MATERIAL ACROSS SCALES: COMBINING MATERIAL FLOW ANALYSIS AND LIFE CYCLE ASSESSMENT TO PROMOTE EFFICIENCY IN A NEIGHBORHOOD BUILDING STOCK

Irmak Turan[1], John E. Fernández[1]
[1]Building Technology, Department of Architecture,
Massachusetts Institute of Technology, Cambridge, MA, USA

ABSTRACT

A building requires significant material input during both its initial construction and over its lifetime for maintenance and upgrades. The sustained material demand of urban buildings, when aggregated, constitutes a large portion of the total material input in a city. This paper presents a methodological framework for quantifying the stock and flows of construction materials in an urban area. We combine material data for archetypical buildings in a neighbourhood with a three-dimensional urban model to create a picture of total construction materials. The proposed methodology is applied to a 0.5 km^2 residential area in Lisbon, Portugal. Through the model we construct a picture of the material composition of the neighborhood's building stock to better understand existing material cycles and investigate ways to make them more efficient.

INTRODUCTION

Cities worldwide are expanding and will continue to do so over the next century as the global urban population grows. As cities get larger, so does the built environment. All the while, the natural resources like minerals and metals needed for construction become increasingly difficult to source.

The Growing Global Building Stock

The built environment – the buildings and infrastructure in an urban system – constitutes a major portion of overall urban material consumption. Globally, minerals use to construct the built environment grew by a factor of 34 over the last century, and accounted for over 35 percent of total raw material consumption in the mid-2000s (Krausmann et al. 2009). Urbanization has led to recent construction booms that account for a significant portion of the total consumption, particularly in countries undergoing economic transition or rapid development. In Hungary and Poland there was a large investment in new housing and transportation infrastructure between 1995 and 2002, as the countries evolved to meet European Union standards (Kovanda and Hak 2008); in roughly the same period in Portugal, construction nearly doubled as the economy transitioned (Niza and Ferrão 2006); and in China, investment in new housing and infrastructure has grown to staggering levels to meet the needs of a fast growing urban population (Fernández 2007).

Moreover, while new construction constitutes the greatest short-term peaks in material additions, there is a constant flow over the lifetime of buildings in all countries. Even as demand levels off, buildings are continually maintained and renewed. Therefore, there is a sustained flow of materials through the built environment over the lifetime of all structures, even after the initial construction.

Measuring Material Stock and Flows

Material flow analysis (MFA) models the resource flows moving through and stocks accumulating within a system over a period of time. It is based on a simple mass balance of inputs, outputs and change in stock (Eurostat 2007):

$$\textit{Input} = \textit{Outputs} + \textit{Change in Stock}$$

An MFA can provide a picture of the resource wealth of, and burdens on, a system. The framework takes into account natural resources (such as energy, water and air) and raw materials (such as biomass, fossil fuels, metals, and minerals). The metrics used to measure the stock and flows can vary and depend on the type of system under study. For societal MFA models, the materials and resources are measured via economic indicators and organized according to the main sectors of urban activity: consumption of goods, services, human metabolism, industrial activity, transportation, and building stock.

MFA studies have been conducted for socioeconomic systems at a range of scales – from the entire globe and individual nations to regions, cities and households. MFA methodologies at the national level, such as that developed by Eurostat, make use of conventionally accepted economic indicators like gross domestic product. As such, MFA studies can be conducted for various countries and compared.

At the regional and city scales, however, the available data and boundary conditions can vary greatly, making it difficult to establish any one widely-accepted MFA methodology. The methods become more varied to account for specific system needs and research question at hand (Rincón et al. 2013). For many regional and urban studies, the Eurostat methodology has been adapted. At the city scale, Eurostat-based MFA studies have been conducted for

Hamburg, Leipzig, Limerick, Lisbon, Paris, Vienna, York and Curitiba (Barrett et al. 2002; Hammer et al. 2006; Browne, O'Regan, and Moles 2012; Barles 2009; Niza, Rosado, and Ferrão 2009; Rosado, Niza, and Ferrão 2014; Conke and Ferreira 2015).

The number of MFA studies at the urban neighborhood scale are even less, albeit growing. Codoban and Kennedy conducted urban metabolism studies for four neighborhoods in Toronto, with areas ranging from 0.25 to 4.5 km^2 (2008). Kellet et al. developed a carbon cycling and emissions study of a 4 km^2 area within a Vancouver neighborhood based on the urban metabolism framework (2013). González et al. created a decision-support tool that uses MFA accounting to predict the resource impact of proposed design alternatives (2013).

Accounting for the Buildings

The building stock within an urban MFA framework generally is measured by disaggregating national or city-level economic and urban data, using metrics such as number of buildings, heights, and building footprints. This approach, using factors and assumptions based on generalized material characterization, allows for quantification of the built environment without detailed surveys of all buildings within the area. Based on these parameters, material factors (in terms of mass per volume or area) can be derived for a system, such as those developed by Lichtensteiger and Baccini for residential buildings in Switzerland (2008).

This method is useful for making generalized assumptions, particularly for larger urban areas with thousands of buildings. But individual neighborhoods within a city are seldom uniform in their resource intensity. Urban patterns can change from one neighborhood to another, due to different demographic and economic profiles. The top-down disaggregation approach does not account for the nuances in urban form, particularly at the granularity required to propose design alternatives and technology options at the building level. Instead, keeping the system boundary restricted to the smaller scale of a city district (such as a neighborhood, quartier, borough, or freguesia) makes it easier to model and can capture the localized consumption patterns and dynamics, paving the path to establishing a neighbourhood resource metabolism. To this end, we propose to calculate the material stock from the bottom up, using national, municipal and local data to construct a small-scale model. This approach draws from the work flow often used for energy simulation at the urban scale (Reinhart and Davila 2015).

Research Goals

The aim of this work is to quantify the stock and flows of construction materials within an urban neighborhood using MFA to explore the potential for transformative new material cycles within a localized built environment. By understanding existing flows and patterns, one can propose design alternatives to enable new circular economies and reuse cycles to reduce the overall environmental burden while maintaining growth and betterment of the existing built environment. The main objectives are three-fold:

1. Develop an overall characterization of the neighborhood building material stock and its associated environmental burdens by combining elements of MFA and life cycle assessment (LCA) methodologies.
2. Identify existing major internal material use cycles and sinks, and the potential for new circular material systems within the neighborhood.
3. Propose strategies for enhancing existing and nascent material loops, and establishing new reuse and recycle pathways within the neighborhood via technological and design interventions.

This paper presents the framework for the first of the three research objectives, quantifying the building material stock and flows within a neighborhood and its associated environmental burdens.

METHODOLOGY

We propose a framework for measuring building material stock and flows within a neighborhood by combining top-down accounting and bottom-up data collection and modeling methods, as illustrated in Figure 1. The methodology couples the fundamental mass balance of MFA with components of life cycle assessment (LCA). The two approaches provide complimentary measures of analysis. MFA accounts for inputs, outputs, and internal cycling within the system boundary. In parallel, LCA informs the service life of building elements and provide measures of the environmental burden associated with building systems and materials.

Part 1: Constructing the Urban Model

Neighborhood and building data is collected and collated from a number of sources: the national census, municipal records and GIS layers, utility data and site surveying.

A simplified three-dimensional representation of the neighborhood is constructed in a CAD software such as Rhinoceros 3D. This representation serves as the framework for the building material stock model as it contains both geometric and non-geometric data for each building within the site. The geometric model is constructed using building footprint and height data obtained from the municipality. Information about the geometry, location, time period of construction, inhabitant demographics and building properties are then assigned to each building. The data is attributed to the buildings at the level at which it exists; in other words, if the data is available only at the municipal level, the same information is applied to all buildings within the neighborhood as further disaggregation is impossible; if the data is detailed by neighborhood

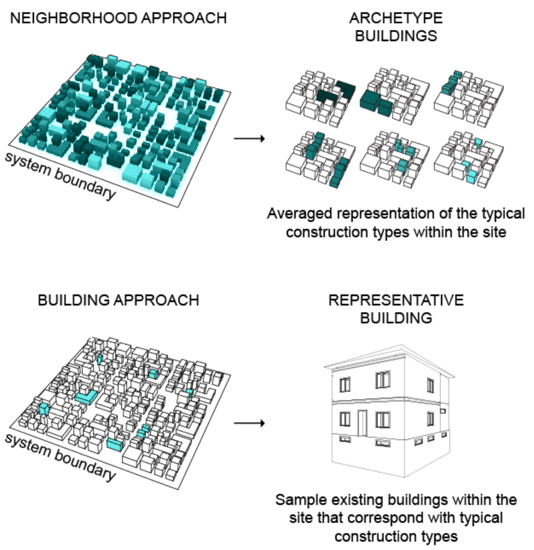

Figure 1 Top-Down and Bottom-Up Modeling

block or statistical subsection, it is assigned to the buildings within each section.

Part 2: Developing Material Characterizations

Based on the individual building profiles, we develop a set of building archetypes to represent the neighborhood’s built stock, defined as per the methodology developed by Sousa Monteiro, Pina and Ferrão (2015). The archetypes are not representative of specific buildings within the site but, rather, an average of many buildings with similar physical properties. Using building information modeling (BIM) software such as Revit, we model each archetype based on its construction, building systems and dimensions. Based on material information from the BIM model, we calculate the material composition of each archetypical building (per square meter). Then, each building within the neighborhood is assigned an archetype. Based on the archetype material composition, we calculate the material composition of each building in the neighborhood.

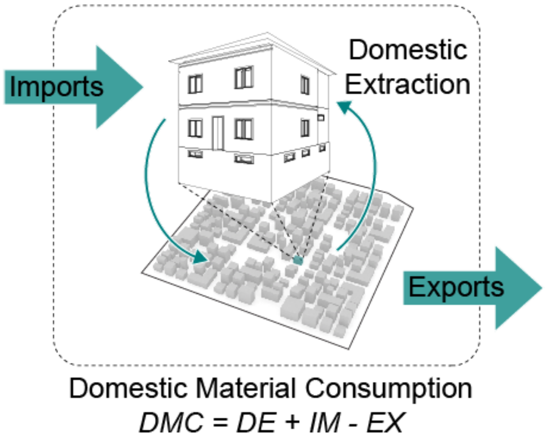

Figure 2 Material Flow through the Neighborhood Building Stock

In order to validate the archetypes, we model and measure select representative buildings in the neighborhood that correspond to each archetype and compare the material characterizations.

Estimating the Material Stock

The MFA indicators we use are adapted from the city-wide material flow accounting methodology developed by Niza, Rosado and Ferrão in their urban metabolism study of Lisbon (2009). The variables are related via the following equation:

$$DMC = DE + IM - EX$$

The indicators are summarized in Table 1 and the material inputs and outputs are schematically illustrated in Figure 2. For the representative buildings, material quantities organized by building system are derived from the Revit model. The major building systems considered are as follows: ceilings, doors, floors, roofs, exterior walls, interior walls, foundation, stairs, and windows. Using these material schedules, the data is further divided to determine the total amount of each material type.

The values derived from the neighborhood-wide data is then compared to the data from the representative buildings. The archetype building values are adjusted according to the output of the representative models.

Table 1
MFA Indicators

INDICATOR		DESCRIPTION
Domestic Extraction	DE	Additions from within the stock, i.e. generated inside the system boundary. In this case, domestic is defined as within the neighborhood system boundary.
Imports	IM	Material coming in from outside system boundary
Exports	EX	Material going out of the system boundary
Domestic Material Consumption	DMC	DMC = DE + IM – EX

System Boundaries

The proposed methodology is intended for modeling urban neighborhoods. It is meant to provide the framework with which individual areas within a city can be assessed and compared. Neighborhoods within a city are seldom uniform in their resource intensity. Different areas have different needs. Therefore, modeling at the smaller scale of a city district – such as a neighborhood, quartier, borough, and freguesia – adds value as it can capture the localized consumption patterns and dynamics.

Estimation of Lifespans

The estimated lifespan of building systems within the homes represents perhaps the greatest uncertainty and results in the greatest error in the analysis. Actual lifespan of the systems often differs from the designed lifespan of a product or component, and are derived from both empirical and historic data. Construcion documentation and permitting records are reviewed alongside onsite surveying of representative buildings to estimate the renovation and upgrade cycles for buildings within the neighborhood. An estimated lifespan is established for each major building system. It is generally assumed that that individual material within a system are not individually replaced but rather that building systems are upgraded as a whole.

Associated Environmental Burden

The environmental burdens associated with the material consumption of the system are derived from life cycle inventories. The primary impact measure is global warming potential (GWP), which is used as a gauge of the burden associated with various flows and proposed interventions. The time scale, dependent on the lifespan of building systems,is particularly critical in the measurement of the envirnmental burden. The present impact of the existing system can be deceivingly different from the impact over an extended time period. For this reason, the lifespan estimations are especially important. Once these are established and flows are detemined, the environmental burden in terms of GWP is a realitvely straightforward conversion.

Figure 3 Encarnação site plan, 1940 & 2015

Case Study

The presented methodology was applied to the Encarnação neighborhood in Lisbon, Portugal. Encarnação is a residential district consisting of over 1,100 semi-detached single family homes originally constructed in the 1940s as social housing. The neighborhood's symmetric street grid, surrounding a central greenway, reflects the garden city concept after which it was modeled (Sousa Monteiro 2015). While the homes have been adapted for modern living, most

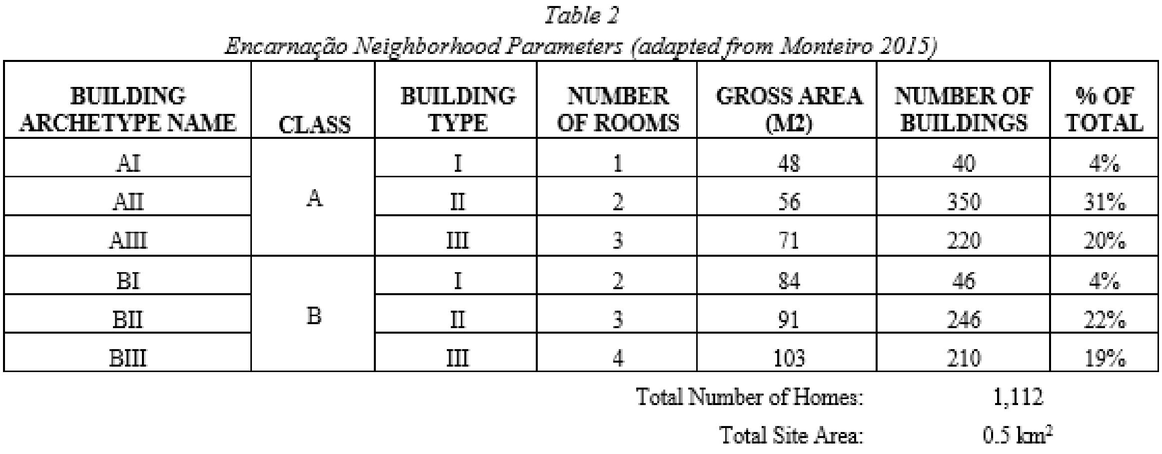

Table 2
Encarnação Neighborhood Parameters (adapted from Monteiro 2015)

BUILDING ARCHETYPE NAME	CLASS	BUILDING TYPE	NUMBER OF ROOMS	GROSS AREA (M2)	NUMBER OF BUILDINGS	% OF TOTAL
AI	A	I	1	48	40	4%
AII		II	2	56	350	31%
AIII		III	3	71	220	20%
BI	B	I	2	84	46	4%
BII		II	3	91	246	22%
BIII		III	4	103	210	19%

Total Number of Homes: 1,112
Total Site Area: 0.5 km^2

retain their original architectural form and have not undergone major physical transformations. The original site plan and current plan are presented in Figure 3.

The homes are modest two-story structures. There are two classes of homes, Class A and Class B; the former being of superior construction quality than the latter. The homes range from two to four bedrooms and have gross floor areas between 48 m^2 and 103 m^2. An analysis of the building construction by Monteiro show that the homes are made of traditional masonry walls with concrete slabs in the wet areas, and wood flooring in all other areas (2015). The six housing typologies identified reflect the various permutations of buildings in Encarnação, as summarized in Table 2. The typology parameters, such as wall thicknesses, are derived by averaging the measurements from sample buildings with the site. As such, no typology represents a specific exisitng building, but rather, an agglomeration of like buildings.

RESULTS

The Encarnação neighborhood served as a test site for the proposed methodological framework for material accounting at the building and neighborhood scales. Through the modeling process we determine a material profile for the neighborhood, establish the associated global warming potential, and map the flow of materials through the site over time. By creating the material characterization of the neighborhood, we can identify the critical building systems that lead to greatest environmental burden and develop design strategies to decrease the impact. The workflow developed through the Lisbon case study is presented in Figure 4.

DISCUSSION

The urban built environment is a major sink of material and resources. Changing the way in which materials are used in buildings over their lifetime has the potential to transform global material flows. However, construction material use today, just as it was a century ago, consists primarily of linear input-output streams; construction materials come in and waste goes out. What if the output, rather than being labeled waste, was input for another project nearby? The output material – whether it be the residuals from new construction activity or the stripped material from existing buildings renovations – has intrinsic value. This value is inevitably less than untarnished raw materials, but if appropriately applied, the output can take the place of the virgin alternative. This proposition is not meant to dismiss existing recycling streams; but rather to compliment these cycles with new reuse cycles. New internal material cycles include both spatial and temporal scales. Existing building stock can either supply current construction activities within the vacinity or, through advanced planning, the future renewal and regeneration as illustrated in Figure 5. For these schemes to work, the cycles must be an integral element of the initial planning and design at the start of a project rather than at end of a building's life, such that a building is designed to be the recipient of internally sourced materials but also the future supplier.

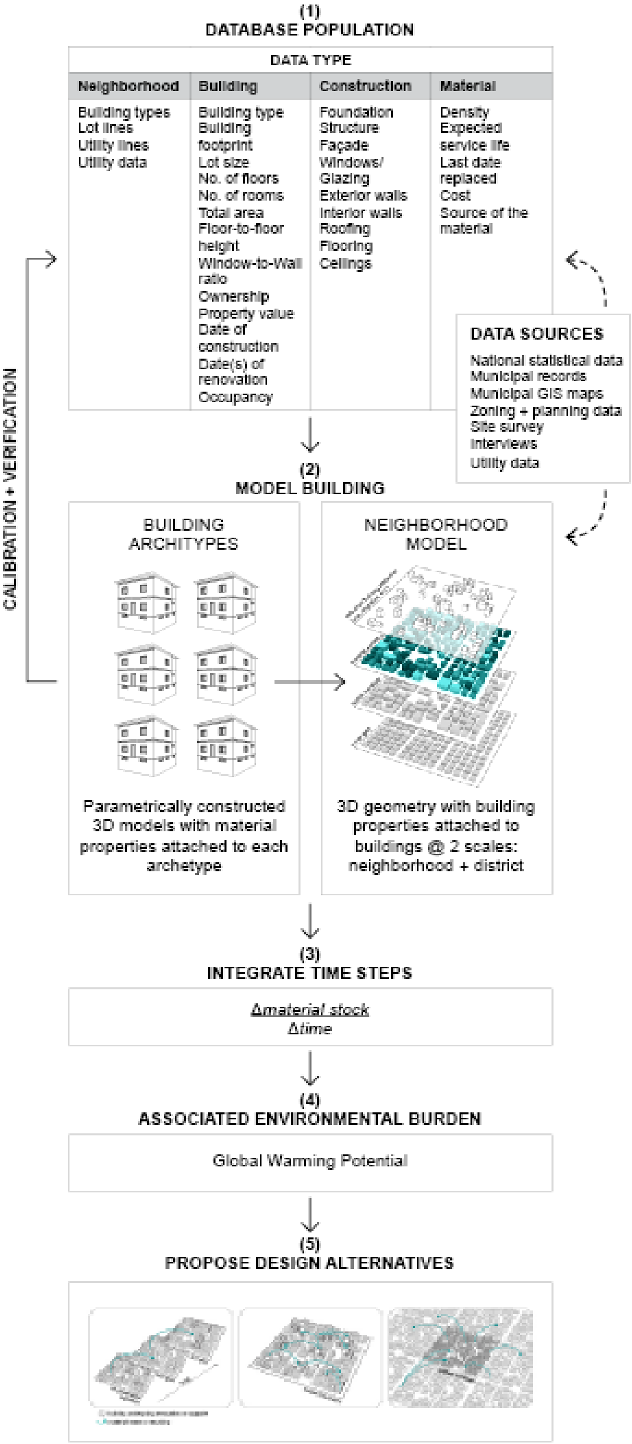

Figure 4 Workflow Schematic

Determining Scale

Cities are not self-sufficient entities. They rely on their surrounding region and hinterlands. The three-tiered MFA study of Paris (measuring flows in the urban center, the larger city and its dense suburbs, and the greater Ile-de-France administrative region) illustrates

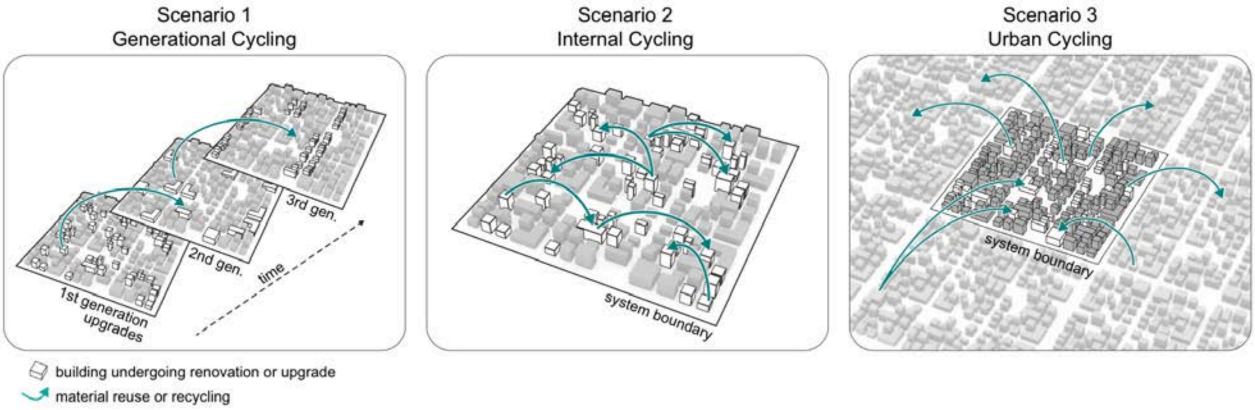

Figure 5 Proposed Reuse Scenarios

the high dependency of the urban center on its surrounding areas in terms of both inputs entering and outputs leaving the system boundary (Barles 2009). As cities are intrinsically reliant on their surroundings they will not become fully independent of outside resources and materials. However, they can become more efficient and establish internal cycles to develop a higher degree of independence. There are opportunities for increased optimization and cycling that are yet to be tapped.

At what scale do these opportunities exist? One may presume that potential cycles exist at a range of scales, from the neighborhood block to the greater metropolitan region. The neighborhood analysis presented in this paper is meant to provide more clarity about the opportunities that lie at the neighborhood scale.

CONCLUSION

The aim of this study was to establish a methodology for measuring the building material stock within a neighborhood. The proposed framework captures the range of building types within the system while also illustrating the overall material and resouce use within the building stock. This requires developing the model from both a top-down and bottom-up approach. Pairing a top-down methodology with bottom-up data is meant to fulfill two objectives: firstly, to validate the quantities measured by the neighborhood information; and secondly, to smooth over variations in datasets for different sites. The methodology is intended to be applicable to a range of urban neighborhoods, quantifying the material intensities accurately and with a degree of detail that is useful for proposing technological and design interventions. To this end, It is recognized that the available data varies from site to site. Pairing neighborhood-level assessment with individual building models will enable validation of the information, despite the variability.

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