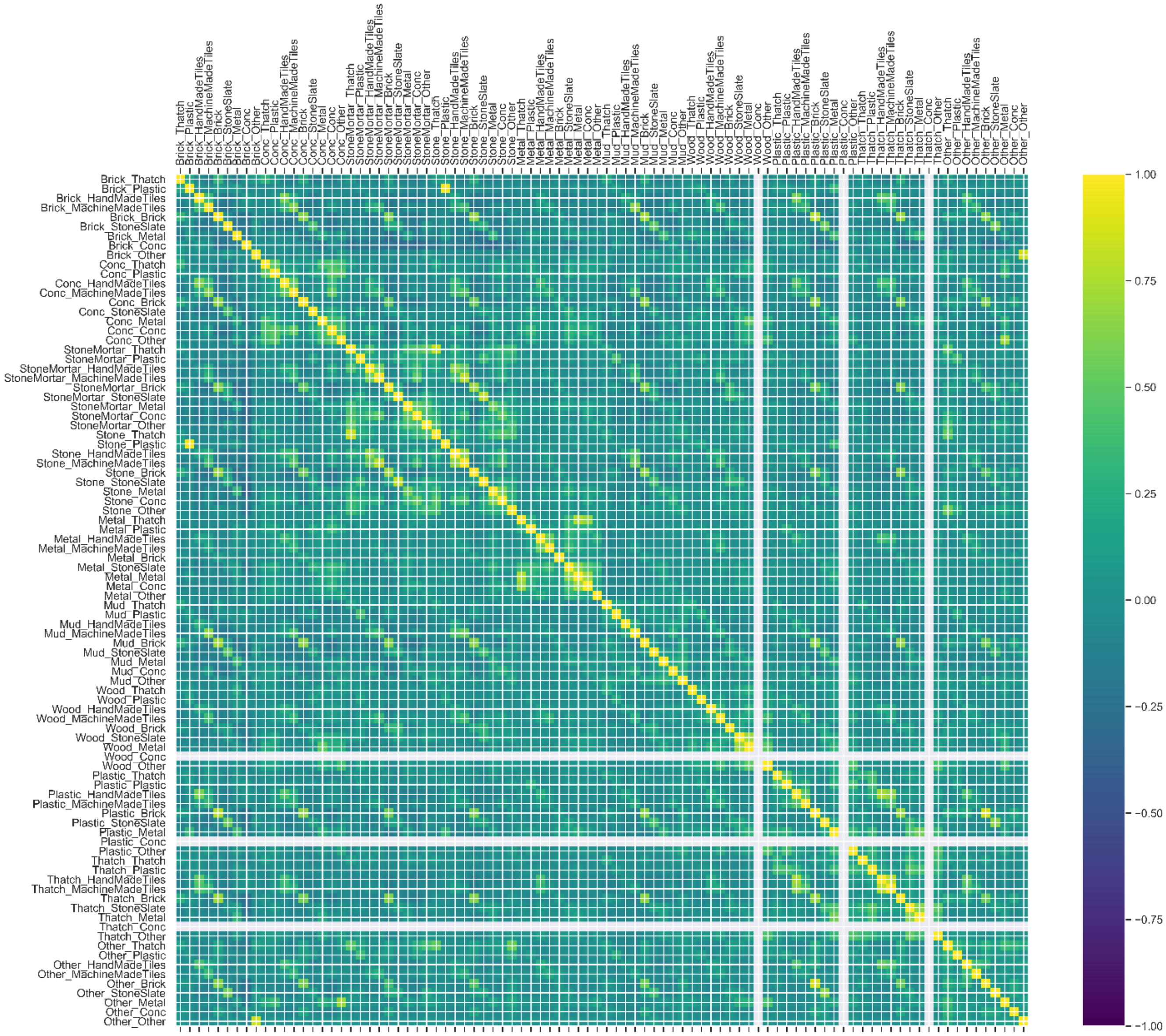


Figure B.1: Co-linearity of variables relating to the composition of households by material used for walls and roofs, displayed as material of *Wall_Roof*. The white vertical and horizontal lines indicate variables which correspond to 0% of household compositions.

B.2 Univariate analysis

Table B.1: Results of the univariate beta regression from regressing the listed variable, noted as material of *Wall_Roof* as in Figure B.1, on the SDI. The mean composition refers to the average prevalence of households comprised of a unique combination of wall and roof materials among towns and cities, as shown in Chapter 4 Figure 4.1. Note that stone for wall materials refers to stone packed with mortar. Bold variables indicate those with a statistically significant relationship with basic needs outcomes, using a $pvalue < 0.05$.

Variable	Mean composition (%)	P-value
Brick_Conc	**41**	**0.00**
Brick_Metal	8	0.34
Brick_Stone/Slate	7	0.36
Brick_Brick	5.7	0.31
Stone_Conc	5.7	0.09
Conc_Conc	**4.4**	**0.00**
Brick_HandMadeTiles	**2.8**	**0.00***
Brick_MachineMadeTiles	2.4	0.64
Mud_HandMadeTiles	2.3	0.22
Stone_Stone/Slate	**2.2**	**0.00***
Mud_metal	**2.0**	**0.00***
Mud_Thatch	**1.5**	**0.00***
Stone_Metal	1.3	0.57
Total	**86.3%**	-

*refers to variables which are found to have a significant but negative relationship with basic needs outcomes.

The results of **Table B.1** indicate that Brick_Conc and Conc_Conc variables have a statistically significant and positive relationship with basic needs outcomes for variables which account for more than 1% of the total household composition of towns and cities on average.

B.3 Link function

Table B.2: Link function selection for multi-variable beta regression at the town and city level, adopting Brick_Conc and Conc_Conc as covariates based on the results of **Error! Reference source not found.**. The results indicate that the complementary log-log link function is most suitable for the final beta regression, with the lowest Bayesian Information Criteria (BIC) and log likelihood.

Link function	AIC	BIC	Log likelihood
Complementary log-log	-814	-797	411
Log-log	-810	-792	409
Logit	-811	-793	410
Probit	-812	-795	410

The application of logit or probit in this case is not appropriate given that they measure only binary outcomes, with the SDI found within a continuous range from 0 to 1. However, the absence of knowledge of the dynamics governing the process that are modelled means that it is appropriate to calculate regression coefficients based on statistical regression measures, i.e., the Bayesian information criteria and log-likelihood, to reason between adopting the complementary log-log or the log-log link function.

B.4 Material composition of areas achieving high basic needs outcomes

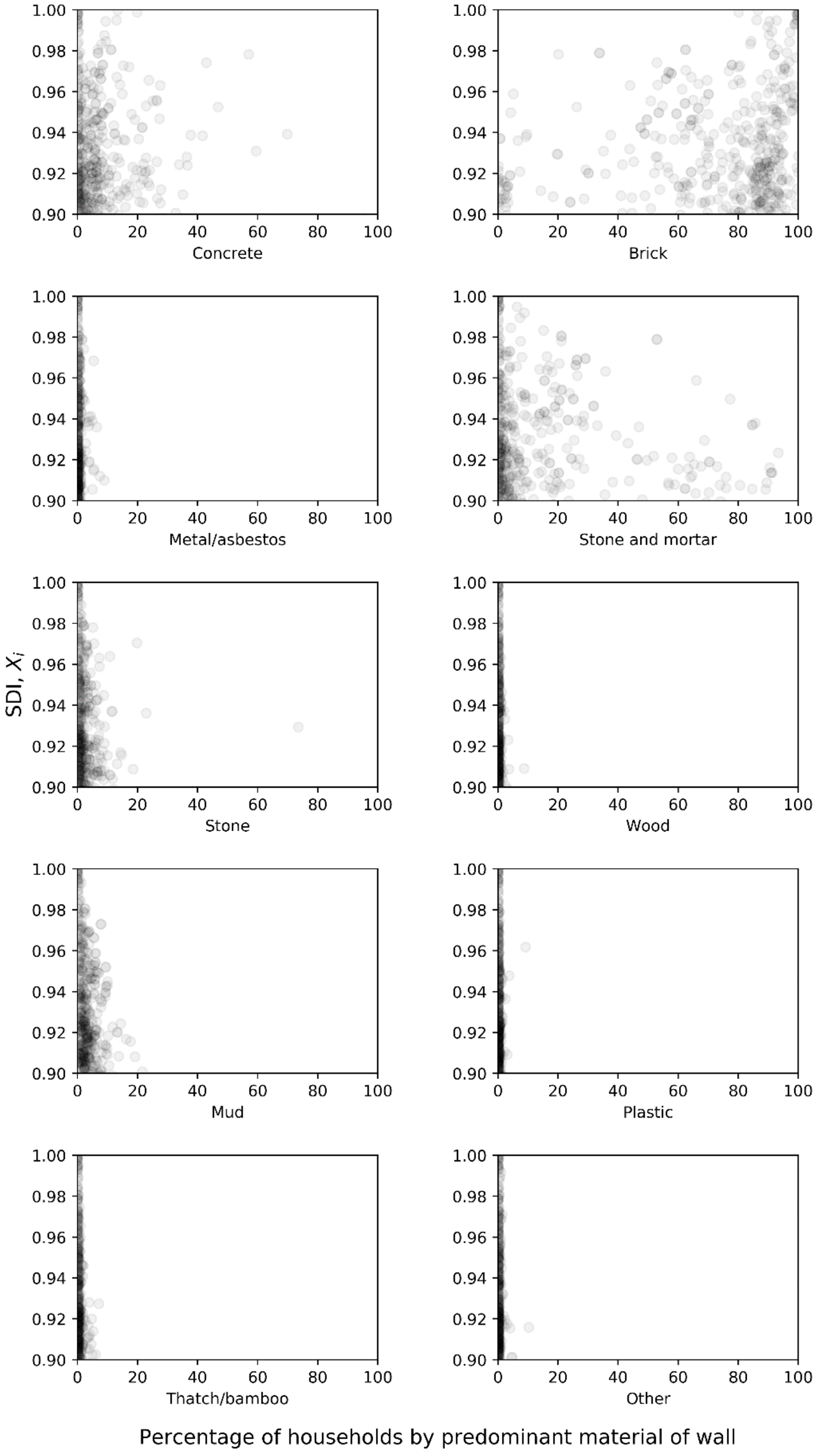


Figure B.2: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of walls, for areas achieving an SDI > 0.9.

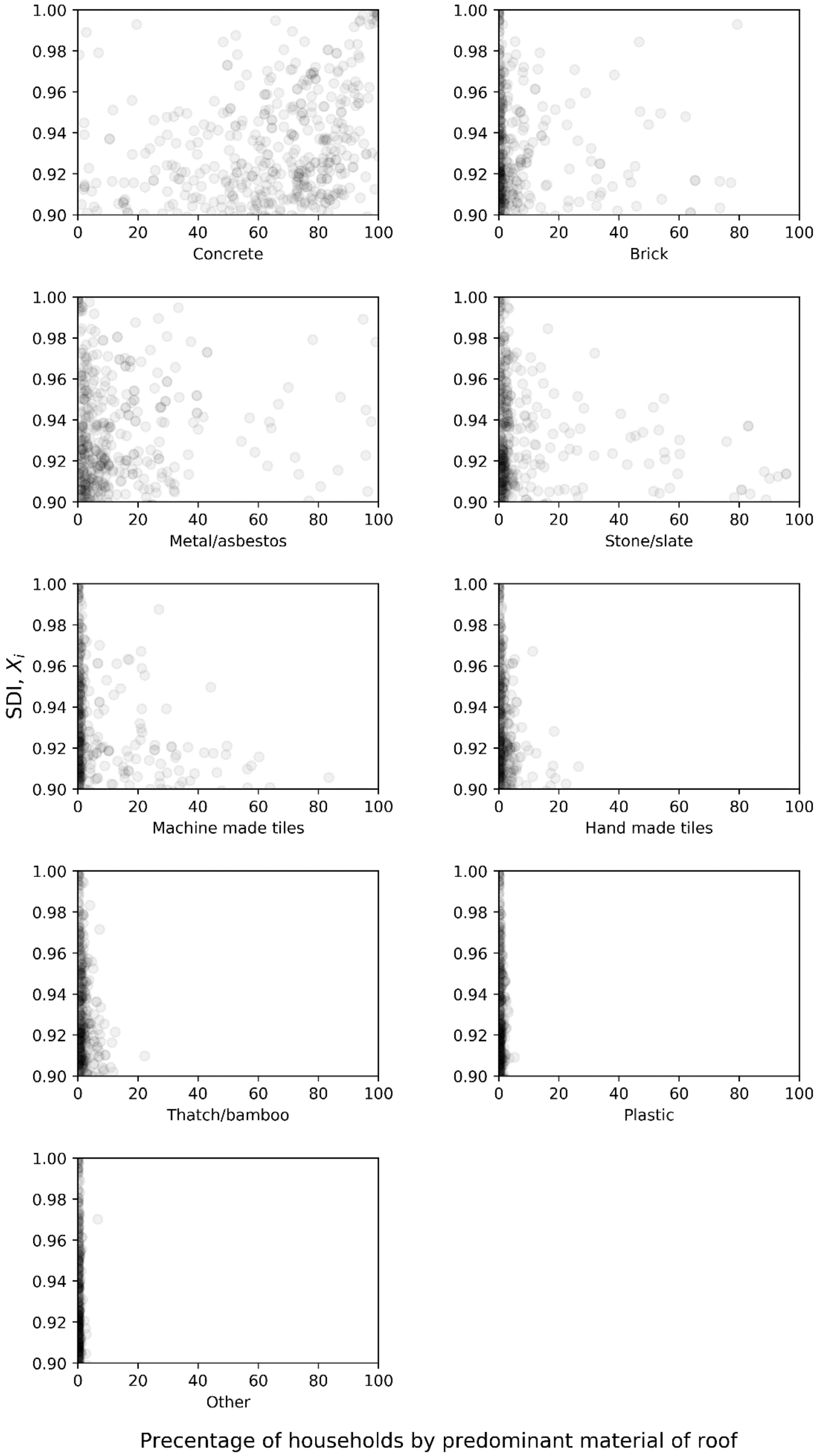


Figure B.3: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of roofs, for areas achieving an SDI > 0.9.

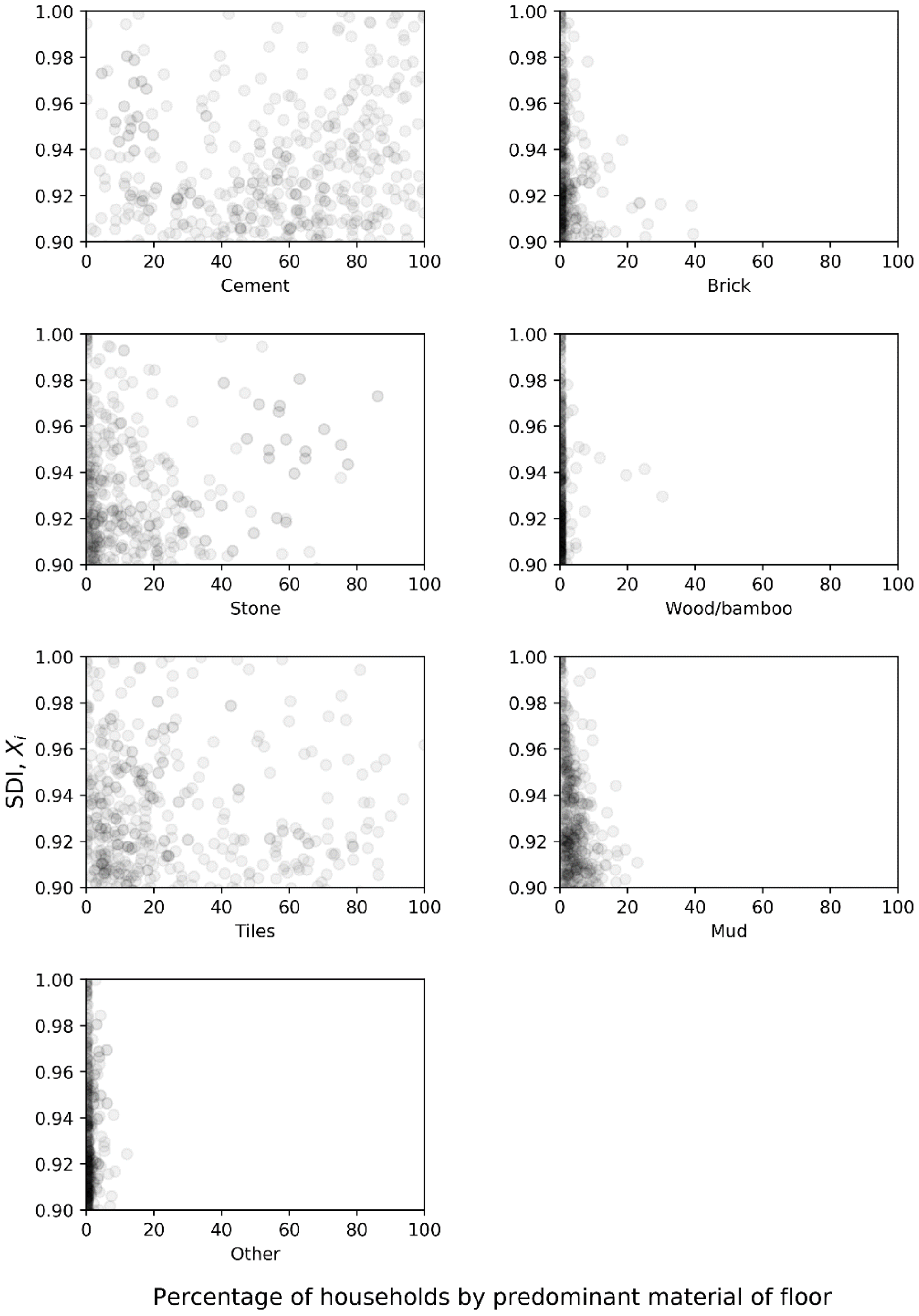


Figure B.4: Average basic needs outcomes measured by the SDI versus the percentage of households present within the wards of India by predominant material of floors, for areas achieving an SDI > 0.9.

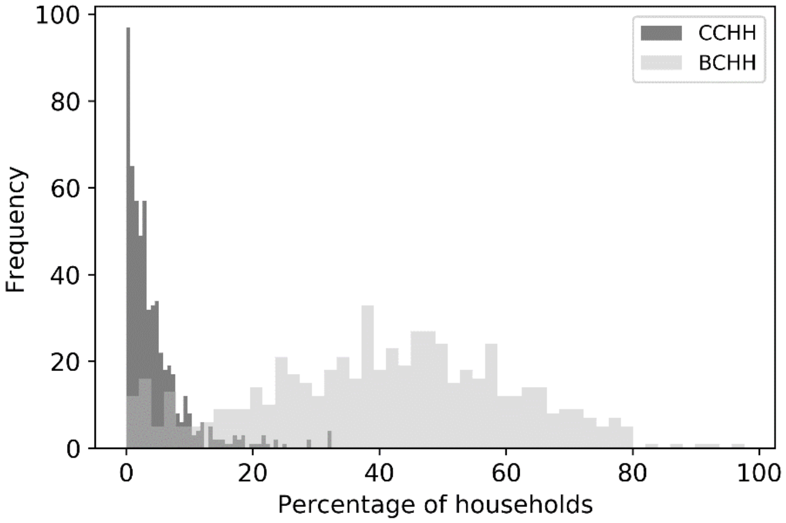


Figure B.5: The frequency distribution of BCHH and CCHH across the towns and cities of urban India. The figure shows that BCHH is widely adopted and at a variety of rates, while CCHH is largely present in a small percentage of towns and cities and is mainly only responsible for a small percentage of the built environment in many areas.

C - Chapter 5 Supporting Information

C.1 Residential buildings

The uniform composition of housing is evident through the available architectural control building drawings and associated documentation provided by the Chandigarh Administration and the Directorate of Census Operation in Chandigarh (1–3). The uniform typology of buildings of Chandigarh is dictated by the architectural control due to the master planning of the city and means that a single city-level archetype is appropriate for comparison to other studies of building archetypes. However, due to data provided by the Chandigarh Administration (1) it is possible to further the archetype classification to create Chandigarh-specific archetypes. As a result, it is possible to map the material intensity coefficient (MIC) data more accurately to the inventory of items within each sector. Building sample drawings can be found following the link to the architectural control drawing repository on the Chandigarh Administration website within the citizen facilitation section (4).

C.1.1 Inventory of items

The process and data used to create the inventory of items for Chandigarh-specific archetype classifications, i.e., where we further homogenize building samples by plot type and government housing scheme is provided within the main text. The inventory of items, i.e., the number of different plot types or government housing schemes within a sector, are collected from layout plans. Figure C.1 shows an example layout plan for sector 35. The inventory of items at the sector level are then aggregated to their respective wards as per the Census ward map (5), see Figure C.1 of the main text, and combined with the MIC values shown in Figure 5.3 of main text. Inventory data pertaining to plot types and numbers within sectors can be found on the Chandigarh Administration website within the citizen facilitation section (6) or alternatively on the website for the Department of Urban Planning Chandigarh (7).

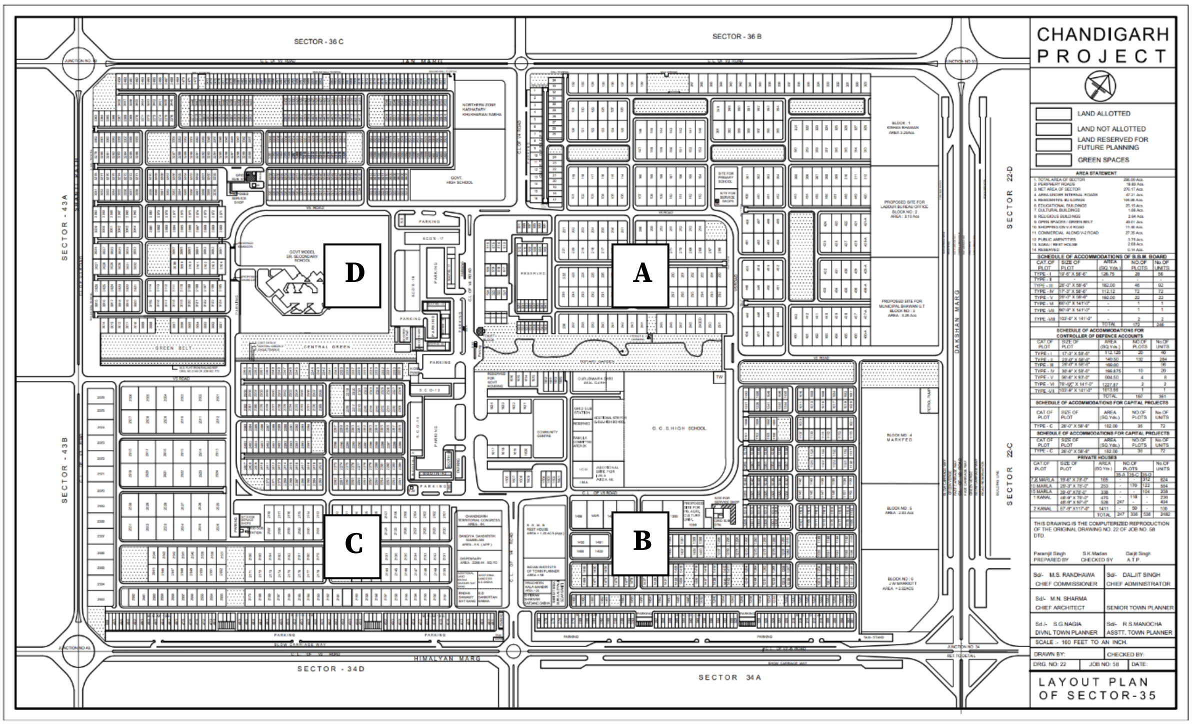


Figure C.1: Example layout plan used to calculate the inventory of items at the sector-level. Each grid, e.g., a, b, c, and d, within sectors corresponds to a sub-sector, summing to 4 in total for each sector. The number of each plot type is summarized within the schedule of accommodation for different project types within the drawing notes. Where the schedule is not provided, and the plot types are labelled within each sub-sector, the plot types are counted manually and related to the construction phase of the sector.

C.1.2 Material and embodied energy intensity coefficients

Building samples are collected through the Chandigarh Administration Citizens Facilitation which stores architectural control drawings for various plot types and government housing schemes. The maximum available number of building drawings relating to the inventory of items are used to calculate MIC values per archetype. In total, 12 building samples are collected for superstructure MIC calculation and 2 building samples collected from the Chandigarh Housing Board (8) to calculate substructure MICs due to the greater detail of foundations provided in comparison with architectural control drawings. An example architectural control drawing is shown in **Figure C.2. Table C.1** contains the material property data used to calculate the total mass and embodied energy of materials and components for all building samples. **Figure C.4:** Total material stock by component across the wards of the Municipal Corporation of Chandigarh.**Figure C.4** shows the MIC for each archetype disaggregated by building component.

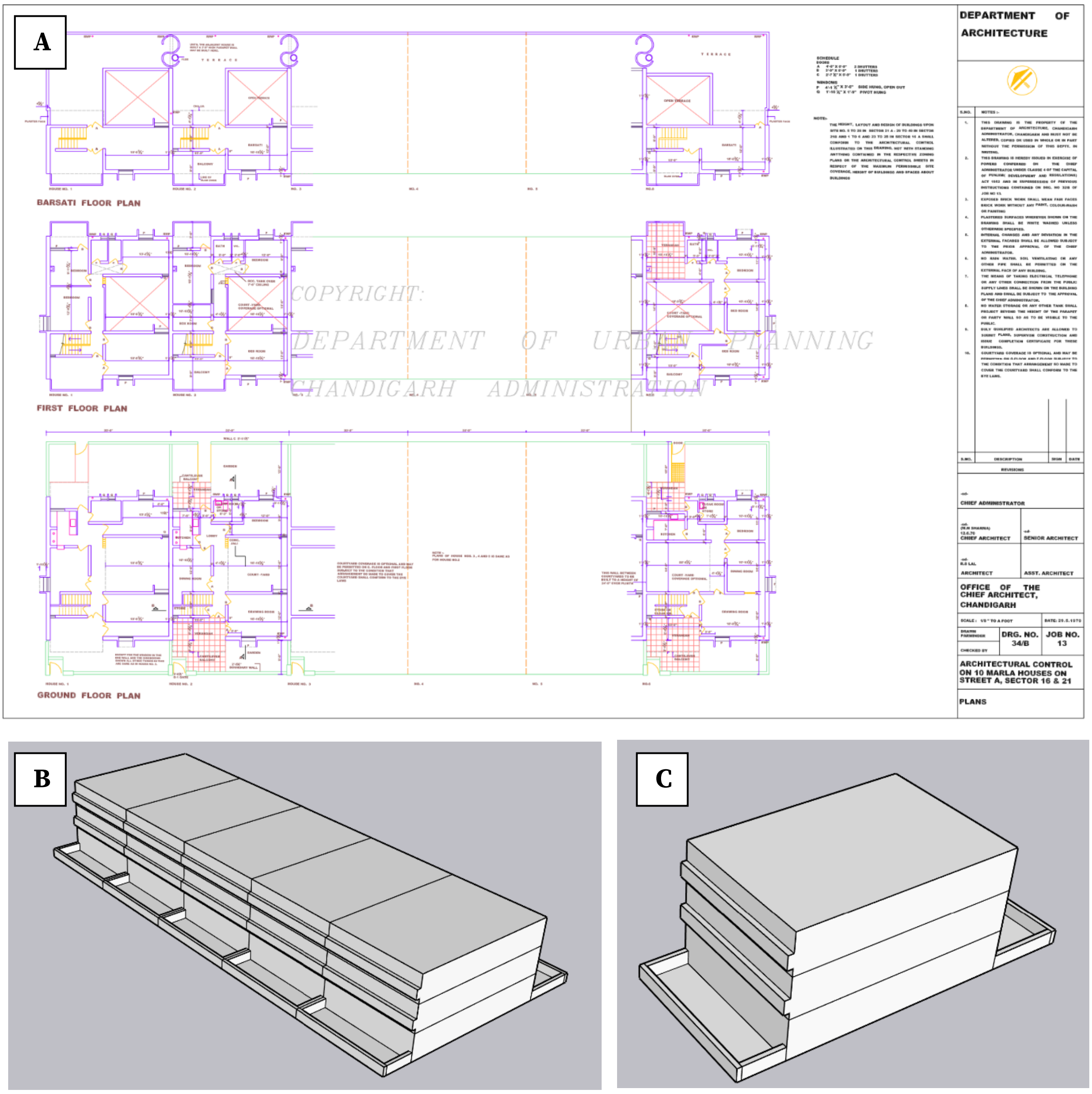


Figure C.2: (A) Example architectural control drawing showing the plan view for a 10 marla housing plot type (4). (B) Simple 3D model of a row of 10 marla housing (authors own) and (C) a simple 3D model of a single 10 marla plot (authors own), where the plot size includes the footprint of the building and the two external areas.

C.1 Residential buildings

Table C.1: Material properties used to calculate the total mass and embodied energy of residential buildings, raw values are provided by (9)

Material	Density (kg/m³)	Embodied energy (GJ/unit)	EC (kgCO2/ton)
Reinforced concrete slab (1% steel)	2300	3.65 (m³)	0.067
Reinforced concrete foundation (0.5% steel)	2300	2.56 (m³)	0.122
Brick	1800	2.41 (m³)	1.82
Steel	7800	20.62 (ton)	2.98
Clay tiles	2300	3.33 (ton)	0.334
Bitumen membrane	1100	2.98 (ton)	0.334

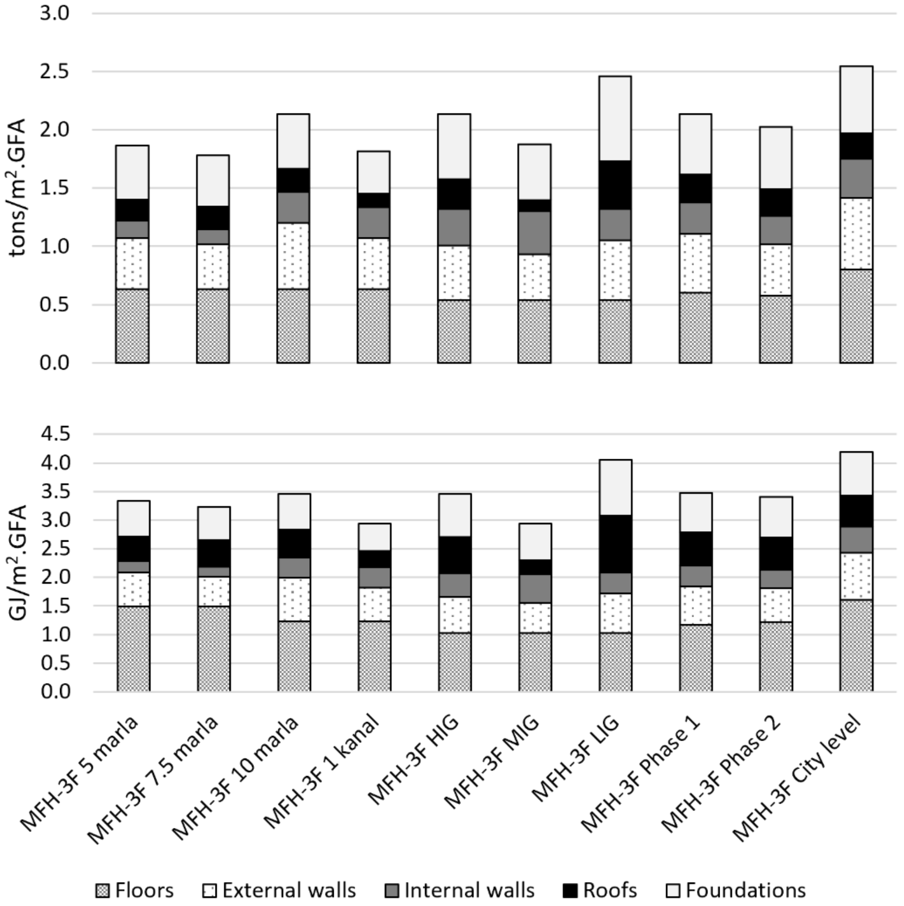


Figure C.3: (Top) MIC disaggregated by materials, and (bottom) embodied energy intensity of materials for MFH-3F housing of brick walls and reinforced concrete floors and roofs. We use twelve building samples corresponding to various plot sizes, m², and government housing schemes which includes high-, 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 ft² or 25m², with one kanal equal to twenty marla.

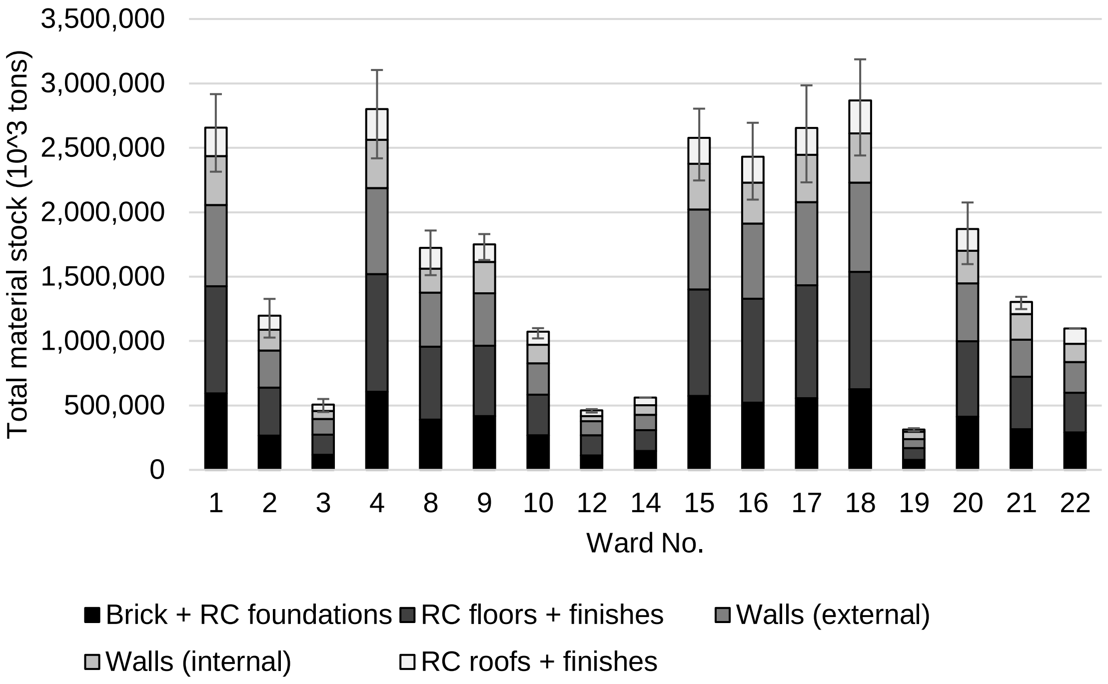


Figure C.4: Total material stock by component across the wards of the Municipal Corporation of Chandigarh.

C.1.3 Summary of key assumptions

While architectural control drawings show standard dimensions for the structural framing and floor and roof finishes, a number of assumptions are made to fill gaps in data per drawing and layout plan. We assume standard dimensions and detailing of buildings where data is not available as a result of the stringent architectural control. Architectural control drawings generally show the roof as half thickness of the floors. Most drawings show the roof as 4.5” RC slab with 1.5” clay tiles and 2 layers of bitumen. Where these details are not provided, we assume these specifications in line with the architectural control. Where the thickness of concrete is not specified for roofs, we calculate the thickness by the difference between the overall specified thickness and roof finishes as per the assumptions or the specifications on drawings. The thickness of bitumen is not specified explicitly and we therefore assume the thickness is 5mm as per (9). Most drawings show floors with 1.5” ceramic tiles for finishes and we assume this specification in line with the architectural control where details are not provided. Structural drawings specifying foundation details show that foundation thicknesses are related to the thickness of the wall. Walls are shown to be either 9” (internal walls) or 13.5” (external walls). Thus, we assume foundation (strip footings) correspond to the wall thickness for all architectural control drawings. As discussed in the main body, the ground conditions of Chandigarh are uniform and the building typologies homogeneous, thus we assume that foundation design is the same across buildings (strip footings under load bearing walls constructed of concrete, RC and brick). Most drawings specify wall thicknesses for internal and external walls of 9” and 13.5” respectively. We assume this thickness for drawings where these are not specified. Brick jails (walls surrounding the roof terrace area) are constructed of brick of half story height and are therefore considered as external walls. For the 5 marla plot type (126m^2), the width of the building is not given. We assume the width is the same as the 7.5 marla plot and verify the overall plot size (130m^2). Plot types often correspond to particular sectors which belong to their own construction phase as per the masterplan. We therefore assume this architectural control is generalized as per the phase and create two building archetypes for phase 1 and 2 to account for unknown plot types within sectors. We assume that steel accounts for 1% of the total volume of concrete for which is used for reinforcing as per the data available from (9). This value corresponds to reinforced slabs which are used for the floor system of all buildings. The drawings show no reinforcement in beams or columns due to load-bearing brick and masonry walls on the interior and exterior of the building and reinforced slabs used for floor systems with no structural beams specified. We assume that construction methods leading to 2011 are the same as in the masterplan, with drawings showing no difference between original drawings (dating from 1956) to revised drawings (dating up to 2008).

C.2 Roads

C.2.1 Inventory of items

We use Geofabrik (https://download.geofabrik.de/asia/india.html) to obtain transport infrastructure data from openstreetmap (OSM). The road types are split into various categories such as residential, path, primary, and secondary etc. and are highlighted on the respective maps of Chandigarh in ArcMAP below. Residential categorizations of roads are most common, accounting for 54% of the total length of roads downloaded. We evaluate primary, residential, secondary, service, tertiary, and trunk road types including their respective *link* data where necessary (as these contain details such as roundabouts and are merged into a single road type). We therefore account for ~93% of the total length of road data available, omitting roads that are unclassified as well as those limited in coverage and thought to be unrepresentative of the total stock (e.g., cycleways and pedestrian/paths).

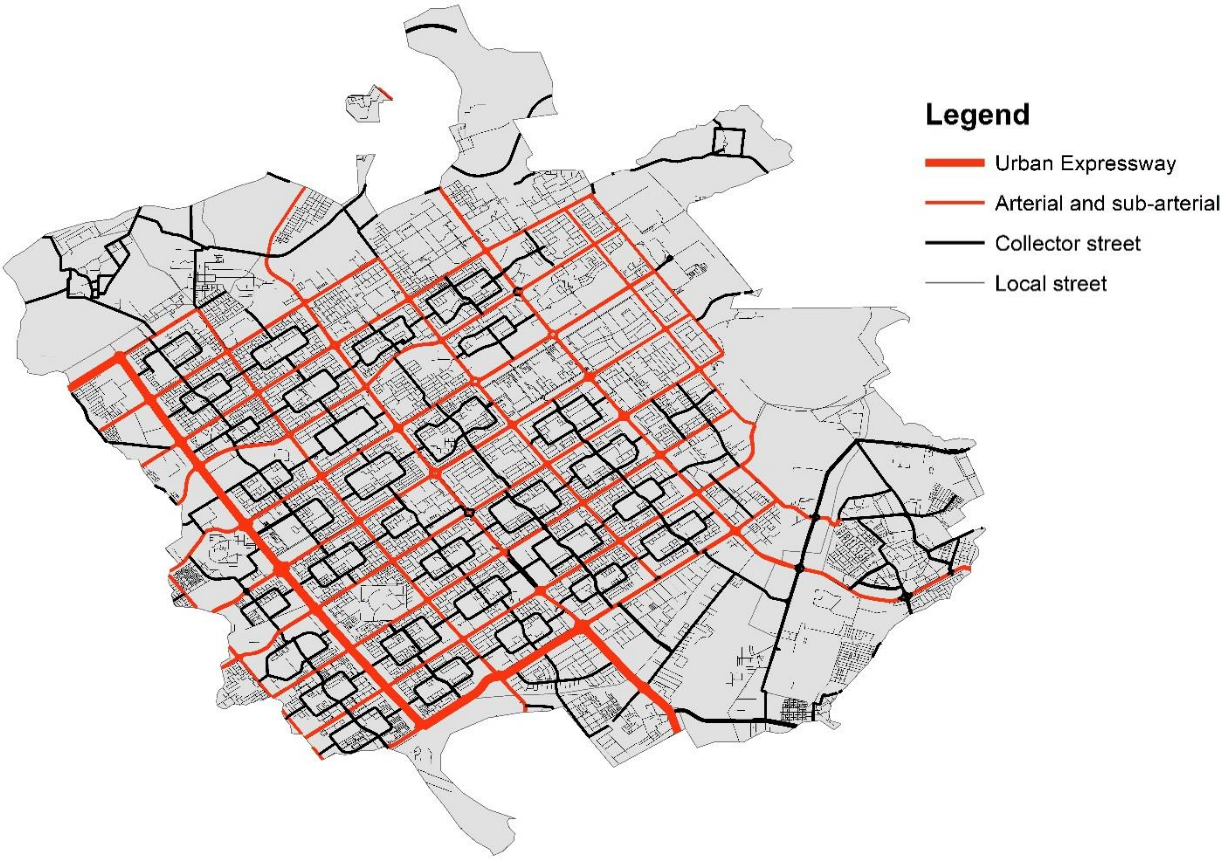


Figure C.5: Map of the road network of Chandigarh adopting OSM data as per the wards of Chandigarh. The various road types of Chandigarh are aggregated into appropriate road archetypes as in **Table C.2** to aid comparability between studies.

C.2.2 Material intensity coefficients

Table C.2: The road types present within Chandigarh and their approximate width as estimated using Google Earth.

Road type	Road type as per Chandigarh's road system	Approximate width, m	Recommended lane widths for roads, m (10)*
Urban expressway	V1	50	40-75
Arterial and sub-arterial roads	V2-V3 (sector perimeter)	30	30-60
Collector street	V4 (entering sectors)	25	15-30
Local street	V5 (leading to residential buildings)	10	10-15

*recommended lane widths as per Table 4.1 URC Geometric Design Guidance.

C.2 Roads

Table C.3: Material intensity of roads as per the national estimate for roads in Vietnam (11) which are used to calculate the total material stock of roads within Chapter 5.

				Material intensity, kg/m					
Road type	**Road composition**	**Material intensity, kg/m²** (11)		Surface layer			Base layer		
		Surface layer	Base layer	Stone	Sand	Asphalt	Stone	Sand	Asphalt
Urban expressway	Asphalt	5.35	99.02	10515	0	268	0	76590	4951
	Sand	0	1531.8						
	Stone	210.3	0						
Arterial and sub-arterial roads	Asphalt	5.35	99.02	6309	0	161	0	45954	2971
	Sand	0	1531.8						
	Stone	210.3	0						
Collector street	Asphalt	5.35	99.02	5258	0	134	0	38295	2476
	Sand	0	1531.8						
	Stone	210.3	0						
Local street	Stone	331.2	1800	3312	409	0	18000	0	0
	Sand	40.9	0						

Table C.4: Material intensity of roads as per the estimated values from an alternate study in Hanoi, Vietnam (12). The final material intensities of each road type within Chandigarh as per the studies are shown in the right-most columns. The lower material intensity values are used to calculate the sensitivity of the overall results in Chapter 5, which is briefly discussed in section 5.4.1.

	Material intensity, kg/m²				**Study road type**	**Total material intensity, kg/m**	**Total material intensity, kg/m ***
Road type	Sand	Limestone/basalt	Cement	Asphalt binder			
Asphalt concrete, low class BTN	108	1142	0	8	Urban expressway	62,900	92,324
					Arterial and sub-arterial	37,740	55,395
					Collector street	31,450	46,163
Bitumen treated crushed stones	75	856	0	5	Local street	9,360	21,721

*total values from Table C.4 from original study values.

C.2.3 Summary of key assumptions

Generally, assumptions are made by relating the raw data, i.e., location/type of road, and the measured road width within Google Earth, to the Chandigarh specific hierarchal road network, the recommended land widths for roads (10) and the road composition as per (11). We assume that all arterial and sub-arterial roads are of the same width, the majority of which are sub-arterial and measure 30m wide. We assume that V1-V4 roads are constructed the same as per the similar visual appearance. V5 roads are assumed to be constructed out of stone as opposed to asphalt and stone, owed to their significantly narrower construction compared to V1-V4 roads and that surface layer is a stone color as opposed to the darker asphalt surface layer from Google Earth imagery. We also assume that service roads are of the same construction as V5. We obtain data from literature for the material intensity of roads and thus assume that the road composition is similar to that in Vietnam as per the study from roads (11). We omit the use of cycleways, footways, living streets, paths, pedestrian, steps, track and unclassified road types which seem to be partially accounted for relative to the road types.

C.3 Comparison of city-level results

Table C.5: Data used to calculate material stock coefficients for comparison to the values of Chandigarh calculated in Chapter 5. Unless referenced otherwise, all values are taken directly from, or calculated using values provided within, the respective study.

City, country, Year	*Population*	*Area, km^2*	*Stock type*	*Total material stock, tons*	*Reference*
Jakarta, Indonesia, 2012	9,900,000	661.5 (13)	Residential buildings	299,700,000	(14)
Bandung, Indonesia, 2012	2,400,000	167.3 (15)	Residential buildings	94,000,000	
Rio de Janeiro, Brazil, 2010	6,318,960	1,200	Residential buildings	78,828,773	(16)
Beijing, China, 2013	21,150,000 (17)	667.2	Roads	159,000,000	(18)
Beijing, China, 2008	14,400,000	1310.9	Residential buildings	470,000,000	(19)
Chiclayo, Peru, 2007	*MS coefficients provided within the study*	*MS coefficients provided within the study*	Residential buildings	*MS coefficients provided within the study*	(20)
Singapore, 2016	5,600,000	716	Residential buildings	132,220,000	(21)
Esch-sur-Alzette, Luxembourg, 2010	32,600	14.35 (22)	Residential buildings	3,440,000	(23)
Manchester, England, 2004	30,232	8	Roads	650,000	(24)
	30,232	8	Buildings	2,250,000	
Wakayama, Japan, 2004	49,819	11	Roads	1,333,000	
	49,819	11	Buildings	10,000,000	

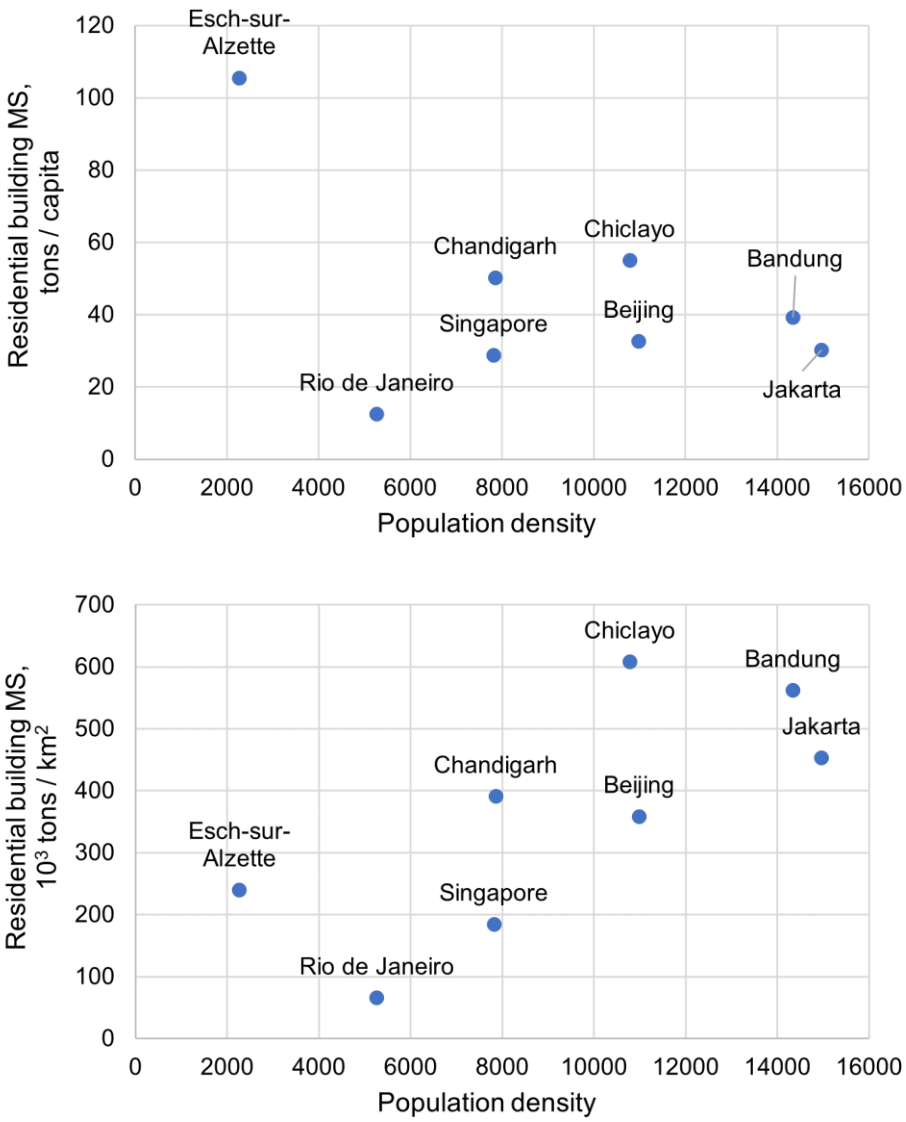


Figure C.6: Relationship between the total MS of residential buildings and population density for (top) MS per capita, and (bottom) MS per km^2, for cities cited in Table C.5.

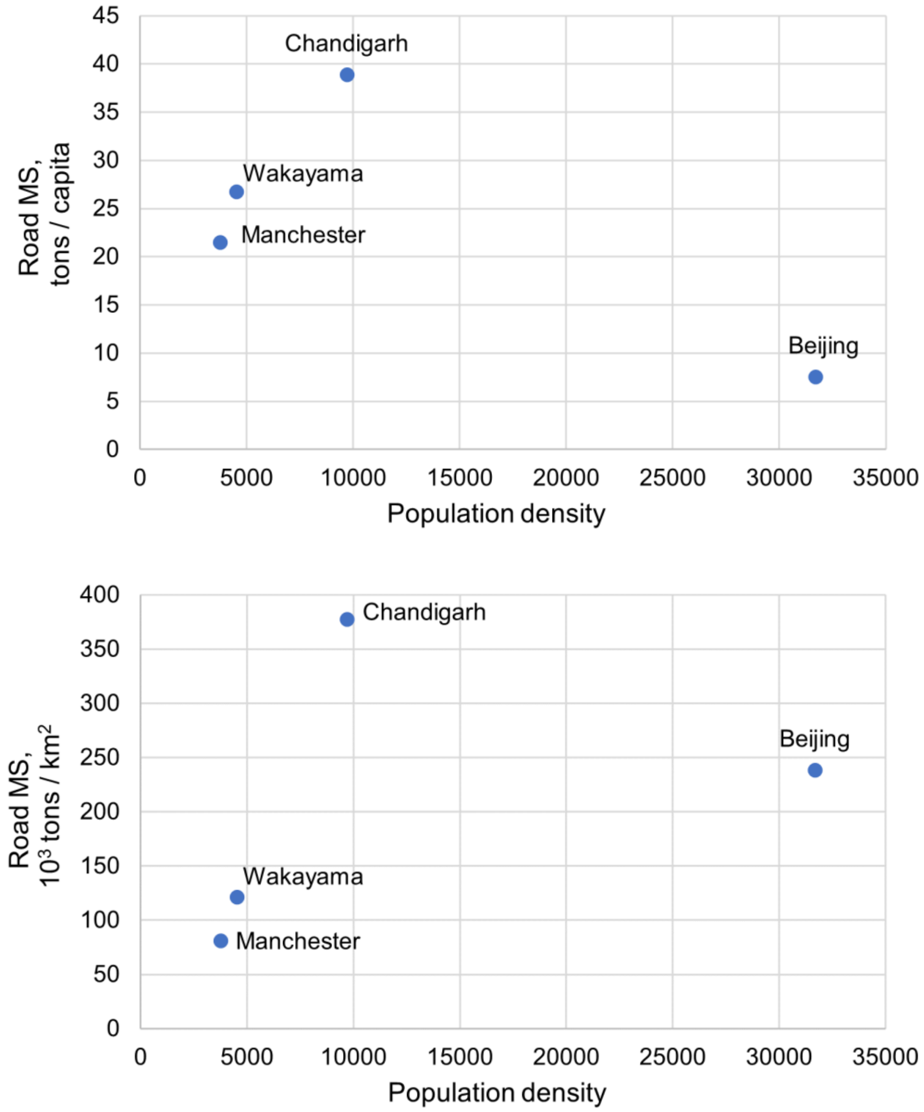


Figure C.7: Relationship between the total MS of roads and population density for (top) MS per capita, and (bottom) MS per km^2, for cities cited in Table C.5.

C.4 Chandigarh ward map

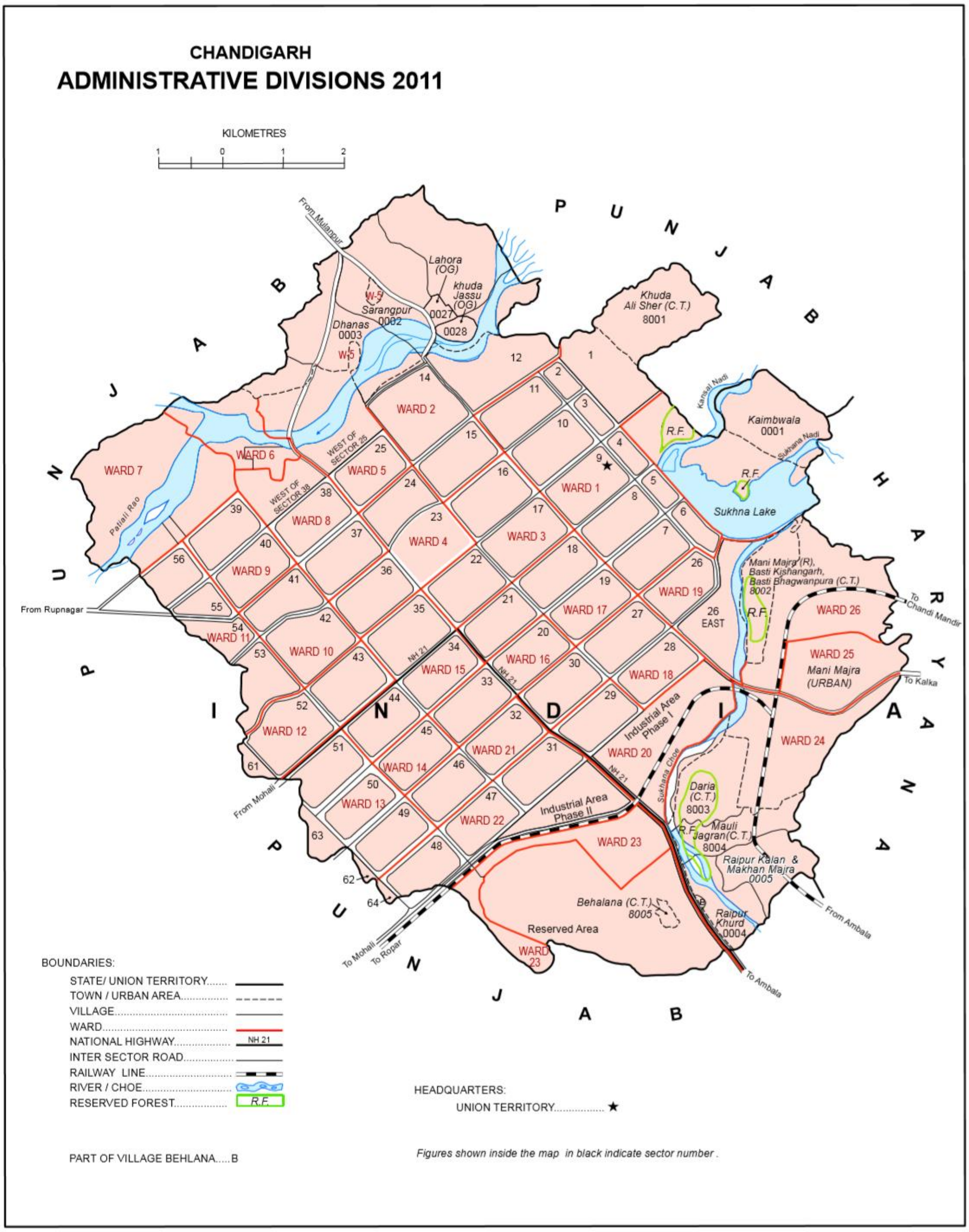


Figure C.8: Map of the administrative divisions of Chandigarh as per the Census of India 2011 (5).

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