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# The physical structure of urban economies — Comparative assessment

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ABSTRACT

Urban metabolism provides a characterization of anthropogenic material flows in urban systems and should contribute to identify the economic activities that were involved on their supply and transformation. Typically, its quantification requires data that is not easily available in different geographies. This paper makes use of a methodology based on monetary input–output tables and international trade statistics that might be easily replicable to many metropolitan areas in the world, and which is intended to provide a first rough estimation of urban material flows.
The paper discusses the results obtained for four metropolitan areas (Lisbon, Paris, Seoul–Incheon and Shanghai), assessing the material requirements of these economies. The urban areas are compared in terms of the quantity and the type of material input, destination of materials within the economy and their distribution among economic activities. The results showed that while Lisbon is the most diverse urban area in terms of the consumption of material types, it is also the urban area with the least diversified manufacturing sector.
The application of this methodology to several urban areas and across multiple years enables the assessment of the technological and economic evolution of those regions.


## 1. Introduction

As urban expansion and new patterns of economic activity have fed on each other, novel configurations for urban areas have emerged, such as mega urban regions, urban corridors and city-regions. Currently, urban areas account for over 48% of the global GDP (Metro Monitor, 2011), with many of these cities having become centers of international trade and commerce and hubs for regional and international connectivity. While the complexity of national economies and their resource use has been assessed in terms of how they relate with future growth prospects (Hausmann and Hidalgo, 2014; Bringezu et al., 2004), this is not the case for urban areas, mainly due to data constraints concerning resource use in cities.

Though cities are recognized as engines of growth, they are also the key drivers for stronger and more relevant global environment–economy interactions (Seto and Satterthwaite, 2010). For instance, urban sustainability concerns have been focusing on water, energy and mobility systems (Bos and Brown, 2012; Graaf and Brugge, 2010; Spickermann et al., 2014; Karaca et al., 2015; Dixon et al., 2014; Marteleira et al., 2014), in terms of quality, security of supply and impacts. However, it is also critical to address the material use. During their development stages, cities encourage or discourage the development of particular economic activities within their boundaries, and at each stage this defines their signature (typology), including jobs, economic output (Spence et al., 2009), their dependence on material resources from elsewhere and, depending on how they process them, their impact on the environment (Kennedy et al., 2007).

The quantification of the requirements of materials to support human activities in cities, and assessing the implications

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of their transformation, including the removal and disposal of waste, is known as the urban metabolism (Wolman, 1965), as a parallel to the metabolisms of ecological systems. To fully describe the metabolism of a city, several factors need to be considered: anthropogenic and natural physical inputs of materials, the transformation of those inputs through urban activities, additions to the stocks and dispersion of wastes beyond the spatial boundaries of the urban systems (Niza et al., 2009).

Progress towards urban sustainability will then depend, at least in part, on the reduction of resource input on the one hand and the further reduction of pollutant output on the other hand. Since material flows through the anthroposphere connect both of those ends, Material Flow Analysis (MFA) methods offer considerable potential assessing the path towards sustainability (Bringezu, 1999). The metrics provided by this type of approach may contribute to understand how natural resources uses correlate with urban economic activities and can enable the definition of priorities for action towards decreasing the pressure cities exert on the environment.

While a significant body of research has been dedicated to the metabolism of countries (Schandl et al., 2009; Wiedmann et al., 2013; Steinberger et al., 2010; Weisz et al., 2006), only a small fraction has been dedicated to the metabolism of urban areas. Furthermore, they are generally applied to a small set of urban areas as they require very detailed and specific data which is not commonly available (e.g., (Niza et al., 2009; Barles, 2009; Schulz, 2007; Hammer and Giljum, 2006; Barrett et al., 2002)). As such, it becomes very difficult to compare the results obtained for different cities, limiting the conclusions that can be drawn from these studies.

This work is based on further developments on urban metabolism quantification methods (Niza et al., 2009; Rosado et al., 2013) in order to enable for material consumption allocation through urban economic activity sectors, making use of monetary input–output tables available at a national or regional level, and scaling them down to the urban scale.

The metabolism of metropolitan areas in Europe (Lisbon and Paris) and Asia (Seoul–Incheon and Shanghai) is measured in order to assess the physical structure of these economies. Urban systems are compared in terms of total and type of material input, destination of material inputs within the economy and within the manufacturing sectors.

## 2. Methodology

The physical structure of an urban economy is described by the material throughput of that economy. These flows can be organized in: inputs — domestic extraction of resources, imports of raw materials and products; consumption — intermediate and final consumption; addition to stock — accumulation of materials in the system; outputs — emissions and wastes, exports of raw materials and products.

The structure of statistical records does not generally include data at urban level; consequently the accounting involves estimating values from existing data, usually at higher scales (namely regional or country level). Niza et al. (2009) and Rosado et al. (2013) developed a method to account and disaggregate urban flows using data produced for several scales. The method is based on EUROSTAT's economy-wide material flow accounting (EUROSTAT, 2001), and requires detailed statistics, particularly at the urban area level (e.g., metropolitan area), such as international trade statistics: to the urban area; transport statistics: within the urban area and between the urban area and other regions of the country; industrial production statistics; mineral extraction; agricultural harvest; forestry; fisheries; industrial waste; municipal solid waste and emissions. While some of these statistics are available for different urban areas around the world, transport statistics are not easily available, making it difficult to know which materials and products are imported from the rest of the country.

These constraints constituted the motivation for developing a new method based on national or regional monetary input–output tables. These tables are organized in most countries by national statistical offices following conventions laid down by the System of National Accounts (SNA) for compilation of statistical economic data. According to the SNA the economy is organized as a set of institutional sectors, legal entities with liabilities of physical assets which engage in transactions. Critical institutional sectors are households, government and firms. In this work, IO tables provided by OECD,[1] for their member countries and 15 other countries, were used. For each country, both domestic and import tables were used, to better reflect the flows of mass and money from other countries' economic sectors to the national economy and also within the national economy. Generally, these tables were published for the years 1995, 2000 and 2005 and describe transactions between 37 economic sectors.

All institutional sectors purchase commodities, also known as goods and services, while firms, organized as activities or economic sectors also produce commodities. Activities also purchase primary factor services, such as labor and capital, which in turn are used by institutional sectors. Finally, there are transactions between different institutional sectors in the domestic economy and also between them and the rest of the world.

The estimation of the urban metabolism through the streamlined UM model proposed in this paper comprises 5 main steps:

1. Estimation of material extraction and imports/exports of products at the national scale;
2. Allocation of the products and materials to the economic sectors that produce them;
3. Decomposition of products and materials to 28 material categories;
4. Calculation of the flow of materials across economic sectors using input–output tables and estimating the mass content for each material and sector (kg per monetary unit);
5. Downscaling results to the urban area through scaling factors.

### 2.1. Estimating domestic extraction and import/exports

The quantification of material flows at the national level is based on domestic extraction and trade statistics. For the domestic extraction, databases like Eurostat, Material Flows[2] and FAO[3] were used. Domestic extraction was characterized for 268 raw materials. Each was assigned a code based on the

[1] http://www.oecd.org/trade/input-outputtables.htm, accessed March 2013.
[2] www.materialflows.net, accessed March 2013.
[3] http://faostat.fao.org/, accessed March 2013.

HS96[4] nomenclature, to be used further on in the allocation of products to economic sectors and allow the conversion of products to material categories. For imports and exports the UN Comtrade[5] database was used, which reports the monetary value and weight of each product traded between two countries. The HS96 nomenclature was used to categorize products.

### 2.2. Allocation of products to production sectors

The allocation of products (of domestic extraction and imports/exports statistics) to the sectors that produced them allows identifying through which sector did those products entered the economy (in the case of domestic extraction and imports) or exited it (in the case of exports). This allocation is performed using correspondence tables linking commodities (expressed in SITC,[6] EW-MFA,[7] HS or CN[8] nomenclatures) to economic activities (expressed in nomenclatures such as ISIC[9] and NACE[10]). These correspondence tables, as well as conversion tables for nomenclatures of materials and for nomenclatures of economic activities, are available in Eurostat at the Reference and Management of Nomenclatures server.[11]

### 2.3. From products to materials

Information about the material composition of products is used, in order to transform the distribution of products across the economy in a distribution of materials. This step contributes to one of the main objectives of urban metabolism studies: assessing the environmental pressure of urban consumption. The extraction of materials used to satisfy society needs is a proxy of the environmental pressure of this society (EEA, European Environment Agency, 1999).

Products are disaggregated in categories of materials using the MATCAT nomenclature and the ProdChar database developed in Rosado et al. (2013). This nomenclature establishes a correspondence between products listed in the CN and the materials that constitute them. It considers 6 main categories of materials (fossil fuels, metallic minerals, non-metallic minerals, biomass, chemical and others), and a total of 28 subcategories, as represented in Table 1. The ProdChar is a product composition database, which indicates for each product the constituent materials, as well as their shares on the weight of the product (for a deeper description of the database, please see (Rosado et al., 2013)). This transformation from products to 28 material subcategories allows the analysis of mass balances for each material in each economic sector, needed to estimate the mass content in the next step.

### 2.4. Estimating the material flows at the national scale

The estimation of material flows from the IO tables requires converting from monetary units to physical units, which can

**Table 1**
Nomenclature for material categories, MATCAT (Rosado et al., 2013).

| | | |
|---|---|---|
| Fossil fuels (FF) | FF1 | Low ash fuels |
| | FF2 | High ash fuels |
| | FF3 | Lubricants and oils and solvents |
| | FF4 | Plastics and rubbers |
| Metals (MM) | MM1 | Iron, steel alloying metals and ferrous metals |
| | MM2 | Light metals |
| | MM3 | Non-ferrous heavy metals |
| | MM4 | Special metals |
| | MM5 | Nuclear fuels |
| | MM6 | Precious metals |
| Non-metallic minerals (NM) | NM1 | Sand |
| | NM2 | Cement |
| | NM3 | Clay |
| | NM4 | Stone |
| | NM5 | Other (fibers, salt, inorganic parts of animals) |
| Biomass (forestry, crops and animal products) (BM) | BM1 | Agricultural biomass |
| | BM2 | Animal biomass |
| | BM3 | Textile biomass |
| | BM4 | Oils and fats |
| | BM5 | Sugars |
| | BM6 | Wood |
| | BM7 | Paper and board |
| | BM8 | Non-specified biomass |
| Chemicals and fertilizers (CF) | CF1 | Alcohols |
| | CF2 | Chemicals and pharmaceuticals |
| | CF3 | Fertilizers and pesticides |
| Others (O) | O1 | Non-specified |
| | O2 | Liquids |

be achieved through the use of mass content values (kg per monetary unit). Eq. (1) shows how the physical flow between domestic sector $i$ to domestic sector $j$ of the material $m$ ($SM_{ij}^{m}$) is estimated, multiplying the monetary flow between those sectors ($SE_{ij}$) with the mass content of that material representative of the sales between those sectors ($SP_{ij}^{m}$). The same principle is applied to sales from the domestic sectors to final consumption ($FCM_{ij}^{m}$, $FCE_{ij}$ and $FCP_{ij}^{m}$), from international economic sectors to domestic sectors or final consumption ($IM_{ij}^{m}$, $IE_{ij}$, $IP_{ij}^{m}$ and $IFCM_{ij}^{m}$, $IFCE_{ij}$, $IFCP_{ij}^{m}$) and from domestic sectors to exports[12] ($EM_{i}^{m}$, $EE_{i}$, $EP_{i}^{m}$).

$$SM_{ij}^{m} = SE_{ij} \times SP_{ij}^{m} \tag{1}$$

To characterize the flows of imports, exports and domestic materials from both IO tables available (one for domestic transactions and exports and one for imports), it is necessary to consider mass content values for each material for all the sales between national economic sectors or between national and international economic sectors. However, these values are unknown and need to be estimated. To simplify the estimation, it was assumed that the mass content values of the sales from sector $i$ to all other sectors or final demand, within each of the three types of sales (imports, domestic and exports), is the same and equal to the sum of the total mass sold by economic sector ($\sum_j SM_{ij}^{m} + \sum_k FCM_{ik}^{m}$) divided by the total monetary value of the sales from that sector ($\sum_j SE_{ij} + \sum_k FCE_{ik}$), as shown in Eq. (2). Considering different mass content for sales

[4] Harmonized system codes (1996 revision).
[5] http://comtrade.un.org/db/dqBasicQuery.aspx, accessed March 2013.
[6] Standard international trade classification.
[7] Economy-wide material flow accounts.
[8] Combined nomenclature.
[9] International standard industrial classification.
[10] Statistical classification of economic activities in the European community.
[11] http://ec.europa.eu/eurostat/ramon, accessed March 2013.
[12] For exports there is only the total amount of monetary value of exports from each sector and no description of the destination sector of those sales, and thus the mathematical formulation only has the index for the origin sector.

between national sectors and between international and national sectors allows taking into account any potential specificities of imported and exported products, which can range from pure raw materials to finished products.

$$\forall_{j,k},\ SP^m_{ij} = SP^m_i = FCP^m_i = \frac{\sum_j SM^m_{ij} + \sum_k FCM^m_{ik}}{\sum_j SE_{ij} + \sum_k FCE_{ik}} \quad (2)$$

The estimated mass content of the imported/exported products is obtained through Eq. (2), using the total mass sales from each international/national sector ($\sum_j IM^m_{ij}$ and $EM^m_i$). These are calculated using the UN Comtrade statistics that records the weight of imported/exported products combined with the correspondence tables described in Section 2.2, and the monetary values of sales available in the input–output tables ($\sum_j IE_{ij}$ and $EE_i$).

To calculate the mass intensities of the domestic sales of each sector (to other domestic sectors or final consumption), mass balances are performed. For each material $m$ and economic sector $i$, the sum of materials sold to the domestic economy ($\sum_j SM^m_{ij} + \sum_k FCM^m_{ik}$), the materials exported ($\sum_j EM^m_i$) and the amount of materials that the sector consumes ($SC^m_i$) must be balanced with the total materials that enter that sector, either through domestic extraction ($DE^m_i$), purchase from other domestic sectors ($\sum_k M^m_{ki}$) or imports from other countries ($\sum_l IM^m_{li}$), as shown in Eq. (3).

$$\sum_j SM^m_{ij} + \sum_k FCM^m_{ik} + \sum_j EM^m_i + SC^m_i = DE^m_i + \sum_k SM^m_{ki} + \sum_l IM^m_{li} \quad (3)$$

Eq. (3) can be rewritten to consider the economic values that are known from the IO tables, as shown in Eq. (4).

$$\sum_j \left(SE^m_{ij} \times SP^m_i\right) + \sum_k \left(FCM^m_{ik} \times SP^m_i\right) + \sum_j \left(EE^m_i \times EP^m_i\right) + SC^m_i = DE^m_i + \sum_k \left(SE^m_{ki} \times SP^m_k\right) + \sum_l \left(IE^m_{li} \times IP^m_l\right) \quad (4)$$

With the calculation of the mass content of imported and exported products, as previously explained, the unknowns in the equation are the domestic mass content ($SP^m_i$) and the own consumption of the sector ($SC^m_i$). The domestic mass content values are therefore calculated as the set of values that enable the verification of Eq. (4) for all combinations of $m$ and $i$, such that all $SC^m_i$ are non-negative values. Values of $SC^m_i$ are then obtained by applying Eq. (4) with the resulting set of domestic mass content values.

It should be noted that, through the correspondence tables between products (SITC) and economic activities (ISIC), it is possible to identify for each material subcategory ($m$) which economic sectors ($i$) produce products that contained that material type. As such, all economic sectors that do not produce products that are constituted by a certain material subcategory were attributed null mass content ($SP^m_i$, $IP^m_i$, $EP^m_i$).

The values of the mass content can be compared across different time periods or between different countries. However, this comparison should be performed with care as changes in these values can come from variations in prices or variations in the type of products that are produced.

*2.5. Scaling down from the national to the urban scale*

The key methodological step to scale down from the national scale to the urban scale consists on using the share of the country's workers that work in the urban area per economic activity (% $UW_i$),[13] whenever the analysis was focused on production factors, and on the share of population (% $UP$) for final consumption. In the case of urban areas, there is also the need to account for the export of products by sector $i$ from the urban area to the rest of the country ($EMU^m_i$) and the import of products by sector $i$ from the rest of the country to the urban area ($IMU^m_i$). As such, Eq. (3) is transformed into Eq. (5) scaling down from the national to the urban scale.

$$\%UW_i \times \sum_j SM^m_{ij} + \%UP \times \sum_k FCM^m_{ik} + \%UW_i \times \sum_j EM^m_i + \%UW_i \times SC^m_i + EMU^m_i = \%UW_i \times DE^m_i + \%UW_i \times \sum_k SM^m_{ki} + \%UW_i \times \sum_l IM^m_{li} + IMU^m_i \quad (5)$$

The terms $EMU^m_i$ and $IMU^m_i$ are by definition non-negative terms and can be calculated using Eq. (5).

It must be noted that the methodology described in this work does not identify the crossing flows within an urban area. However, as the total material input to an urban area is determined by the total final consumption and the exports, the materials that cross the urban area are also not accounted in the inputs, thus assuring a material balance.

## 3. Case studies

Four metropolitan areas were chosen as case studies to develop the presented methodology, two European (Lisbon and Paris) and two Asian (Seoul–Incheon and Shanghai). The administrative limits of each region were considered as boundaries. Data availability for the chosen areas determined that the base year for the study was 2000. The four metropolitan areas were chosen namely because their socioeconomic characteristics are very diverse, in terms of sheer size, population and relative wealth, as illustrated in Table 2. Seoul–Incheon is the largest metropolitan region with an area above thirteen thousand square kilometers, more than four times Lisbon's area. Seoul–Incheon is also the most populous of the metro areas, followed by Shanghai, with eight and six times more population, respectively, than the least populated, Lisbon.

Shanghai is the densest metro area with more than two thousand habitants per square kilometer, which is more than twice denser than Lisbon. It is interesting to notice that while Seoul–Incheon is the most populous urban area, Shanghai is a much more compact city, with the population density of Seoul–Incheon being three quarters as that of Shanghai.

The wealthiest area per capita is Paris, followed by Lisbon. The metro economies that contributed more to the national

[13] As explained in (Niza et al., 2009) and (Rosado et al., 2013) a city's consumption may be assumed as a function of the number of workers, the number of inhabitants, or their purchasing power. For example, a linear relationship between domestic extraction and the number of workers for a particular economic activity might be assumed. In this case, the urban area's domestic extraction will be a percentage of the national extraction that is equal to the percentage of national workers in that economic activity that are in the metropolitan area. When dealing with economic sectors the limiting factor for consumption is the number of workers.

**Table 2**
Demographic and output indicators of the four metropolitan areas.

| | Area ($km^2$) | Population (thousand) | Share of national population | Pop. density ($hab/km^2$) | Nominal GDP (mils $) | Share of national GDP | GDP per capita (thousands $) |
|---|---|---|---|---|---|---|---|
| Lisbon[a] | 3002 (2003) | 2662 (2001) | 26% (2001) | 887 | 65,842 (2000) | 38% (2000) | 24.73 |
| Paris[b] | 12,012 (2006) | 10,952 (1999) | 19% (1999) | 912 | 391,505 (2000) | 28% (2000) | 35.75 |
| Seoul–Incheon[c] | 13,595 (2000) | 21,258 (2000) | 46% (2000) | 1.564 | 376,748 (2000) | 49% (2000) | 17.72 |
| Shanghai[d] | 7705 (2000) | 16,408 (2000) | 1% (2000) | 2.130 | 144,904 (2000) | 5% (2000) | 8.83 |

[a] http://www.ine.pt/.
[b] http://www.insee.fr/.
[c] http://kosis.kr/eng/.
[d] http://www.stats-sh.gov.cn/.

economy are Seoul, with almost half of the country output, and Lisbon, with more than a third. Shanghai, on the other hand, represented only 5% of the country GDP, which can be explained by the large country that is China, with Shanghai having only 1% of the population of the country at the time.

As represented in Fig. 1, the GDP of the four urban areas results predominantly from the services sectors (between 52% and 83%). The same occurs in the national economies, however these show higher shares of GDP deriving from the agriculture (between 3% and 15%) and industry (between 23% and 46%) sectors when compared to the urban economies.

This distribution of GDP per economic activity is reflected on the breakdown of employment, as can be seen when comparing Fig. 1 with Fig. 2. The main differences are, as expected, related to the agriculture and mining sector which have a much larger contribution for employment than for GDP.

## 4. Results

Results obtained are compared in terms of the total material input, the local consumption and the weight of the different economic sectors, as measured by the materials allocated to their activities.

### 4.1. Total material use

Material consumption values, shown in Table 3, suggest that there is no correlation between the size of the urban areas (in terms of population) and the material consumption per capita. Seoul–Incheon is the most populated urban area, followed by Shanghai, Paris and Lisbon, whereas in terms of both material input and local consumption, Paris has the highest flows, followed by Seoul–Incheon, Shanghai and Lisbon.

Also, while Paris was the richest urban area, Lisbon was had the highest consumption per capita (both in terms of material input and local consumption). Seoul–Incheon urban area had the second highest material input and material consumption but a lower GDP per capita when compared to Lisbon. Furthermore, Shanghai had a lower GDP per capita when compared to the other urban areas under analysis, but its material input and local consumption per capita was of the same order as all other urban areas.

Other studies have attempted to estimate the material consumption of Lisbon (Rosado et al., 2013) and Paris (Barles, 2009). For Lisbon, the local consumption was estimated to be between 7.61 and 10.76 tonnes per capita, for the time period of 2003–2009. For Paris, the local consumption was estimated to be 7.1 tonnes per capita in 2003. These values are much lower than the ones obtained. This might be due to the fact that these methods rely on the existence of very detailed transport statistics to account for the imports to and exports from the urban areas. However, these statistics are not able to fully account for all the materials that are transported. For example, in the case of Portugal, the transport statistics do not register anything that is transported in vehicles with less than 3 tonnes capacity (Niza et al., 2009). Also, crossing flows assume a particular importance in these methodologies, particularly if their flows are accounted in one direction but not in the other. On the other hand, the monetary values of such transactions have a higher probability of being registered. Furthermore, the application of the proposed methodology allows the disaggregation between economic activities, which is not possible if only the entries and exits of materials are registered. As such, there is a clear need to develop further studies and engage in

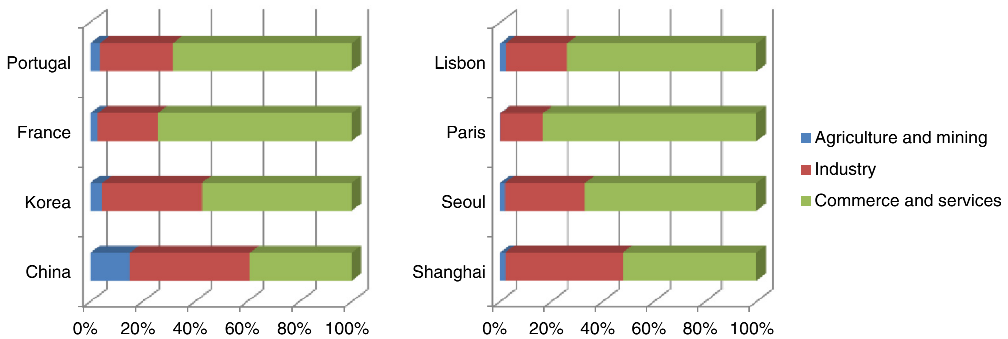


**Fig. 1.** GDP breakdown by economic sector for the urban areas and national economies, 2000.

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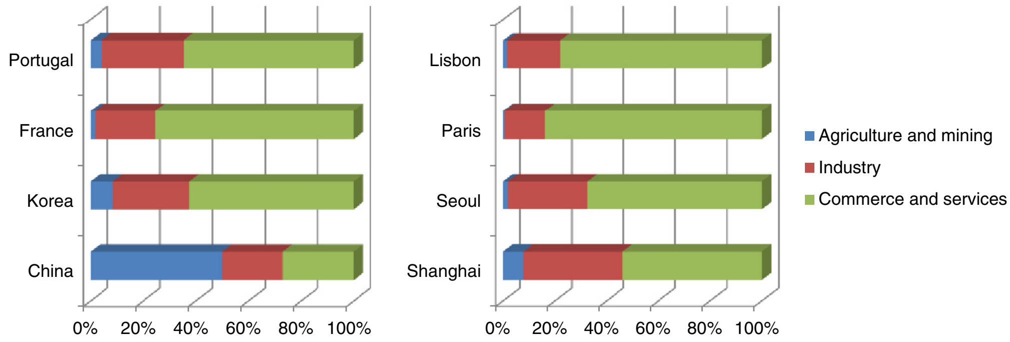


**Fig. 2.** Employment breakdown by economic sector for the four urban areas and respective countries, 2000.

intensive data collection efforts to properly validate and further refine the existing methods.

### *4.2. Material input by material type*

When assessing the structure of the material input, as shown in Fig. 3, it is possible to see that non-metallic minerals and biomass are generally the most important material categories, accounting for between 58%, in the case of Seoul–Incheon, and 83%, in the case of Shanghai, of the total material input. The main exception to this is Seoul–Incheon, in which fossil fuels (30% of total material input) are more relevant than biomass (9%).

All urban areas rely on very high shares of non-metallic minerals — above 46%. This share may be explained by the boom of construction that these cities experienced in the 90s and beginning of the 2000s (Coxx, 2011; Walcott and Clifton, 2006; Niza et al., 2009; Szirmai, 2012).

While Lisbon, Paris and Shanghai have significant biomass needs, above 20%, the urban area of Seoul–Incheon uses only 9% of biomass. However, in terms of fossil fuels, the Seoul–Incheon urban area uses a much higher amount than the other areas, reaching up to 30% of the total material input. The high share of fossil fuels consumption in Seoul–Incheon should be related to the particularly high industrialization level of the metropolitan area as described in Child Hill and June (2000). On the other hand, Shanghai is characterized by using a very small amount (in proportion) of fossil fuels, around 10%.

Assessing the MATCAT material subcategories it was identified that in the case of the non-metallic minerals (NM), the subcategory NM4 (stone), represents more than 95% of the material input in Seoul–Incheon, Shanghai and Lisbon, while in Paris it corresponds to below 80% with NM1 (sands) being responsible for 17%. In terms of biomass, the subcategories BM1 (agricultural biomass), BM6 (wood), and BM8 (non-specified biomass), are the most relevant. Together, they account for over 75% of all biomass used in each urban area. The material input per capita of each material subcategory for each urban area is shown in Table 4.

To assess the diversity of material usage in the urban areas under analysis, Fig. 4 shows the cumulative share of total material input, with the 28 materials subcategories defined in MATCAT. For each urban area, the subcategories are ordered by their share of total material input, from the highest to the lowest. The results show that only a small number of subcategories have a significant share of total material input in all urban areas.

The urban areas of Lisbon and Paris are the more diverse in terms of material input subcategories, while Shanghai is the most dependent on specific material subcategories. Interestingly, these results contrast with the results obtained from the material input structure, shown in Fig. 3, which suggests that Shanghai and Paris have somewhat similar material types' requirements. This is due to the fact that there is one subcategory in each major material category that is responsible for more than 60% of the input of those categories in Shanghai.

This diversity of materials used in the urban areas of Lisbon and Paris can be observed by the fact that to achieve a share of 90% of the material input, they required 10 and 11 different subcategories of materials, respectively. Seoul–Incheon and Shanghai, on the other hand, required only 7 and 5 subcategories, respectively. The division of these subcategories in the main categories is as follows:

- Lisbon: 10 subcategories, being 4 related to fossil fuels, 2 to biomass, 3 to non-metallic and 1 to metallic minerals;
- Paris: 11 subcategories, being 4 related to fossil fuels, 3 to biomass, 3 to non-metallic and 1 to metallic minerals;

**Table 3**
Total and per capita material input and material consumption of the Lisbon, Paris, Seoul–Incheon and Shanghai metropolitan areas, 2000. Own calculations.

| | Material input | | Local consumption | |
|---|---|---|---|---|
| | Total [kt] | Per capita [t/cap] | Total [kt] | Per capita [t/cap] |
| Lisbon | 50,232 | 18.9 | 45,396 | 17.1 |
| Paris | 192,228 | 17.6 | 170.245 | 15.5 |
| Seoul–Incheon | 397,134 | 18.7 | 348,532 | 16.4 |
| Shanghai | 248,346 | 15.1 | 241,146 | 14.7 |

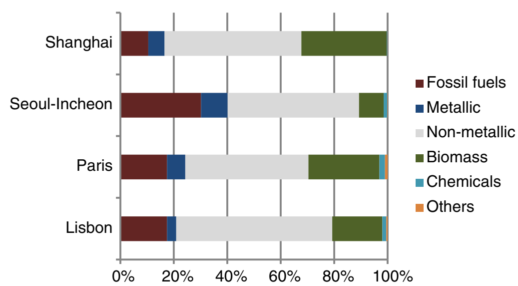


**Fig. 3.** Material input structure of the four urban areas, 2000. Own calculations.

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**Table 4**
Per capita material input by material subcategory the Lisbon, Paris, Seoul–Incheon and Shanghai metropolitan areas, 2000. Own calculations.

| | Lisbon | Paris | Seoul–Incheon | Shanghai |
|---|---|---|---|---|
| FF1 | 1.56 | 1.32 | 2.83 | 1.31 |
| FF2 | 0.47 | 0.48 | 0.75 | 0.07 |
| FF3 | 0.64 | 0.56 | 0.95 | 0.09 |
| FF4 | 0.63 | 0.71 | 1.11 | 0.12 |
| MM1 | 0.56 | 1.06 | 1.54 | 0.69 |
| MM2 | 0.04 | 0.07 | 0.05 | 0.04 |
| MM3 | 0.05 | 0.06 | 0.14 | 0.13 |
| MM4 | 0.00 | 0.01 | 0.00 | 0.00 |
| MM5 | 0.00 | 0.00 | 0.00 | 0.00 |
| MM6 | 0.00 | 0.00 | 0.13 | 0.05 |
| NM1 | 1.31 | 1.35 | 0.09 | 0.01 |
| NM2 | 0.17 | 0.08 | 0.10 | 0.01 |
| NM3 | 0.66 | 0.65 | 0.03 | 0.01 |
| NM4 | 8.67 | 5.82 | 8.81 | 7.67 |
| NM5 | 0.21 | 0.20 | 0.15 | 0.05 |
| BM1 | 1.87 | 2.50 | 0.93 | 1.44 |
| BM2 | 0.11 | 0.10 | 0.07 | 0.05 |
| BM3 | 0.08 | 0.06 | 0.07 | 0.03 |
| BM4 | 0.05 | 0.07 | 0.02 | 0.04 |
| BM5 | 0.05 | 0.08 | 0.05 | 0.00 |
| BM6 | 0.71 | 0.44 | 0.27 | 0.26 |
| BM7 | 0.26 | 0.28 | 0.14 | 0.02 |
| BM8 | 0.40 | 1.13 | 0.17 | 2.99 |
| CF1 | 0.02 | 0.02 | 0.04 | 0.00 |
| CF2 | 0.18 | 0.21 | 0.15 | 0.02 |
| CF3 | 0.08 | 0.14 | 0.06 | 0.02 |
| O1 | 0.02 | 0.02 | 0.01 | 0.00 |
| O2 | 0.07 | 0.16 | 0.02 | 0.01 |

- Seoul–Incheon: 7 subcategories, being 4 related to fossil fuels, 1 to biomass, 1 to non-metallic and 1 to metallic;
- Shanghai: the 5 subcategories are divided into 1 of fossil fuels, 2 of biomass, 1 of non-metallic and 1 of metallic.

It is important to notice that while the diversity of material input may indicate a diversified economy, results need to be considered carefully, as they may also indicate that some urban areas do not have material intensive industries, leading to no type of material being dominant. To better understand these results, an assessment of the material consumption by economic sector was performed.

### *4.3. Material consumption per economic sector*

The material inputs for each sector of the economy are shown in Fig. 5. The method developed in the current paper (based on IO tables) determines that the material input to each economic sector is the self-consumption of products by companies required to deliver their production and services to final demand and exports (e.g., machinery, office paper, fuels, wasted raw materials). This has two consequences in terms of analysis. First, the importance of manufacturing in terms of material flows turns underweighted since its output (products manufactured) is not accounted in the sector but in all other sectors. The total material input to each economic sector can be calculated as the sum of its self-consumption with the total mass that leaves the sector through sales. Second, products consumed by the sector (but that do not end as a useful output) eventually turn waste, meaning that this material input can be assumed as a proxy of industrial waste.

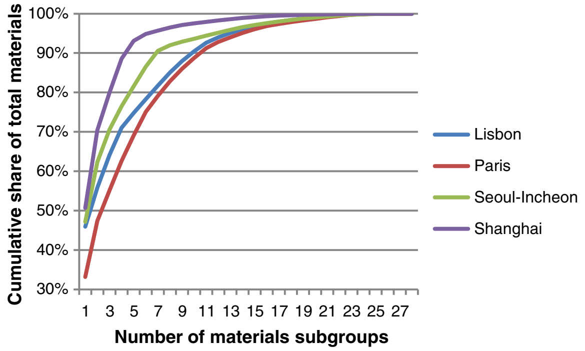


**Fig. 4.** Cumulative share of the 28 material categories in the four metro areas, 2000. Own calculations.

As illustrated in Fig. 5, despite the differences in total material input, Lisbon, Paris and Seoul–Incheon present similar shares of material consumption by economic sector with commerce representing between 17% and 20%, the final consumption between 20% and 28%, the gross fixed capital formation (GFCF) between 19% and 32% and exports between 10% and 12%.

Most of the materials entering Shanghai urban area are directed towards GFCF (43%), suggesting significant impacts in the future of the urban area, as it mainly includes material with long life spans that remain in the urban fabric for several years (stock accumulation), undoubtedly demanding long last consumption of material resources for its activity and maintenance. The manufacturing sector and final consumption are also relevant sectors, representing 15% and 16% of the material input, respectively.

In what concerns exports, Shanghai is the metro area that directs the lowest share of materials to that end, with only 3% of the materials being exported from the urban area.

The almost null material use in agriculture and mining is not surprising, as the areas under analysis are densely populated, much more than the rest of country they belong to, with little space available for exploring raw materials such as biomass or minerals.

The material consumption per capita in each economic sector is shown in Table 5.

Measuring the material consumption of the different types of manufacturing (Fig. 6) may be seen as a proxy of the

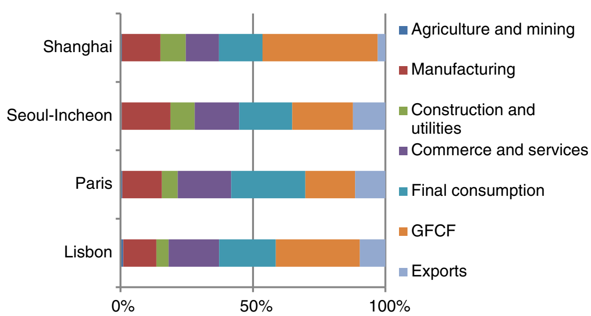


**Fig. 5.** Material consumption per economic sector in the four metro economies, 2000. Own calculation.

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**Table 5**
Material consumption per economic sector in the four metro economies, 2000. Own calculation.

| | Lisbon | Paris | Seoul–Incheon | Shanghai |
|---|---|---|---|---|
| Agriculture and mining | 0.19 | 0.12 | 0.09 | 0.08 |
| Manufacturing | 2.36 | 2.62 | 3.43 | 2.20 |
| Construction and utilities | 0.88 | 1.06 | 1.72 | 1.45 |
| Commerce and services | 3.60 | 3.53 | 3.13 | 1.89 |
| Final consumption | 4.04 | 4.91 | 3.74 | 2.50 |
| GFCF | 5.98 | 3.30 | 4.29 | 6.58 |
| Exports | 1.82 | 2.01 | 2.29 | 0.44 |

industrial structure of each urban area (at least in terms of the dependence of the industrial sectors in natural resources) and therefore of the environmental pressure of each industrial sector.

Metro areas that seem to have a more equitable share of material consumption per industry type are Shanghai and Seoul, where the share of materials in three of the industries is between 22% and 30%. The exceptions are the construction companies and the metallic products companies. In these metro areas, construction companies weigh between 6% and 8% of the material self-consumption of the manufacturing sector and the metallic products companies around 12%. In Lisbon there is an industrial sector that weighs considerably more in terms of consumption than others, with the biomass products companies consuming 37% of the materials in manufacturing.[14] In the Paris metro area, the chemicals and fuels companies and the machinery and equipment companies consume 35% each.

In general, the chemicals and fuels industry is very significant in the urban areas under analysis, being responsible for more than 20% of the products consumed by manufactories in all the metro areas. In addition to Lisbon, the biomass products industry is also very relevant in most urban areas, representing around 21% in Paris 22% in Seoul–Incheon and 29% in Shanghai. Exception made to Lisbon, with only 15% of the share, the machinery and equipment's companies (high added value companies) of the other metro areas also represent an important share of the material consumption of manufacturing with more than 25%.

Evidencing the material dependence of the manufacturing sectors, Fig. 7 shows the cumulative share of the material input for those activities. The manufacturing sector was divided into the 18 economic sectors, described on the OECD input–output tables. For each urban area, the economic activities are ordered by their share of total material input, from the highest to the lowest. If we consider the number of different sectors that represent a consumption of 90% of the materials consumed by manufacturing, results show that Paris and Seoul–Incheon spread their material use through more different economic sectors than Lisbon and Shanghai, which are slightly more dependent on specific sectors.

The most self-consuming sectors that contribute until a 90% cumulative share in the metro areas are:

- Lisbon: 10 sectors, being 3 related to the production of biomass products, 2 of chemical, fuels and related products, 1 of construction products, 2 of metallic products and 2 of machinery and equipment;

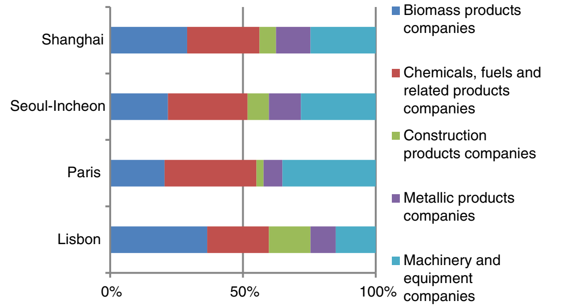


**Fig. 6.** Material consumption of manufacturing companies, per industry type, for the four metropolitan areas, 2000. Own calculations.

- Shanghai: 10 sectors, being 2 related to the production of biomass products, 3 of chemical, fuels and related products, 1 of construction products, 1 of metallic products and 2 of machinery and equipment;
- Paris: 12 sectors, being 2 related to the production of biomass products, 2 of chemical, fuels and related products, 1 of construction products, 2 of metallic products and 5 of machinery and equipment;
- Seoul–Incheon: 12 sectors, being 2 related to the production of biomass products, 3 of chemical, fuels and related products, 1 of construction products, 2 of metallic products and 4 of machinery and equipment;

When comparing the diversity of the industries, in terms of share of total material consumption, with the socioeconomic characteristics of the urban areas, there does not seem to exist a clear relation between the structure of the manufacturing sector and the GDP per capita, as the differences in the manufacturing sector are not as striking as the differences in GDP. This might be due to the large share of GDP that comes from commerce and services in each urban area, as shown in Fig. 1.

Although potential correlation between factors should be taken very carefully considering the number of case studies assessed, it is however interesting to notice that, in this study, urban areas with more diversified manufacturing sectors (in terms of the materials share) are also the ones that have more population.

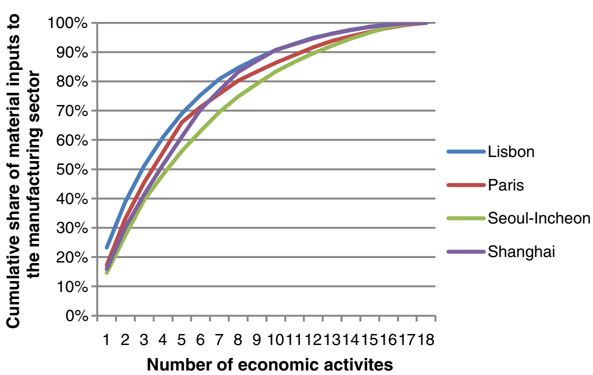


**Fig. 7.** Cumulative share of material input to the 18 economic sectors of the manufacturing sector in the four metro areas, 2000. Own calculations.

[14] Together with some important agro-industries, a very important paper mill factory is also located in the Lisbon metropolitan area.

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## 5. Conclusions

Urban areas are key drivers of economic growth, through technical change, and their environmental impacts have become one of the more important topics due to the growing urbanization trends worldwide. In this context, cities are increasingly perceived as complex systems whose understanding requires a holistic approach, such as that provided by the urban metabolism methods which are intended to characterize the materials that flow in the urban area, how they are transformed by different economic activities and ultimately how they pressure the environment, namely through their extraction and the generation of wastes.

This paper presents an innovative method to quantify the metabolism of urban areas, based on input–output data at a national level and scaling down approaches to derive urban scale metabolism. The methodology was applied to four urban areas (Lisbon, Paris, Seoul–Incheon and Shanghai), using the year 2000 as reference.

The number of urban areas under analysis (4) determines that it is not possible to draw strong conclusions, but only raise hypothesis that need to be validated through the analysis of other urban areas. Results should then be read with caution. Additionally, more detailed analyses of the relation between the physical structure of the metro economies and associated activity sectors and the economic structure demands could be performed through the collection of a higher amount of data (such as other economic indicators), and should be performed in the future.

Nevertheless results obtained in the context of this paper showed that while the metabolisms of all urban areas are very dependent on non-metallic minerals, Lisbon, Paris and Shanghai are also very dependent on biomass and Seoul–Incheon consumes significant shares of fossil fuels.

In terms of the destination of the materials that enter the urban areas, Paris and Seoul–Incheon direct around 42% of their material input to their economic sectors, particularly the manufacturing and the commerce sectors, while Shanghai and Lisbon directs them more towards GFCF.

The integration of more socioeconomic indicators and the application of these studies to several urban areas and across multiple years, e.g., as suggested in Ferrão and Fernandez (2013) could enable the assessment of the technological and economic evolution of those regions, as well as the clustering of urban areas based on their development stages, like the ones described in Kennedy (2011), and technological and social evolution patterns.

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## References

Barles, S., 2009. Urban metabolism of Paris and its region. J. Ind. Ecol. 13 (6), 898–913.

Barrett, J., Vallack, H., Jones, A., Haq, G., 2002. A material flow analysis and ecological footprint of York. Technical Report. Stockholm Environment Institute, Stockholm, Sweden.

Bos, J.J., Brown, R.R., 2012. Governance experimentation and factors of success in socio-technical transitions in the urban water sector. Technol. Forecast. Soc. Chang. 79 (7), 1340–1353.

Bringezu, S., 1999. Material flow analyses supporting technological change and integrated resource management. Paper presented to the Third ConAccount Meeting: Ecologizing Societal Metabolism Amsterdam, November 21st 1998. Centre of Environmental Science, Leiden University.

Bringezu, S., Schutz, H., Steger, S., Baudisch, J., 2004. International comparison of resource use and its relation to economic growth — the development of total material requirement, direct material inputs and hidden flows and the structure of TMR. Ecol. Econ. 51, 97–124.

Child Hill, R., June, W.K., 2000. Global cities and developmental states: New York, Tokyo and Seoul. Urban Stud. 37 (12), 2167–2195.

Coxx, W., 2011. The evolving urban form: Seoul. NewGeography (http://www.newgeography.com/content/002060-the-evolving-urban-form-seoul, downloaded May 2013).

Dixon, T., Eames, M., Britnell, J., Watson, J.B., Hunt, M., 2014. Urban retrofitting: identifying disruptive and sustaining technologies using performative and foresight techniques. Technol. Forecast. Soc. Chang. 89, 131–144.

EEA, European Environment Agency, 1999. Environmental indicators: typology and overview. Technical Report No. 25. EEA, Copenhagen (http://www.eea.europa.eu/publications/TEC25).

EUROSTAT, 2001. Economy-wide Material Flow Accounts and Derived Indicators: A Methodological Guide. Statistical Office of the European Union, Luxembourg.

Ferrão, P., Fernandez, J., 2013. Sustainable Urban Metabolism. MIT Press.

Graaf, R., Brugge, R., 2010. Transforming water infrastructure by linking water management and urban renewal in Rotterdam. Technol. Forecast. Soc. Chang. 77 (8), 1282–1291.

Hammer, M., Giljum, S., 2006. Materialflussanalysen der Regionen Hamburg, Wien und Leipzig. (Material flow analysis of the regions of Hamburg, Vienna and Leipzig) NEDS Working Papers #6 (08/2006), Hamburg, Germany.

Hausmann, S., Hidalgo, C.A., 2014. The Atlas of Economic Complexity: Mapping Paths to Prosperity. MIT Press, Cambridge, MA.

Karaca, F., Raven, P.G., Machell, J., Camci, F., 2015. A comparative analysis framework for assessing the sustainability of a combined water and energy infrastructure. Technol. Forecast. Soc. Chang. 90 (B), 456–468.

Kennedy, C., 2011. The Evolution of Great World Cities. Urban Wealth and Economic Growth. University of Toronto Press, Toronto.

Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. J. Ind. Ecol. 11 (2), 43–59.

Marteleira, R., Pinto, G., Niza, S., 2014. Regional water flows — assessing opportunities for sustainable management. Resour. Conserv. Recycl. 82, 63–74.

Metro Monitor, Global, 2011. BI — Brookings Institution, Metropolitan Policy Program, 2012 (Washington, DC).

Niza, S., Rosado, R., Ferrão, P., 2009. Urban metabolism: methodological advances in urban material flow accounting based on the Lisbon case study. J. Ind. Ecol. 13 (3), 384–405.

Rosado, L., Niza, S., Ferrão, P., 2013. An urban material flow accounting case study of the Lisbon metropolitan area using the urban metabolism analyst method. J. Ind. Ecol. 18 (1), 84–101.

Schandl, H., Fischer-Kowalskib, M., Grunbuhela, C., Krausmann, F., 2009. Socio-metabolic transitions in developing Asia. Technol. Forecast. Soc. Chang. 76 (2), 267–281.

Schulz, N.B., 2007. The direct material inputs into Singapore's development. J. Ind. Ecol. 11 (2), 117–131.

Seto, K., Satterthwaite, D., 2010. Interactions between urbanization and global environmental change. Editorial overview. Curr. Opin. Environ. Sustain. 2, 127–128.

Spence, M., Annez, P.C., Buckley, R.M., 2009. Urbanization and Growth (Commission on Growth and Development). The International Bank for Reconstruction and Development. The World Bank.

Spickermann, A., Grienitzb, V., Gracht, H.A., 2014. Heading towards a multimodal city of the future?: multi-stakeholder scenarios for urban mobility. Technol. Forecast. Soc. Chang. 89, 201–221.

Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of materials use: a socioeconomic and geophysical analysis. Ecol. Econ. 69, 1148–1158.

Szirmai, V., 2012. Urban sprawl in Europe. Reg. Stat. 2 (1), 129–148.

Walcott, S.M., Clifton, W.P., 2006. Metropolitan spatial dynamics: Shanghai. Habitat Int. 30, 199–211.

Weisz, H., Krausmann, F., Amann, C., Eisenmenger, N., Erb, K.H., Hubacek, K., Fischer-Kowalski, M., 2006. The physical economy of the European Union: cross-country comparison and determinants of material consumption. Ecol. Econ. 58, 676–698.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2013. The material footprint of nations. Proceedings of the National Academy of Sciences (201220362).

Wolman, A., 1965. The metabolism of cities. Sci. Am. 213, 179–190.

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