A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model

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Summary

This article describes a new methodological framework to account for urban material flows and stocks, using material flow accounting (MFA) as the underlying method. The proposed model, urban metabolism analyst (UMAn), bridges seven major gaps in previous urban metabolism studies: lack of a unified methodology; lack of material flows data at the urban level; limited categorizations of material types; limited results about material flows as they are related to economic activities; limited understanding of the origin and destination of flows; lack of understanding about the dynamics of added stock; and lack of knowledge about the magnitude of the flow of materials that are imported and then, to a great extent, exported.

To explore and validate the UMAn model, a case study of the Lisbon Metropolitan Area was used. An annual time series of material flows from 2003 to 2009 is disaggregated by the model into 28 material types, 55 economic activity categories, and 18 municipalities. Additionally, an annual projection of the obsolescence of materials for 2010–2050 was performed. The results of the case study validate the proposed methodology, which broadens the contribution of existing urban MFA studies and presents pioneering information in the field of urban metabolism. In particular, the model associates material flows with economic activities and their spatial location within the urban area.

Introduction

The objective of establishing a robust method to quantify urban material flows, in order to characterize the urban metabolism of different cities worldwide, has been attempted by some researchers, but it has not yet been fully achieved because there are still some methodological gaps. Several studies for different urban areas have been conducted to quantify urban material stocks and flows. These include studies of Lisbon (Niza et al. 2009), Singapore (Schulz 2007), and York in the United Kingdom (Barrett et al. 2002). In addition, Hammer and Giljum (2006) quantified material flows for Hamburg, Vienna, and Leipzig, whereas Barles (2009) quantified material flows of Paris. Material flow accounting (MFA) is the basis for all of these studies, but it needs to be adapted to several constraints and particularities when applied to cities, hence the need for innovative methods to account for materials entering and leaving an urban area.

Two overall gaps are identified in several articles dedicated to a review of existing urban metabolism studies. First, it is clear from the literature (e.g., Kennedy et al. 2011; Niza et al. 2009; Barles 2010; Weisz and Steinberger 2010) that urban MFA studies lack a unified methodology. Different studies use different methodologies and this is likely to be detrimental to the consolidation and reliability of results. Without a unified methodology, urban metabolism studies can only be considered

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on a case-by-case basis and will fail to aid in the development of more-general conclusions that might contribute to the design of more-sustainable urban systems. The main motivation for the work presented here is to provide a comprehensive systematic procedure for urban metabolism studies that avoids the frequently adopted bulk MFA perspective and establishes a new methodological framework intended to quantify urban material flows and stocks and their correlation with economic activities.

The second gap, which strongly contributes to the first, concerns the lack of data. Kennedy and colleagues (2011), for instance, mention that despite the importance of the overall volume of socioeconomic material and energy use in cities, the harmonized data sets are provided by statistical offices almost exclusively at the national level. Therefore, attempts to generalize patterns and trends of urban-specific resource use from the literature have, so far, proven to be incomplete.

To address the second gap, Niza and colleagues (2009) pioneered a methodology developed specifically for quantifying urban material flows based on the Eurostat (2001) methodology, downsizing it from economy-wide to urban material flows. It was tested in a case study that characterized the urban metabolism of the city of Lisbon by quantifying its material balance for 2004. This study, as with the majority of the urban MFA literature (e.g., Barles 2009; Best Foot Forward [BFF] 2002; Hammer and Giljum 2006), categorized materials into the five classes used in Eurostat (2001). This considerably reduces the practical use of its results, particularly in guiding the development of waste management or sustainable consumption policies. For example, aluminum and steel are both metallic minerals with a significant economic value, but they require significantly different techniques to be recycled. In previous urban metabolism studies, there is no discrimination between them because they are categorized as metallic minerals. Another example of a broad category of materials is the Eurostat (2001) fossil fuels (FFs) category, which aggregates plastics and fuels. This does not allow for identification of the amount of plastics that could be recycled nor the amount of FFs that are used for energy and that result in greenhouse gas emissions that cannot be captured for waste management purposes. The limits imposed on the usefulness of urban metabolism studies by an overly broad categorization of materials is the third gap.

Similarly, in previous urban metabolism studies, material consumption was estimated for very broadly aggregated economic sectors, allowing only very rough conclusions to be drawn about which sectors are the main drivers of material consumption. An inability to more adequately identify the economic sectors that are the main drivers of material consumption constitutes the fourth gap of current urban flow accounting methodologies.

Another gap is associated with a limited understanding of the origin and destination of flows within the urban boundaries (Hammer and Giljum, 2006). Previous urban MFA studies account for flows that enter or leave the system, but there is no characterization of the life cycle phase of the flows inside the system. For example, the origin of imported materials and the municipality where they are locally extracted, the materials that are transformed by the local industry, and the product destination at their end of life (EOL) are not usually identified. This fifth gap is detrimental to establishing policies for a more sustainable use of urban material flows.

The sixth gap relates to the lack of understanding about the changes in stocks of materials over time in cities, because previous studies generally provide a static picture of material stocks. They show materials entering the economy and the accumulation in stocks, but do not provide information about the dynamics of the consumption-throwaway cycle, losing potential insights that can be obtained by understanding future materials availability from products reaching their EOL.

The spatial scale of urban metabolism studies presents additional difficulties. First, the lack of commodities statistics at a small spatial scale requires that values be estimated. This estimation may result in overestimates of material consumption, because many regional and national administrative offices, whose workforce is not involved in material-intensive activities such as manufacture and extraction, are concentrated in urban areas. Additionally, daily commuters—who eat, travel, and shop during the day in the city they work in, plus the material flows from urban infrastructure, such as ports, train stations, or airports, that are distributed not only in the city, but also elsewhere in the rest of the country or in other countries—may potentially contribute to overestimates of the material consumption in urban areas. This can be identified as the seventh gap: a poor understanding of the flows into the urban area whose only relationship to the urban area being studied is that they cross through it on their way to somewhere else. This article refers to these flows as "cross flows."

In this article, a new urban MFA model—the urban metabolism analyst (UMAn)—was developed to overcome the described gaps by the following:

- Assigning product composition to 28 harmonized material types; this addresses gap 3 (limited discrimination of material types)
- Disaggregrating the data spatially and by economic sector and characterizing the life cycle phase of products to address gaps 2 (lack of material flow data at the urban level), 4 (limited resolution of economic activities responsible for material consumption), and 5 (limited understanding of the origin and destination of flows)
- Including information about product lifespan to reduce gap 6 (lack of understanding about the dynamics of added stock); this aids in understanding the potential that stocks may have in the recovery of useful materials
- Decoupling cross flows from imports and exports to better understand their magnitudes, but also the significance of local industrial production; this reduces gaps 5 (limited understanding of the origin and destination of flows) and 7 (lack of knowledge about the magnitude of cross flows)

The UMAn model is particularly suited to conducting urban metabolism studies within the European Union (EU) because it relies on Eurostat standard statistical data for products, a characteristic that strongly contributes to addressing gap 1 (lack of a unified methodology for conducting urban metabolism studies).

In the next section, the UMAn model and related methodology are described. Next, the results of its application to the Lisbon Metropolitan Area (LMA) are presented and compared with results of other studies of urban areas. Finally, conclusions are drawn about the contribution of the model and the main results of its application to the case study.

A New Urban Metabolism Model: Methodological Details

The UMAn model has four main components in which a set of nested calculation routines process available data to produce a detailed map of material resources and throughput for different economic activities. The four components are as follows:

- Platform: theoretical foundations of the model specifying the adjustments made to scale the economy-wide MFA to the urban scale, addressing specific issues of urban areas, particularly the relevance of imports, both intranational imports (which are brought into the urban area from within the country that the urban area is in) and international imports (which are brought into the urban area from a country other than the country the urban area is in), and also the potential existence of significant cross flows
- Statistics: data needed for the mathematical calculations in the model
- Plugins: databases describing the flows of products and goods (according to the standard nomenclatures used by Eurostat and the Organization for Economic Co-operation and Development [OECD]) in terms of their material composition, average lifespan, and life cycle phase
- Calculator: the operational core of the model that involves four sequentially nested steps and that uses the platform, statistics, and plugins, allowing for accounting for several variables, namely: products and materials and related MFA indicators; throughput projections based on products and materials added to stocks; assignment of products and materials to the economic activities of the metropolitan area; and the spatial disaggregation of the products and materials

The previously described gaps in the study of urban metabolism and the ways in which the various components of the UMAn model address these gaps are summarized in table 1. In the next paragraphs, the components and intermediate phases of the model are presented.

Platform

The methodology of MFA plays an important role in the proposed urban metabolism model, but in order to meet the model's needs, this methodology must be adapted from the economy-wide scale to the scale of urban areas. For urban areas, the amount of materials extracted and the manufacturing sector are less important than they are to entire countries (e.g., Barles 2009). Potentially, a large part of the material flows in an urban area originate from outside its boundaries (Bai 2007): Import and export categories assume a higher relevance in the quantification of material flows at this scale of analysis. Further, an urban area can have flows that travel through it, crossing into and then out of the boundaries of their urban area on their way toward their destination. These cross flows can assume a great importance in metropolitan areas where the "Rotterdam effect" is felt (as is the case of Lisbon [Niza et al. 2009] or Hamburg [Hammer and Giljum 2006]), referring to the role of big harbors (e.g., Rotterdam or Antwerp) serving as gateways for international trade (Weisz et al. 2005).

Additionally, because metropolitan areas are part of a country, a split between the imports and exports from foreign countries and other regions of the country should be performed.

One of the major issues here relates to the openness of cities (i.e., the lack of a clear boundary in terms of existing statistical information). Because data for imports and exports are not explicit about their final destination or origin, it is difficult to understand whether imports are staying within the economy or just passing through, likewise for exports.

Statistics

One of the major difficulties in quantifying material flows at regional or urban scales has to do with the availability of data at the established boundaries. Although some material flow data for regions or metropolitan areas are available, some of the needed information has to be assembled using data from a combination of sources. Data sources used by the Eurostat and national statistical offices to compile economy-wide MFAs can be applied to the specificities of metropolitan areas, but an additional major data source must also be used: the Standard Goods Classification for Transport Statistics. The Standard Goods Classification for Transport Statistics (NST 2007) provides statistical information about products, based on their economic activity of origin. It is available for four modes of transport: road; rail; air; and water (Eurostat 2012a). The Standard Goods Classification for Transport Statistics is related to other statistical nomenclatures, namely, the EU Classification of Products by Activity and the Statistical Classification of Economic Activities (NACE) (Eurostat 2012a).

The Standard Goods Classification for Transport Statistics is useful for studies of urban metabolism because it is available at the Eurostat's Nomenclature of Territorial Units for Statistics (NUTS) 2 level. This nomenclature has five levels of hierarchical classification. Each country from the EU is assigned a NUTS 1 level. Regions within the country are the NUTS 2 level, and these regions are divided into the NUTS 3 level (Eurostat 2013a). In the case of Portugal, the NUTS 3 level corresponds to municipalities. The use of this source ensures

Table 1 Gaps in urban material flow accounting that are addressed by the UMAn model

Gap	*UMAn developments to bridge the gap*
1. Lack of a unified methodology	Using statistical data provided by the OECD and Eurostat to perform urban MFA allows for the establishment of a model that has the potential to be universally applied within the European Union.
2. Lack of material flows data at the urban level	The use of generalized national statistics coupled with regional statistics allows for the calculation of consumption within the metropolitan areas, providing a means of generalizing patterns of consumption for urban areas.
3. Limited discrimination of material types	The disaggregation and harmonization of material types using the material composition plug-in database and the accounting of products allows for measuring flows for 28 categories of materials instead of only five.
4. Limited resolution of consumption by economic activity	National transportation and international trade statistics are used to attribute an economic activities sector to each product transaction.
5. Limited understanding of the origin and destination of flows	The characterization of the supply chain is made by combining the products and materials composition and the life cycle phase of the product plug-in database. This allows identifying, within the metropolitan area, the economic activities involved in the manufacture of final products for consumption.
6. Lack of understanding about the dynamics of added stock	The measurement of the dynamics of stocks is performed by combining the lifespan plug-in database and the throughput description parameter, allowing for measuring the potential amount of materials becoming obsolete each year.
7. Lack of knowledge about the magnitude of cross flows	The establishment of clear calculation techniques for metropolitan areas and the decoupling of cross flows from imports and exports are addressed with the materials accounting procedure.

Notes: UMAn = urban metabolism analyst; OECD, Organization for Economic Co-operation and Development; MFA, material flow analysis.

a proper accounting of flows in and out of metropolitan areas that match a specific NUTS 2 level, because it tracks all movements of products and goods within the region. In the specific case of the LMA, the boundaries of the defined metropolitan area and the NUTS 2–Lisboa region coincide, which reduces the need for further calculation in order to scale the data from the region to the metropolitan area. In cases where the NUTS 2 boundaries and the defined metropolitan area do not coincide, the MFA will have to be conducted at the NUTS 2 level and disaggregated into municipalities (the NUTS 3 level), making it possible to calculate values for the metropolitan area using the spatial distribution part of the UMAn model.

To estimate domestic extraction (DE) in an urban area, some of the data sources are directly used, whereas others involve calculations that scale the data from the national level to the level of the metropolitan area. For example, a linear relationship between DE and the number of workers for a particular economic activity might be assumed. In this case, the urban area's DE will be a percentage of the national DE that is equal to the percentage of national workers in that economic activity that are in the metropolitan area. Specifically, the absence of workers in the economic activity "mining of iron ores" (13.10 NACE code, rev 1.1) in an urban area suggests that there is no iron extracted in the urban area's boundaries.

Plugins

In order to provide the product composition and product lifespan and to assign a life cycle phase to the product, three supporting databases were built: One characterizes the material composition of products; another identifies the average lifespan of products; and another identifies the life cycle phase of each product (whether the product is livestock, raw materials, intermediate products, final goods, or waste). This set of databases, designated ProdChar (Products characterization) in the aim of the UMAn model, describes 13,135 types of products corresponding to the fifth level of disaggregation of the combined nomenclature (CN) used in the International Trade Statistics (ITS) (European Commission [EC] 2011). The CN is used to classify goods that are reported in customs in the European Community. It is related to the harmonized system (HS) nomenclature, with further subdivisions (Eurostat 2012b). The HS is run by the World Customs Organization (WCO) and forms the basis for international trade negotiations, being used by most trading nations (Eurostat 2012b).

Table 2 MatCat nomenclature

Fossil fuels	Low ash fuels High ash fuels Lubricants and oils and solvents Plastics and rubbers
Metals	Iron, steel alloying metals, and ferrous metals Light metals Nonferrous heavy metals Special metals Nuclear fuels Precious metals
Nonmetallic minerals	Sand Cement Clay Stone Other (fibers, salt, or inorganic parts of animals)
Biomass (forestry, crops, and animal products)	Agricultural biomass Animal biomass Textile biomass Oils and fats Sugars Wood and fuels Paper and board Nonspecified biomass
Chemicals and fertilizers	Alcohols Chemicals and pharmaceuticals Fertilizers and pesticides
Others	Nonspecified Liquids

Note: MatCat = material categories.

A thorough description of the development of these three databases is given in Rosado (2012).

Material Composition

A new nomenclature with 28 material categories–the material categories nomenclature (MatCat)—was developed to split products into materials for the UMAn model (table 2). This nomenclature represents:

1. a balance between the coarse aggregation of the nomenclature defined by the Eurostat (2001) for imports and exports and the finely disaggregated spectrum of material categories defined by the same agency for domestic extraction (e.g., for minerals, it includes 153 material categories) and
2. a resource-management-based classification, which is a proxy for the potential of recovery of the materials in products.

MatCat is used to formulate the material composition matrix ($M_{n,m}$) of the ProdChar, where n represents the 13,135 types of products in the CN and m represents the 28 material categories described in table 2. The elements of the matrix are given in terms of the percentage of the total product weight by material category. Thus, the notation for this material composition matrix is given by equation (1):

$$\mathbf{M}_{n,m} = \begin{bmatrix} \mathbf{m}_{1,1} & \mathbf{m}_{1,2} \cdots & \mathbf{m}_{1,28} \\ \mathbf{m}_{2,1} & \ddots & \vdots \\ \vdots & & \mathbf{m}_{13134,28} \\ \mathbf{m}_{13135,1} & \mathbf{m}_{13135,2} \cdots & \mathbf{m}_{13135,28} \end{bmatrix} \quad (1)$$

with $n = 1, \cdots, 13{,}135$ *types of products and* $m = 1, \cdots,$ 28 material categories

In order to create this matrix, extensive literature research was conducted. The data sources used to characterize the material composition of products are described in Rosado (2012). They include United Nations University (UNU) (2008), EU (2011), and Defra (2009), among others. As an example, according to Defra (2009), the mass percentages of materials found in CN product type 87032190 (motor cars and other motor vehicles principally designed for the transport of persons) are 4% lubricants and oils and solvents, 22% plastics and rubber, 58% iron, steel alloying metals, and ferrous metals, 2% light metals, 4% nonferrous heavy metals, 1% sand (in the form of glass), 4% textile biomass, and 5% nonspecified.

A subset of $M_{n,m}$ is $M_{z,m}$, which includes only the product types that are considered to be final goods (9,785 of 13,135 product types). Thus, $M_{z,m}$ is a 9,785 × 28 matrix.

Product Lifespan

To understand the dynamics of resource flows and improve the knowledge of future availability of resources for reuse, recycling, or recovery, a lifespan database was developed. This database includes information about the average lifespan of products (in years) and a distribution function for each. Sources supporting this database are also described in Rosado (2012). The chosen distribution function was the Weibull (as proposed by some researchers, e.g., Elshkaki et al. 2005; Melo 1999) because it provides a good fit for the lifespan of most of the products. The distribution is described by equation (2):

$$f\,(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(x/\lambda\right)^{k}}, & x \geq 0 \\ 0, & x < 0 \end{cases} \quad (2)$$

In this equation, x represents the average lifespan of a product and k and λ are the shape and scale parameters for the distribution curve, respectively. Estimates for k are chosen based on values used in the scarcely available literature (e.g., Melo 1999; Davis et al. 2007) to adjust the k value to empirical information for each product (Melo 1999). For most products, k was set equal to 10 to reflect the potential amounts flowing out of the system on an annual basis.

A throughput matrix (equation (3)) was built ($T_{n,y}$), where n is product types and y the percentage of products becoming obsolete each year.

$$\mathbf{T}_{n,y} = \begin{bmatrix} \mathbf{t}_{1,1} & \mathbf{t}_{1,2} \cdots & \mathbf{t}_{1,x} \\ \mathbf{t}_{2,1} & \ddots & \vdots \\ \vdots & & \mathbf{t}_{13134,x} \\ \mathbf{t}_{13135,1} & \mathbf{t}_{13135,2} \cdots & \mathbf{t}_{13135,x} \end{bmatrix} \quad (3)$$

$$\textit{with } n = 1, \cdots, 13{,}135 \textit{ types of products and } y = 1, \cdots, x \textit{ years}$$

Taking the previously mentioned example (Defra 2009), the CN product type 87032190 (motor cars and other motor vehicles principally designed for the transport of persons) has an average lifespan of 12.5 years, with some vehicles retiring much earlier than that and some retiring much later. Its obsolescence is distributed annually according to the Weibull distribution.

Life Cycle Phase

Materials and products that are transported into the urban region being modeled (be they from intra- or international origin) enter the metropolitan economy in different life cycle phases (e.g., raw materials or final goods). As final goods, they will eventually become wastes (namely, municipal solid wastes) and emissions. As raw materials or preprocessed goods, they will be transformed within the metropolitan area and contribute to industrial wastes and emissions, becoming part of the final goods that are consumed within the metropolitan area or transferred outside of it. In order to assure a correct balance of materials, it is important to identify the final goods going directly to consumption and the amount of preprocessed goods, so that they can be balanced with sectorial wastes and emissions and exports. The life cycle phase characterization matrix ($S_{n,g}$) was built to perform the assignment of phases to product types (equation (4)), with n being the product type and g the percentage in the following product state (life cycle phase) categories: livestock ($g = 1$); raw materials ($g = 2$); intermediate products ($g = 3$); final goods ($g = 4$); and waste ($g = 5$).

$$\mathbf{S}_{n,g} = \begin{bmatrix} \mathbf{s}_{1,1} & \mathbf{s}_{1,2} \cdots & \mathbf{s}_{1,5} \\ \mathbf{s}_{2,1} & \ddots & \vdots \\ \vdots & & \mathbf{s}_{13134,5} \\ \mathbf{s}_{13135,1} & \mathbf{s}_{13135,2} \cdots & \mathbf{s}_{13135,5} \end{bmatrix} \quad (4)$$

$$\textit{with } n = 1, \cdots, 13{,}135 \textit{ types of products and } g = 1, \cdots, 5 \textit{ lifecycle phase of product}$$

Assumptions used when categorizing products according to this nomenclature are described in Rosado (2012). For example, the CN product type 87032190 (motor cars and other motor vehicles principally designed for the transport of persons) was identified as a final good.

Calculator

Materials Accounting

Modeling the mass balance of products in urban areas involves accounting for the amount of imports from outside the country and from other regions within the country, the extraction within the area, the exports to other countries or other regions within the country, and the outputs to the environment.

Domestic extraction is calculated using harvesting and production data of the urban area (e.g., agricultural production and industrial extraction), whenever available. If not available, estimation may be based on MFA national values (Eurostat 2001) weighted by the number of workers per economic activity and additional information, such as the relative purchasing power, as in Niza and colleagues (2009). In the LMA case, extraction numbers were obtained in the Portuguese statistical office (INE) because it is available at the NUTS 2 level. An exception to this was data for nonmetallic minerals that were available only at the NUTS 1 level from the industrial production statistics and also a few biomass-based products (e.g., fibers, wood, and hunting and gathering) that were available through Eurostat at the NUTS 1 level.

Transport statistics are used to measure imports and exports. These are Eurostat statistics available for 20 categories of products as classified by the NST nomenclature. For LMA, the accounting was based on intra- and international imports and exports by four transportation modes (road, rail, water, and air) at the NUTS 2 level. The calculation of the domestic material consumption (DMC) within the urban area for each of the 20 product categories defined in NST nomenclature ($\mathrm{DMC}_{\mathrm{nst}}$) considers the amounts of intra- (nat) and international (int) imported products (IMP), materials extracted within the urban area (DE), and intra- and international exported products (EXP), as shown in equation (5), where nst refers to each of the 20 product categories defined in the NST nomenclature.

$$\begin{aligned} \mathrm{DMC}_{\mathrm{nst}} &= \mathrm{DE}_{\mathrm{nst}} + \mathrm{IMP}_{\mathrm{nst,int}} + \mathrm{IMP}_{\mathrm{nst,nat}} - \mathrm{EXP}_{\mathrm{nst,int}} \\ -\mathrm{EXP}_{\mathrm{nst,nat}} &= \begin{bmatrix} \mathrm{de}_1 \\ \mathrm{de}_2 \\ \vdots \\ \mathrm{de}_{20} \end{bmatrix} + \begin{bmatrix} \mathrm{imp}_{1,\mathrm{int}} + \mathrm{imp}_{1,\mathrm{nat}} \\ \mathrm{imp}_{2,\mathrm{int}} + \mathrm{imp}_{2,\mathrm{nat}} \\ \vdots \\ \mathrm{imp}_{20,\mathrm{int}} + \mathrm{imp}_{20,\mathrm{nat}} \end{bmatrix} \\ &\quad - \begin{bmatrix} \mathrm{exp}_{1,\mathrm{int}} + \mathrm{exp}_{1,\mathrm{nat}} \\ \mathrm{exp}_{2,\mathrm{int}} + \mathrm{exp}_{2,\mathrm{nat}} \\ \vdots \\ \mathrm{exp}_{20,\mathrm{int}} + \mathrm{exp}_{20,\mathrm{nat}} \end{bmatrix} \end{aligned} \quad (5)$$

$$\textit{with nst} = 1, \cdots, 20 \textit{ categories of products}$$

After this operation is complete, $\mathrm{DMC}_{\mathrm{nst}}$ is converted into DMC_n, or DMC by CN product type (of the ITS, describing all traded products in an economy). This step allows for obtaining the DMC for 13,135 types of products. The conversion is accomplished by applying a mass percentage related to the sum of all CN product types that belong to each respective NST product category, as follows:

- for international trade (it): ratios are defined by the international trade (int), for imports (itsimp) and exports (itsexp);
- for intranational trade (nt): ratios are defined by the extraction (de), industrial production (np), and international trade (its). Intranational import ratios are calculated taking into account the mixture of products that are extracted, produced, and imported by the country (nat). Similarly, intranational export ratios are calculated taking into account the mixture of products extracted, locally produced, and exported by the country.

The following two equations, equations (6) and (7), present the conversion to CN product types for inter- and intranational trade imports in mathematical terms.

$$\text{impit}_n = \frac{\text{itsimp}_n}{\sum_{n\cap^{\text{nst}}}^{\text{itsimp}}} \times \text{IMP}_{\text{nst,int}} \tag{6}$$

$$\textit{with } n = 1, 2, \ldots, 13{,}135 \textit{ types of products } (CN)\,;\textit{nst} = 1, \ldots, 20 \textit{ categories of products } (NST)\,;\textit{int} = \textit{international imports}$$

$$\text{impnt}_n = \frac{\text{itsimp}_n + \text{np}_n + \text{de}_n}{\sum(\text{itsimp}_{n\cap^{\text{nst}}} + \text{np}_{n\cap^{\text{nst}}} + \text{de}_{n\cap^{\text{nst}}})} \times \text{IMP}_{\text{nst,nat}} \tag{7}$$

$$\textit{with } n = 1, 2, \ldots, 13{,}135 \textit{ types of products } (CN)\,;\textit{nst} = 1, \ldots, 20 \textit{ categories of products } (NST)\,;\textit{nat} = \textit{intranational imports}$$

Equation (8) provides the urban area's DMC of the 13,135 types of products in the CN (DMC_n).

$$\text{DMC}_n = \text{DE}_n + \text{IMP}_n - \text{EXP}_n = \begin{bmatrix} \text{de}_1 \\ \text{de}_2 \\ \vdots \\ \text{de}_{13135} \end{bmatrix} + \begin{bmatrix} \text{impit}_1 + \text{impnt}_1 \\ \text{impit}_2 + \text{impnt}_2 \\ \vdots \\ \text{impit}_{13135} + \text{impnt}_{13135} \end{bmatrix} - \begin{bmatrix} \text{expit}_1 + \text{expnt}_1 \\ \text{expit}_2 + \text{expnt}_2 \\ \vdots \\ \text{expit}_{13135} + \text{expnt}_{13135} \end{bmatrix} \tag{8}$$

$$\textit{with } n = 1, \cdots, 13{,}135 \textit{ types of products}$$

The product types in the CN include goods that are at different life cycle stages (e.g., raw materials, intermediate goods, and final goods). Thus, a fraction of the product types in DMC_n are final goods and another fraction is raw materials or intermediate products that are likely to be transformed by industry into final goods. The vector for material consumption of final goods (9,785 of the 13,135 types of products in the CN) is referred to as DMCfg. Local production data are used to simulate the processing of raw and intermediate goods into final goods. The result is the local production of final goods. This step is critical to (1) account for the materials that will constitute the material stock of the urban area (materials that will be used by the urban economy for more than 1 year) and (2) help close the mass balance with wastes and emissions.

Using the life cycle phase characterization matrix ($\text{S}_{n,g}$), as described in the section titled "*Life Cycle Phase*," and multiplying it by DMC_n converted into a diagonal matrix produces a matrix of product types in different life cycle phases (DMCsp; equation (9)).

$$\text{DMCsp}_{n,g} = \widehat{\text{DMC}_{n,n}} \times \text{S}_{n,g} = \begin{bmatrix} \text{dmc}_{1,1} & 0 \cdots & 0 \\ 0 & \ddots & \vdots \\ \vdots & & 0 \\ 0 & 0 \cdots & \text{dmc}_{13135,13135} \end{bmatrix} \times \begin{bmatrix} s_{1,1} & s_{1,2} \cdots & s_{1,5} \\ s_{2,1} & \ddots & \vdots \\ \vdots & & s_{13134,5} \\ s_{13135,1} & s_{13135,2} \cdots & s_{13135,5} \end{bmatrix} \tag{9}$$

$$\textit{with } n = 1, \cdots, 13{,}135 \textit{ types of products};\; g = 1, \cdots, 5 \textit{ lifecycle phase of products}$$

The Industrial Production Statistics (IPS) data set was used in order to determine the amount of nonfinal goods that are processed by the local industry. This data set is available at the NUTS 1 (national) level and uses the PRODCOM nomenclature. The PRODCOM nomenclature is used in IPS in Eurostat and provides data for mining and quarrying, as well as manufacturing activities (Eurostat 2013b). This nomenclature has a direct link not only with the NACE code for the economic activities, but also with the CN (Eurostat 2013b). Once the amount of nonfinal goods that are processed by the local industry is known, the ratio of the number of workers per four-digit NACE code is used to estimate the local production (LP) of each product type at the NUTS 2 level.

In equation (10), final goods that are locally produced and allocated to the urban area's domestic material consumption (DMClp) are estimated. These represent the fraction of the total final goods locally produced that correspond to the amount of nonfinal goods (including waste) in the split matrix (DMCsp) and the emissions for the local industrial sector (E). The amounts of industrial emissions and waste produced from the combustion of FFs were already established; this step provides a means of estimating the urban emissions from FF combustion, the solid fraction of wastewater, the embodied water in vegetables, and construction and demolition wastes (Niza et al. 2009) to complete the balance between material inputs, addition to stock, and outputs.

$$\text{DMClp}_{n,g=4} = \text{LP}_{n,g=4} \times \left(\frac{\sum_{n,g\neq 4}^{\text{DMCsp}}}{\sum_{n,g=4}^{\text{LP}} + \sum^{\text{E}}} \right) \tag{10}$$

with $n = 1, \cdots, 13{,}135$ *types of products*; $g = 1, \cdots,$ 5 *lifecycle phase of products*

The remaining local production of final goods is exported (EXPlp). The mathematical operations presented so far allow a material balance for a metropolitan area to be made. The urban area's domestic extraction (DE), intra- and international imports (IMP) and exports (EXP) (including waste), and emissions (E) are computed. A material balance with cross flows can be represented by equation (11).

$$\text{DE}_n + \text{IMPit}_n + \text{IMPnt}_n - \text{EXPit}_n - \text{EXPnt}_n - \text{E} = 0 \tag{11}$$

with $n = 1, \cdots, 13{,}135$ *types of products*

When local production is included, it is possible to isolate a partial fraction of the cross flows (EXPcf) and a more detailed material balance can be formulated (equation (12)).

$$\text{DE}_n + \text{IMPit}_n + \text{IMPnt}_n - \text{EXPlp}_n - \text{EXPcf}_n - \text{E} = 0 \tag{12}$$

with $n = 1, \cdots, 13{,}135$ *types of products*

The material balance provided by this method allows the accounting of several variables: (1) extraction within the urban area's borders; (2) imports and exports by origin (intra- or international) and by product type; 3) outputs to the environment; and (4) locally produced final goods by destination (consumption within the urban area's borders or export). Obtaining a measure of the cross flows is possible, partially addressing the seventh gap identified in table 1. For the amount of cross flows to be better understood, additional data sources need to be used to more rigorously identify, from the local production, the amount of exported nonfinal goods.

The identification and accounting of (1) the direct final goods, (2) the nonfinal goods that are transformed in the urban area, as well as (3) the identification of the amount of cross flows provides information about the supply chain in the urban area, hence addressing aspects of the fifth gap identified in table 1. Equation (13) allows for the final goods that are consumed within the urban area to be distributed among 28 material categories (MC). This is performed by multiplying the diagonal matrix of domestic material consumption of final goods (DMCfg) with the material composition matrix (M).

$$\begin{aligned}\text{MC}_{z,m} &= \widehat{\text{DMCfg}}_{z,z} \times \text{M}_{z,m} \\ &= \begin{bmatrix} \text{dmcfg}_{1,1} & 0 \cdots & 0 \\ 0 & \ddots & \vdots \\ \vdots & & 0 \\ 0 & 0 \cdots & \text{dmcgf}_{9785,9785} \end{bmatrix} \\ &\times \begin{bmatrix} \text{m}_{1,1} & \text{m}_{1,2} \cdots & \text{m}_{1,28} \\ \text{m}_{2,1} & \ddots & \vdots \\ \vdots & & \text{m}_{9784,28} \\ \text{m}_{9785,1} & \text{m}_{9785,2} \cdots & \text{m}_{9785,28} \end{bmatrix}\end{aligned} \tag{13}$$

with $z = 1, \cdots, 9{,}785$ *types of final goods and* $m = 1, \cdots,$ 28 *material categories*

Using this equation, it is possible to address the third gap (overly broad categorization of materials) in urban metabolism studies (by providing detailed material consumption for 28 material categories in the urban area).

Throughput Over Time

Twenty-eight materials throughput over time matrices (MTm, where m is material categories 1 through 28) are obtained by multiplying a diagonal matrix of the vector that represents each material from the final goods material category matrix (MCm, where m is material categories 1 through 28) by the final goods elements of the throughput matrix (T, as described in the section titled "*Product Lifespan*"). This final goods throughput matrix is referred to as $\text{T}_{z,y}$. In the LMA case study, a time frame $x = 40$ years was chosen to include the throughput dynamics of material stocks, including the stocks in infrastructures and buildings (on average, because, in some cases, they might have more than a 50-year lifetime). However, the model is flexible enough to provide the throughput dynamics for more or fewer years, depending on the user needs or the case study, as shown by equation (14).

$$\begin{aligned}\text{MTm}_{z,y} &= \widehat{\text{MCm}}_{z,z} \times \text{T}_{z,y} \\ &= \begin{bmatrix} \text{mcm}_{1,1} & 0 \cdots & 0 \\ 0 & \ddots & \vdots \\ \vdots & & 0 \\ 0 & 0 \cdots & \text{mcm}_{9785,9785} \end{bmatrix} \\ &\times \begin{bmatrix} \text{t}_{1,1} & \text{t}_{1,2} \cdots & \text{t}_{1,x} \\ \text{t}_{2,1} & \ddots & \vdots \\ \vdots & & \text{t}_{9784,x} \\ \text{t}_{9785,1} & \text{t}_{9785,2} \cdots & \text{t}_{9785,x} \end{bmatrix}\end{aligned} \tag{14}$$

with $z = 1, \cdots, 9{,}785$ *types of final goods*, $y = 1, \cdots,$ x *years and* $m = 1, \cdots, 28$ *material categories*

The computation of the materials throughput matrix described by equation (14) provides information that addresses the sixth gap (a lack of understanding about the dynamics of added stock).

Distribution by Economic Activity

The ITS provides the destination economic activities (AD) for each imported product. The UMAn model computes the distribution of products per economic sector using this data source, assuming that imports into the urban area from intranational trade have the same destination as international imports of the same type of goods. The distribution matrix (in percent) is described in equation (15), where *c* refers to the economic activities by the two-digit NACE code.

$$\mathbf{AD}_{z,c} = \begin{bmatrix} \mathbf{ad}_{1,01} & \mathbf{ad}_{1,02} \cdots & \mathbf{ad}_{1,99} \\ \mathbf{ad}_{2,01} & \ddots & \vdots \\ \vdots & & \mathbf{ad}_{9784,99} \\ \mathbf{ad}_{9785,01} & \mathbf{ad}_{9785,02} \cdots & \mathbf{ad}_{9785,99} \end{bmatrix} \quad (15)$$

$$\textit{with } z = 1, \cdots, 9{,}785 \textit{ types of final goods and } c = 01, \cdots, 99 \textit{ two digit NACE codes}$$

The two-digit NACE codes (01 to 99) encompass 55 different groups of economic activities (Eurostat 2013c). The bulk DMCfg vector, combined with the distribution of the different economic activities, creates the economic activity distribution matrix EA, which is described in mathematical terms in equation (16). This operation allows for describing economic activities in terms of their material consumption and their two-digit NACE code.

$$\begin{aligned} \mathrm{EA}_{z,c} &= \widehat{\mathrm{DMCfg}}_{z,z} \times \mathrm{AD}_{z,c} \\ &= \begin{bmatrix} \mathrm{dmcfg}_{1,1} & 0 \cdots & 0 \\ 0 & \ddots & \vdots \\ \vdots & & 0 \\ 0 & 0 \cdots & \mathrm{dmcfg}_{9785,9785} \end{bmatrix} \\ &\times \begin{bmatrix} \mathrm{ad}_{1,01} & \mathrm{ad}_{1,02} \cdots & \mathrm{ad}_{1,99} \\ \mathrm{ad}_{2,01} & \ddots & \vdots \\ \vdots & & \mathrm{ad}_{9784,99} \\ \mathrm{ad}_{9785,01} & \mathrm{ad}_{9785,02} \cdots & \mathrm{ad}_{9785,99} \end{bmatrix} \end{aligned} \quad (16)$$

$$\textit{with } z = 1, \cdots, 9{,}785 \textit{ types of final goods and } c = 01, \cdots, 99 \textit{ two digit NACE codes}$$

The allocation of the DMC to the different economic activities, coupled with the information about the amounts of products and respective original economic activity, provides additional information and helps to address the fourth (limited resolution of consumption by economic activity) and fifth (limited understanding of the origin and destination of flows) gaps.

Spatial Distribution

The spatial distribution matrix (SD) is a function of the mix of economic activities in the subareas (NUTS 3) within the urban area. The distribution of the material consumption per subarea is based on the assumption that there is a linear relationship between the number of workers per economic activity in each area and the total number of workers per economic activity at the NUTS 2 level (w_c), with *sa* referring to the NUTS 3 level subareas, as follows with equation (17).

$$\mathbf{sd}_{\mathbf{c},\mathbf{sa}} = \frac{\mathbf{w}_{\mathbf{c},\mathbf{sa}}}{\sum_{\mathbf{c}}^{\mathbf{w}}} \quad (17)$$

$$\textit{with } sa = 1, 2, \ldots, n \textit{ NUTS3 level areas}; c = 01, \cdots, 99 \textit{ two digit NACE codes and } w = \textit{number of workers}$$

The spatial distribution matrix (SD) is depicted in equation (18).

$$\mathbf{SD}_{c,sa} = \begin{bmatrix} \mathbf{sd}_{01,1} & \mathbf{sd}_{01,2} \cdots & \mathbf{sd}_{01,v} \\ \mathbf{sd}_{02,1} & \ddots & \vdots \\ \vdots & & \mathbf{sd}_{98,v} \\ \mathbf{sd}_{99,1} & \mathbf{sd}_{99,2} \cdots & \mathbf{sd}_{99,v} \end{bmatrix} \quad (18)$$

$$\textit{with } sa = 1, 2, \ldots, v\textit{NUTS3 level areas} \\ \text{(where } v \text{ is the total number of NUTS3 level areas)}; \\ c = 01, \cdots, 99 \textit{ two digit NACE codes}$$

The distribution of materials per subarea ($\mathrm{MSD}_{z,sa}$) is obtained through equation (19) (using the first NUTS 3 level area as an example).

$$\begin{aligned} \mathrm{MSD}_{z,1} &= \mathrm{EA}_{z,c} \times \mathrm{SD}_{c,1} \\ &= \begin{bmatrix} \mathrm{ea}_{1,01} & \mathrm{ea}_{1,02} \cdots & \mathrm{ea}_{1,99} \\ \mathrm{ea}_{2,01} & \ddots & \vdots \\ \vdots & & \mathrm{ea}_{9784,99} \\ \mathrm{ea}_{9785,01} & \mathrm{ea}_{9785,02} \cdots & \mathrm{ea}_{9785,99} \end{bmatrix} \\ &\times \begin{bmatrix} \mathrm{sd}_{01,1} \\ \mathrm{sd}_{02,1} \\ \vdots \\ \mathrm{sd}_{99,1} \end{bmatrix} \end{aligned} \quad (19)$$

$$\textit{with } z = 1, \cdots, 9{,}785 \textit{ types of final goods}; c = 01, \cdots, 992 \textit{ digit level NACE code}$$

The spatial distribution complements the previously described variables and helps address the second (lack of material flow data at the urban level), fourth (limited resolution of consumption by economic activity), and fifth (limited understanding of the origin and destination of flows) gaps.

UMAn is summarized graphically in figure 1 and applied to the LMA in the next section.

Case Study: Lisbon Metropolitan Area

The LMA is legally defined as an association or a form of intermunicipality cooperation (Nunes Silva and Syrett

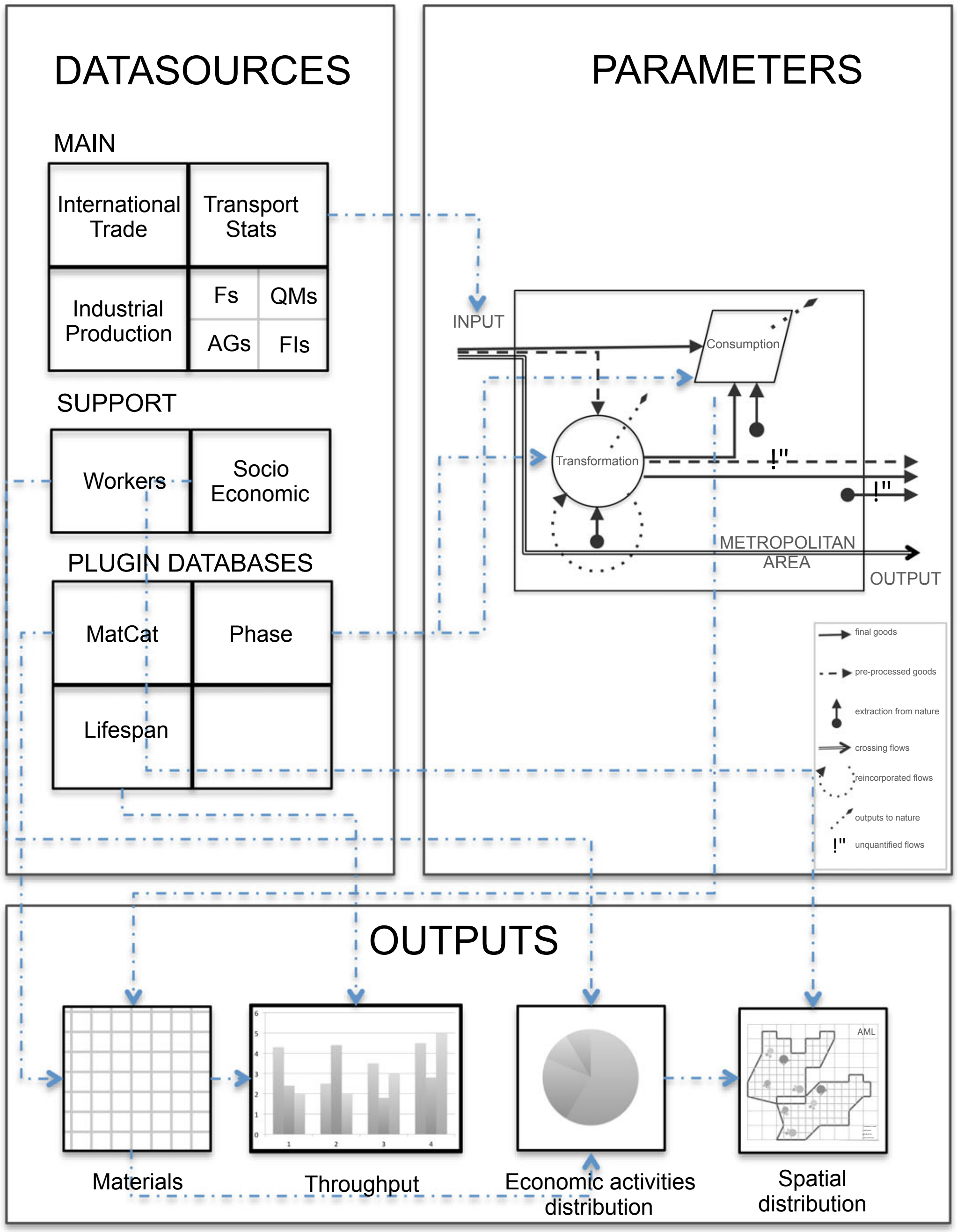

Figure 1 Urban metabolism model main features and interactions. Fs = forestry statistics; QMs = quarry and mining statistics; AGs = agriculture statistics; FIs = fisheries statistics; workers = number of workers data; socioeconomic = socioeconomic data about population and relative purchasing power; MatCat = material categories; phase = Stage in the life cycle.

2006), comprising the nine municipalities of Lisbon district, north of the Tagus River (Amadora, Cascais, Lisbon, Loures, Mafra, Odivelas, Oeiras, Sintra, and Vila Franca de Xira), and the nine municipalities of Setúbal district, south of the Tagus River (Alcochete, Almada, Barreiro, Moita, Montijo, Palmela, Sesimbra, Setúbal, and Seixal). In figure S1 in the supporting information available on the Journal's website, a map of the LMA and the municipalities' locations is provided.

The LMA covers 2,957.4 square kilometers, which represents 3.3% of Portugal's area, but its nearly 3 million inhabitants represent around 30% of the Portuguese population (INE 2013). It is a highly attractive pole of economic activity and employment, assuming a central role on the international activities of the country (CML 2005).

Some of the municipalities are densely populated, such as Lisbon with 547,733 inhabitants in 2011, Sintra with a population of 377,835, Loures with a population of 205,054, and

Amadora with a population of 175,136. Other municipalities are almost rural, such as Montijo with a population of 51,222 and Alcochete with a population of 17,569.

Data

Where possible, data were gathered for the period 2003–2009 (see the Supporting Information on the Web). Data for transport statistics, domestic extraction, and almost all waste and emissions were available at the NUTS 2 level for the entire study period, but detailed information on industrial waste produced from 2003 to 2007 was not available. In this case, estimates were made based on 2008 values, and ratios for each type of waste in 2008 were applied to the total industrial waste produced in the LMA from 2003 to 2007.

Results

An MFA balance was made for the period 2003–2009 (on an annual basis) and the UMAn model was applied to produce values for materials accounting, throughput over time, distribution by economic activity, and spatial distribution. A comparison between the results for the LMA with the results from other urban regions was also performed.

Table 3 presents the DMC in the LMA, in 28 material categories. Dividing the materials into more than a handful of categories addresses gap 3 (limited discrimination of material types). Total DMC varies from approximately 22.5 million metric tons (tonnes) in 2003 to approximately 30 million tonnes in 2007, decreasing to 21.5 million tonnes in 2009. Approximately 45% of these materials were directly consumed (final goods), whereas the remaining had to undergo transformation before final consumption.

Figure 2 shows the LMA material balance in 2005 and gives consumption, changes in stocks, and outputs to the environment. Nonmetallic minerals represent the main fraction of materials in both the overall input flows (50%) and the addition to the stock (more than 80%). Biomass and FFs are the second- and third-most relevant input materials. The second-most important material category added to stock is metallic minerals.

As described in the section titled "*Calculator*," the model provides more detailed information than can be shown in figure 2. For instance, in the case of the LMA, the most important fraction of the domestic processed output is the carbon incorporated in emissions (50%), followed by dissipative flows (21%) and municipal (MSW) and industrial (IW) solid wastes (18%). Recycling represents only about 17% of the total solid wastes (MSW, IW, and construction wastes) produced in 2005.

For the input flows and increase in stock, most of the nonmetallic mineral material category is made up of stone, cement, and sand. The most important subcategories in each of the other major material categories—FFs, metallic minerals, and biomass—are as follows:

- Low ash fuels are the most important material in the FFs category (66%).
- Food, comprising agricultural and animal biomass, is the most relevant category of biomass consumption (67%), although wood and fuels, and paper and board, also have significant values.
- Iron and steel (75%) is the dominant metallic mineral category consumed.

In summary, the LMA has been consuming a large amount of construction minerals, although decreasing in the last couple of years. Additionally, nondurable goods, such as fuels and food, are consumed in large amounts, which has implications for immediate effects on atmospheric pollution and wastewater management. Less-significant amounts are associated with durable goods, particularly iron- and steel-based products that will have an effect on waste management in the future as a result of the accumulation in the material stocks in the LMA.

Overall, material consumption patterns were relatively stable from 2003 to 2009, without significant changes in the share of materials consumed, even though the total DMC varies from year to year. In 2008 and 2009, there was a slight gain in the relative weight of biomass consumed and a reduction in consumption of nonmetallic minerals. This is mainly the result of a reduction in the consumption of construction minerals. In fact, in 2008 and 2009, there was a significant reduction of finished new buildings along with an overall reduction in construction activities (INE 2012a).

The throughput dynamics was performed using the materials throughput matrix of the UMAn model, as described in the section titled "*Throughput*" (see figure 3). This analysis allows, for instance, prioritizing recovery goals for particular material types. According to the results, there are three main periods where three different material categories are more relevant in terms of potential amounts available for recovery:

- From 2010 to 2013: Products put into place between 2003 and 2009 that are FF based, such as oils and plastic, are retired and this material category comprises the bulk of the recyclable material flow for all products put in place during the 2003–2009 time frame.
- From 2015 to 2027: The retirement of products put into place between 2003 and 2009 that contain metallic minerals results in metallic minerals being the single largest contributor to the total recyclable material flow for products put into place during the 2003–2009 time frame, with two major peaks (2019 and 2024).
- From 2034 on: A steady increase in the retirement of products put into place between 2003 and 2009 that contain nonmetallic minerals is observed. This phenomenon expectedly extends beyond the studied time frame (2050), considering the average durability of products they are part of (e.g., buildings and infrastructures).

The dynamics shows a delay of approximately 40 years before the amount of recyclable materials from products put into place during the 2003–2009 time frame peaks. Nevertheless, even now, approximately 1 million tonnes of durable goods currently produced are potentially available for recovery every

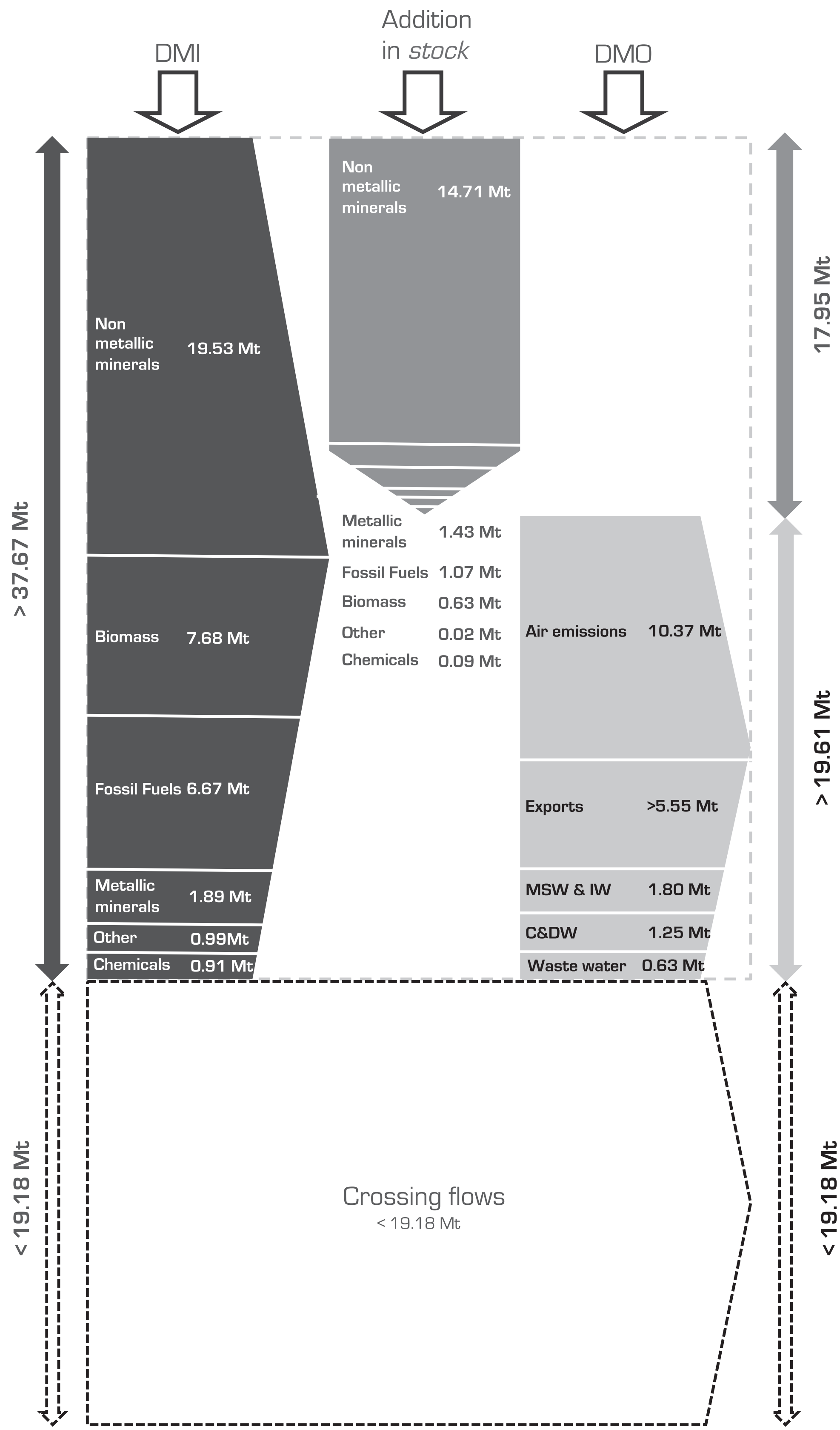

Figure 2 Lisbon metropolitan material balance in 2005 (million tonnes [Mt]). DMI = direct material input; DMO = direct material output; MSW = municipal solid waste; IW = industrial solid waste; C&DW = construction and demolition waste.

Table 3 Domestic material consumption (DMC) in the Lisbon Metropolitan Area by material type, 2003–2009 (tonnes)

Material type	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Fossil fuels	4,079,318	5,287,823	5,119,690	5,077,145	5,598,891	4,160,923	3,903,699
Low ash fuels	2,902,294	3,754,826	3,671,344	3,889,124	4,234,317	2,993,937	2,851,537
High ash fuels	63,608	80,611	76,450	64,472	82,092	68,769	60,028
Lubricants, oils, and solvents	759,929	1,026,142	960,439	779,512	864,702	632,509	589,720
Plastics and rubbers	353,487	426,245	411,457	344,036	417,780	465,708	402,413
Metallic minerals	1,182,147	1,470,121	1,451,358	1,216,415	1,517,376	1,386,880	1,331,120
Iron, steel alloying metals, and ferrous metals	942,265	1,164,525	1,147,964	967,148	1,222,615	1,128,539	1,089,759
Light metals	122,892	160,167	162,607	130,787	160,023	131,553	127,517
Nonferrous heavy metals	116,550	144,938	140,323	118,077	134,255	126,160	113,337
Special metals	178	191	189	176	178	144	108
Nuclear fuels	0	0	0	0	0	0	0
Precious metals	261	300	274	228	305	484	398
Nonmetallic minerals	11,333,136	14,741,514	14,986,825	11,555,696	13,330,229	10,273,891	9,797,489
Sand	2,350,048	2,898,132	2,937,254	2,378,742	2,809,036	2,201,522	2,098,193
Cement	3,356,985	4,582,288	4,403,630	3,445,443	4,006,820	2,965,621	2,826,160
Clay	284,761	405,396	398,314	343,934	332,641	248,341	209,910
Stone	5,229,855	6,724,408	7,132,545	5,287,833	6,073,049	4,776,258	4,586,991
Other (fibers, salt, or inorganic parts of animals)	111,487	131,290	115,083	99,745	108,683	82,148	76,236
Biomass	4,440,472	6,122,273	5,895,012	5,235,836	6,319,711	5,773,912	5,338,623
Agricultural biomass	2,820,204	3,880,939	3,739,594	3,415,599	4,125,989	3,450,340	3,150,388
Animal biomass	383,247	520,953	535,458	489,769	611,233	518,747	487,599
Textile biomass	72,230	86,716	84,378	67,772	87,639	102,180	90,858
Oils and fats	149,679	242,322	178,803	160,416	177,291	141,279	144,176
Sugars	153,417	209,636	213,307	182,972	237,976	193,906	185,959
Wood and fuels	347,033	541,997	502,174	425,085	516,073	374,823	410,647
Paper and board	509,777	631,178	633,211	488,253	556,883	977,971	857,992
Nonspecified biomass	4,885	8,531	8,087	5,971	6,627	14,665	11,004
Chemicals and fertilizers	625,959	775,855	699,990	538,199	654,158	543,464	506,922
Alcohols	15,335	21,253	21,748	18,829	24,014	19,826	18,907
Chemicals and pharmaceuticals	167,038	201,765	207,061	163,036	208,092	193,884	173,807
Fertilizers and pesticides	443,585	552,837	471,181	356,334	422,052	329,754	314,208
Other	877,989	1,297,870	757,693	692,093	1,686,237	741,929	676,796
Nonspecified	438,784	641,068	89,210	106,713	929,821	131,116	106,475
Liquid	439,205	656,802	668,483	585,380	756,417	610,813	570,320
Total	**22,539,021**	**29,695,457**	**28,910,566**	**24,315,384**	**29,106,603**	**22,880,999**	**21,554,650**
Tonnes per capita	**8.23**	**10.76**	**10.40**	**8.70**	**10.36**	**8.12**	**7.61**

year. When compared to the amounts of wastes from durable goods recovered in 2005 (approximately 600,000 tonnes, according to the Urban Waste Statistics of INE for 2005; INE 2012b), approximately 400,000 tonnes of materials could still potentially be recovered in the region. These results illustrate how the UMAn model addresses gap 6 (the lack of understanding about the dynamics of added stock).

The next step is allocating the materials to different economic activities by creating the economic activity distribution matrix (equation (16)). The results given in table 4 demonstrate the ability of the model to address gap 4 (the limited resolution of consumption by economic activity). The economic activities of retail and wholesale trade consume the largest share of materials—approximately 15 million tonnes—followed by manufacturing activities, with more than 7 million tonnes (mostly FFs and nonmetallic minerals). The third-largest consumer of materials is construction, with approximately 3 million tonnes. The attribution of material consumption into different economic activities may provide valuable information to assess the resilience of the metropolitan area while providing information on the amounts of materials needed to supply the population and the regional economy. Additionally, if this allocation is coupled with information on the spatial distribution of consumption, allowing the identification of areas where specific materials are concentrated, it may unveil different dimensions of centrality within the LMA (see table 4). By

Table 4 Domestic material consumption (DMC) per economic activity and municipality of the Lisbon Metropolitan Area, 2005

	DMC by statistical classification of economic activities (NACE) 1.1 category (tonnes)													*DMC per person (tonnes per capita)*	*End Use DMC per person (tonnes per capita, weighted by relative purchasing power)*
Municipality	*A+B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L+M*	*N*	*O+P+Q*		
Alcochete	348	0	21,823	4,894	25,578	90,213	394	47	37	2,350	114	65	258	10.4	10.7
Almada	67	0	65,623	17,195	157,143	584,923	3,394	1,999	460	15,155	14,545	1,006	3,784	5.7	9.7
Amadora	23	0	292,192	11,302	220,787	829,766	2,132	1,910	955	13,274	11,991	1,455	3,472	8.7	8.4
Barreiro	0	0	229,749	23,561	44,668	254,122	877	2,117	182	5,693	866	327	2,430	7.8	8.7
Cascais	301	0	382,638	15,196	202,748	927,599	5,893	2,797	1,012	31,044	2,961	1,218	10,420	9.4	11.9
Lisboa	647	149,446	1,491,191	411,195	800,340	4,998,151	32,445	106,797	28,468	217,971	173,806	6,845	40,278	17.3	16.3
Loures	236	0	330,837	103,738	230,613	1,475,112	2,117	6,625	717	19,303	3,291	511	6,087	12.0	8.6
Mafra	241	0	96,601	4,360	77,671	322,439	938	748	255	5,111	1,176	264	1,083	8.3	8.2
Moita	186	0	31,308	1,550	56,219	124,126	431	284	119	2,557	390	185	1,101	3.3	6.8
Montijo	937	0	51,870	1,779	48,643	249,937	686	592	120	5,178	3,199	273	1,379	9.8	10.0
Odivelas	75	0	226,302	2,007	151,705	532,127	1,553	1,119	304	7,042	1,882	281	2,174	6.8	7.5
Oeiras	229	0	438,400	18,322	244,040	1,526,633	3,591	8,539	1,370	33,564	180,698	770	9,828	15.8	13.1
Palmela	596	0	1,010,402	2,314	90,760	349,755	710	832	104	2,914	1,330	258	1,425	26.2	8.2
Seixal	65	0	469,869	4,724	183,246	483,741	1,494	1,354	315	9,922	1,402	412	2,831	7.1	8.1
Sesimbra	67	0	238,304	1,261	90,873	90,133	744	367	94	9,376	314	210	692	4.6	8.4
Setúbal	313	91,967	407,247	95,764	98,749	517,724	2,042	3,626	420	13,722	3,753	742	2,802	9.3	9.1
Sintra	456	0	1,689,786	11,554	419,372	1,802,344	4,967	4,116	1,249	33,460	5,097	1,285	5,901	6.2	7.8
Vila Franca de Xira	326	0	139,371	9,465	137,078	658,837	1,452	2,741	460	11,580	2,587	495	2,163	6.8	8.3
TOTAL	5,111	241,413	7,613,513	740,180	3,280,231	15,817,683	65,860	146,612	36,641	439,215	409,399	16,602	98,107		

Notes: A+B = agriculture, hunting, and forestry plus fishing; C = mining and quarrying; D = manufacturing; E = electricity, gas, and water supply; F = construction; G = wholesale and retail trade and repair of motor vehicles, motorcycles, and personal and household goods; H = hotels and restaurants; I = transport, storage, and communication; J = financial intermediation; K = real estate, renting, and business activities; L+M = public administration and defense and compulsory social security plus education; N = health and social work; O+P+Q = other community, social, and personal service activities plus activities of households plus extraterritorial organizations and bodies.

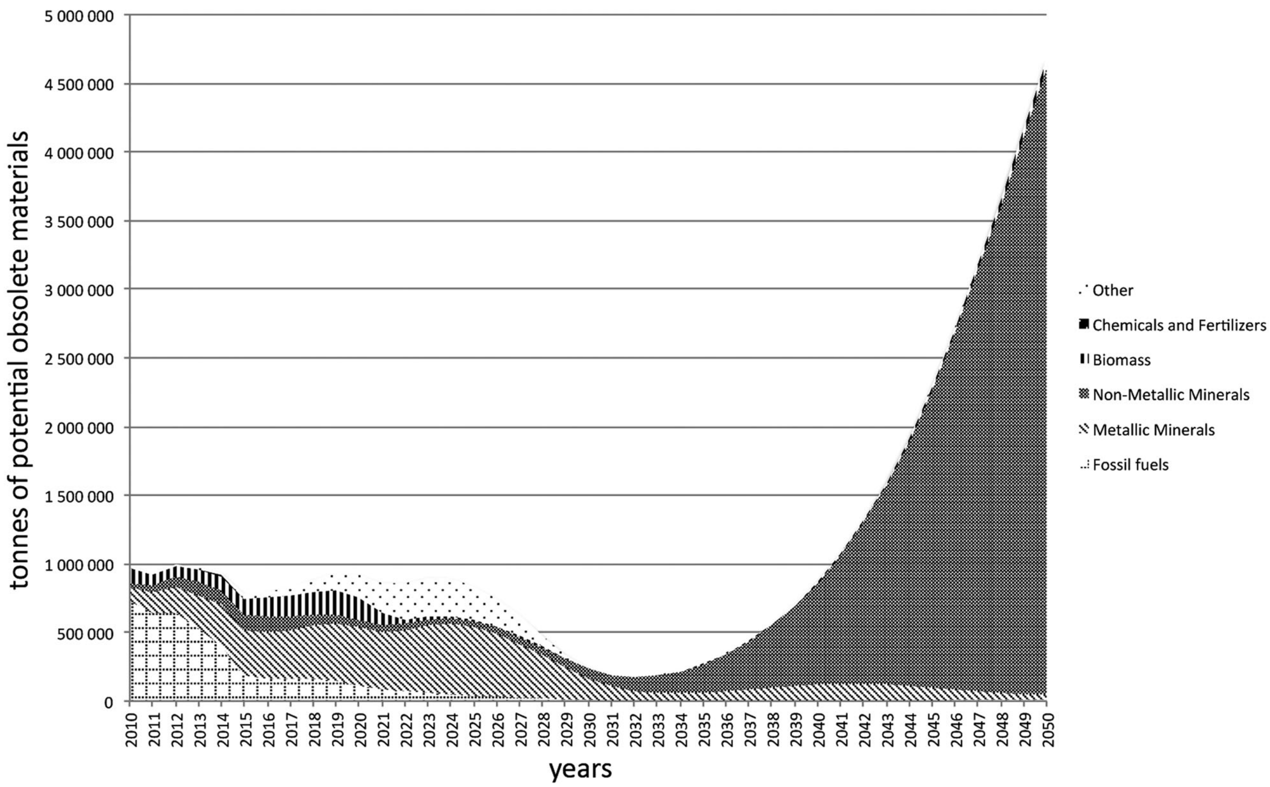

Figure 3 Throughput dynamics of materials that entered the Lisbon Metropolitan Area from 2003 to 2009 (tonnes).

incorporating the spatial distribution into the analysis (equation (19)), it can be seen that there is a large variation of the material consumption between the different municipalities in the LMA. There is a clear difference between the Lisbon district (the northern portion of the LMA), where the largest fraction of materials is consumed, whereas the Setúbal district (the southern portion) consumes very low material quantities, as would be expected because of the large difference in the populations of the two areas. According to the census data provided by INE in 2011 (INE 2013), the Lisbon district had 2.25 million inhabitants and the Setúbal district 0.85 million inhabitants.

In per capita terms (see table 4), there is also a significant difference in DMC from one municipality to another, ranging from a minimum of 3.3 tonnes per capita in the Moita municipality to 26.2 tonnes per capita in Palmela. DMC in the municipality of Lisbon is 17.3 tonnes per capita. The difference between per capita values for the different municipalities is not as large when end-use DMC per capita values are compared; these values are weighted by the relative purchasing power of the inhabitants for each municipality in the context of the total purchasing power of the LMA. End-use DMC values range from 6.8 tonnes per capita in Moita to 16.3 tonnes in Lisbon.

Further, looking at the concentration of materials in the economic activities, three examples can be highlighted—Lisbon, Loures, and Palmela municipalities. In all three, the materials allocated to the economic activities greatly surpasses the material consumption allocated to the population, suggesting that these municipalities are potentially the main suppliers of materials within the LMA. Some facts may support this hypothesis, namely:

- The main regional wholesale market (MARL 2012) is located in Loures.
- Palmela, though an important agricultural area, is also important in terms of industry and infrastructure. The biggest automobile manufacturing cluster in the country exists in the region and important transportation infrastructure has been recently built, particularly the Lisbon-Palmela-Setúbal railway (Florentino and Nascimento 2009). This area will also be the future location of LOG Z, a third generation logistics platform (logz 2012).
- Lisbon is the capital city of Portugal, with many jobs and a large number of commuters (Niza et al. 2009), hence boosting the need for a higher concentration of economic activities to accommodate their consumption needs.

Though results from studies with different methods should be interpreted with caution, the numbers calculated for the LMA are within the range of values calculated for other European metropolitan areas, as shown in table 5. This table shows that per capita consumption estimates in the LMA are larger than the average of the table's studies for biomass and lower than average for metallic minerals. Also, these results indicate that the LMA is the lowest consumer of FFs and the highest consumer of biomass of the metropolitan

Table 5 Comparison of estimates of types of materials consumed in several metropolitan areas (tonnes/person)

	Material category					
			Minerals			
City/region	*Biomass*	*Fossil fuels*	*Metallic*	*Nonmetallic*	*Nonspecified*	*Total*
Lisbon Metro (DMC 2005)	2.12	1.84	0.52	5.39	0.53	**10.40**
York region (2000)[a]	1.01	3.26	0.15	7.51	0.01	**11.94**
Greater London (2000)[b]	1.65	2.05	0.13	3.91	0.73	**8.47**
Hamburg Metro (DMC 2001)[c]	2.05	4.29	6.00		– 0.24[d]	**12.10**
Vienna Metro (DMC 2003)[c]	1.12	2.61	5.10		0.38	**9.20**
Average value for these studies	1.59	2.81	5.74		0.28	**10.42**

[a]Barret and colleagues (2002);
[b]BFF (2002);
[c]Hammer and Giljum (2006).
[d]As explained by Hammer and Giljum (2006), note 7 in page 19, the existence of a negative value can be explained by the relatively large chemical and cosmetic industry in the Hamburg area that transforms raw materials accounted for in the major material classes, but exports large amounts of these types of products that are assigned to a nonspecified material category.
Note: DMC = domestic material consumption.

areas in this table. The difference in FF consumption might be explained by the fact that stronger economies, such as Germany and the United Kingdom, usually tend to consume more FFs (e.g., to feed industries), whereas transitional economies, such as Portugal (Niza and Ferrão, 2006), tend to consume relatively more nonmetallic minerals (for construction) and biomass.

In contrast to the other metropolitan area studies whose results are summarized in table 5, the UMAn model disaggregates the broad material categories so that more-specific estimates of the types of materials consumed is available, as shown in table 3. Further, none of the metropolitan area studies other than the UMAn LMA study provide an estimate of the changes in material stocks. Also, for the studies other than the UMAn LMA study, there is very little information about where in the metropolitan area the material flows occur (e.g., the Vienna, Hamburg, and Paris studies separated the study area into up to three concentric rings around the urban core). In addition, the studies other than the UMAn LMA study provided only highly aggregated estimates about the allocation of material consumption to economic activities (e.g., the York study assigns material flows to three categories of economic activity, whereas the UMAn model assigns material flows to more than a dozen categories of economic activity).

One test of the model's reliability is whether the estimates provided by the model result in a material balance for the region as a whole. For the LMA case study, the material input and output estimation is within 3.3% of closing the balance. In other words, the model's estimate of net addition to stocks accounts for nearly all of the difference between direct material input and direct material output. Further, when comparing estimations of FF produced by the model with direct data for sales of FFs from the Energy Directorate (DGEG 2013) the difference is approximately 1.2% for the overall period.

Conclusions

This article describes an urban metabolism model (UMAn) supported by a set of methodological approaches to promote standardization and harmonization of urban metabolism studies within the EU. This model addresses several methodological gaps that were identified in previous studies by:

- Adapting the economy-wide MFA method standardized and promoted by Eurostat and the OECD. A new MFA method adapted to urban areas is successfully achieved, taking advantage of available statistical information, more easily overcoming problems with data gathering, and allowing for standardization on urban areas.
- Allowing the disaggregation of overall material flows into more detailed material categories, economic activities and spatial areas. These features represent an innovation in not just urban metabolism models, but also MFA methods.
- Depicting more accurately the supply chain of goods and products. One of the greatest challenges for an urban-area MFA relates to the difficulty in determining the life cycle phase of each product flowing within the boundaries of the economy, hence causing eventual double-counting issues. Though researchers producing studies at the scale of a nation can track down the origin, extraction, and imports of materials, for metropolitan areas this is more difficult because of the lack of clear administrative boundaries and also life cycle double-counting problems. By tracking down intra- and international transportation movements in and out of the urban area, attributing a life cycle state to products, and simulating the local production of final goods, the UMAn model avoids double counting of materials in the urban area. This approach to LCA is possible because of the creation of three plug-in databases that

were built for this model. These plugins provide information on material composition, product lifespan, and life cycle phase.
- Performing a material balance for the urban area by comparing the sum of imports, domestic extraction, and local production to the sum of the accumulation of material stocks, exports, and wastes and emissions. This allows, to a certain extent, understanding the magnitude of cross flows (and the real exports of materials) that occur in the urban area, though it was not possible to fully separate exports of locally extracted and produced goods from the exports of imported goods.

To explore and validate the proposed model, the LMA was used as a case study.

A comparison shows that overall values obtained by the UMAn model for the LMA are consistent with the values obtained by several metropolitan metabolism studies that rely on other approaches. Additionally, a material balance around the LMA corroborates the model's reliability because the difference between inputs, stocks, and outputs is approximately 3.3%. Finally, the model's estimate of the flow of FFs is within 1.2% of the value provided by an independent data source.

The application of the model to other metropolitan areas (namely, some of those already studied such as Vienna, Paris, or Hamburg) will be an important step to test the model and potentially establish a standard method to assess urban (metropolitan) metabolism. Further research is needed to fully understand the factors that drive the uncertainty of results and decrease the gap in closing the material balance. Also, further work is needed to detail the quantification of the cross flows by fully distinguishing them from the exports of goods extracted and produced locally.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Supporting Information S1: This supporting information provides information on the data sources used to apply the UMAn model to the Lisbon Metropolitan Area (LMA) as well as a map of the municipalities in the LMA.