A refined waste flow mapping method

Addressing the material and spatial dimensions of waste flows in the urban territory through big data: the case of the Amsterdam Metropolitan Area

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Fundamental changes in the societal use of biophysical resources are required for a sustainable transformation. Current (urban) metabolism research traces flows of energy and materials and products to capture resource use along value chains from resource extraction to production and consumption and the discharge of wastes and emissions. However, spatial relation, local carrying capacity and qualitative characteristics of the urban landscape are only featured in very few studies, even if they are becoming crucial elements towards future sustainable development. Simultaneously, spatial studies tend to neglect the dimension of processes of flows and the generated stocks that influence the construction and performance of space. Big data and GIS technologies have the potential to leverage the integration between the two fields of knowledge. Therefore, the article explores the development of an innovative method - Activity-based Spatial Material Flow Analysis -that integrates qualitative and quantitative flow specifications in material content and geographical space, starting from the analysis of waste flows relative to the Amsterdam Metropolitan Area (NL). Lastly, the article reflects on the results of the application of the AS-MFA method, namely a series of flow maps. Each flow map is a significant data-based network representation of a part of the urban metabolism within the AMA in a specific period of time.

Introduction

Since the industrial revolution, processes of urbanisation have become ever more resource-intensive (Girardet, 2017). Urban territories consume almost 75% of the world's resources and generate 50%–80% of the world's greenhouse gas emissions and half of all global waste (Lucertini and Musco, 2020). This unsustainable process is one of the significant societal and urban planning challenges. It requires a different approach to understand and interpret urban territories and their relation to resource production and consumption. The challenge mentioned above can only be addressed by significantly expanding our knowledge base, by integrating data from different sources and by renewing the current analytical and planning frameworks (Shiller et al.,2017; EEA, 2016). In this context, the project REsource Management in Peri-urban Areas: Going Beyond Urban Metabolism (REPAiR) was initiated to investigate and develop new methods aiming at the understanding of waste flows and at the quantitative reduction of the latter in specific dispersed territories. REPAiR, rooted in the European Horizon 2020 framework, applies – for the first time – a geodesign approach to reveal the space-specific flows and challenges of waste and resource management using life cycle analyses and Urban Metabolism (UM) frameworks.

UM frameworks are based on a metaphor that conceptualises cities as living organisms (Lucertini & Musco, 2020). With the aim of understanding resource processes of a hypothetical town, Wolman (1965) pioneered the UM concept. Only recently, Kennedy et al. (2007: 44) aptly broadened UM definition to "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste". Consequently, UM describes the continuous flows of resources *in* (e.g. energy, materials, water), *out* (e.g. waste, pollutants, materials) of and *within* (stocks) a given system boundary (city, territory, metropolitan area). The assessment of flows and stocks of materials within a chosen geographical boundary and temporally defined system is conventionally defined as Material Flow Analysis (MFA) (Brunner and Rechberger, 2004; Broto et al., 2012). The fundamental principle of MFA is the conservation of matter (Allesch and Brunner, 2015). Since the system has defined boundaries, the principle of mass conservation aids in the accounting exercise that follows: inflows equals to the outflows plus changes in stocks and depletion (Allesch and Brunner, 2015). Every system, as each process within the system, has to be balanced according to the mass balance principle (Brunner and Rechberger, 2004). To the processes within the system, usually, a black-box approach is applied, studying and balancing out only the inputs and outputs of the main processes. Until today, MFA is one of the most common methods in UM framework. The advantages of the current UM framework can be summarised as follows (Pincetl and Bunje,2009; Kennedy et al., 2014):

- Identification of system boundaries,
- Identification and classification of flows,
- Calculation of system inputs and outputs,
- Study of specific urban sectors concerning sustainability goals,
- Identification of adaptive approaches to solutions and their consequences
- integration of social dynamics with biophysical sciences/technology.

However, the current UM method includes some limitations (Shahrokni, 2015):

- Extensive data collection and resource requirements
- Lack of data for specific territories
- Lack of spatialisation of data
- The necessity to process a considerable amount of data
- Difficulties in identifying cause-and-effect relationships of the metabolic flows

This article addresses the first three limitations primarily. If we consider a system equal to a territory, with features that are continually interacting emerging and adapting to political, economic and natural environments, we should avoid doing an extensive large data collection and accountability exercise (Kennedy, 2012). Instead, we should aim to provide links with specific activities, actors and locations. Furthermore, urban system components (such as society, economy, built environment, politics) can influence material flow dynamics. Lastly, cities are reliant on a more extensive hinterland to meet their resource use and waste disposal, that can easily get disregarded in case system's boundaries are drawn to include the dense urban areas only. The recognition of inconsistencies in the current UM approach underscores the necessity to develop an alternative, interdisciplinary method to understand resource flows in urban territories (Williams, 2019; Zhang, 2013). Therefore the central question behind this article is how to add a more precise spatial dimension to material flows.

In the following sections, the article explains a refined UM approach to map material flows in which we address more explicitly environmental and spatial impacts (Minx et al., 2011; Schremmer et al., 2011; Pincetl et al., 2012). Firstly, the article explains the role and the use of big data in the elaboration of a refined flow mapping. Secondly, it describes the innovative methodology called Activity-based Spatial Material Flow Analysis (AS-MFA) and the test of the latter on the Amsterdam Metropolitan Area (AMA). Lastly, the paper discusses the limitations and benefits of the AS-MFA, starting from the results of the case study.

Role of big data in UM

At the heart of UM and MFA studies lies data, in particular highly multi-layered sets of information (such as amounts, geographical coordinates, material composition of products), not easy to understand and generally defined: big data (Ward and Barker, 2013). According to Xu and colleagues (2015), big data needs to be 'big' in complexity, not necessarily in size. The degree of complexity is constituted by the different types, lack of structure and mixed semantics that a database contains. Data may come from multiple sources in several non-interoperable formats and need to be processed and analysed. Another type of significant data complexity comes from ill-defined societal behaviour that the data describes.

Within the environmental and geographical domains, the most direct application of big data is to improve the development of more realistic complex systems models to capture better essential features of environmental, geographical and behavioural dynamics (Axtell et al., 2001). The use of big data in UM studies is not a new practice. UM studies have long relied on the sectoral, industrial or public aggregated data to measure resource and energy supply and demand in urban areas. With big data, UM studies can amongst others develop more accurate models towards effective policy interventions; achieve a more precise definition of spatial-temporal resolutions in transportation-related areas through GPS travel trajectory and geotagged social media data; calculate the environmental footprint of human activities.

Opening up the black box: AS-MFA Methodology

A more accurate understanding of the urban system under scrutiny is crucial to pinpoint interlinkages between drivers, pressures and impacts, as well as response measures (Minx et al., 2011). The 'black box' approach of conventional MFA has clear limitations in that respect, as mentioned in the introduction. For that reason, a new approach has been initiated, aimed at linked actors and activities within - and extending beyond - that black box. Through this method, coined the Activity-based Spatial Material Flow Analysis (AS-MFA), specific activities relating to material flows and stocks in specific areas, the involved actors and their interrelations can be identified (Geldermans et al., 2017).

By means of the AS-MFA method, the region under scrutiny is investigated through a combination of grey-box and network approaches. See Zhang (2013) for a detailed difference between black box, grey-box and network process in urban metabolism. In a grey-box approach, the components of the system and their material inputs and outputs are accounted for. A network system identifies the links between the components and thereby highlights key players, processes, and locations.

Scope and approach of the AS-MFA

Within the framework of the *Resource management in Peri-urban Areas* project (REPAiR), where the method originates, the AS-MFA focused primarily on the output side, specifically regarding waste flows, while anticipating the future integration of inputs and throughputs into the model as well. Contrary to common MFA studies, mass balancing is not a priority within the AS-MFA approach. Instead, it builds on available data-points that are later aggregated in a multitude of different ways to facilitate data exploration and understanding of its complexity. The AS-MFA relies on the processing of big *bottom-up* data instead of disaggregating already aggregated *top-down* data sources. Another difference between the AS-MFA and a traditional MFA is that the latter requires strict delineation of system boundaries and choice of nodes, also in terms of geography. This way, everything that happens outside the chosen system boundary is simply disregarded, and what happens within the chosen node, gets aggregated. In the case of AS-MFA, the chosen geographical boundary only serves as a filter for the data points that do not fall within it. As long as at least one side of the flow falls within the boundary, the flow is represented on a map with the same level of detail both outside as inside the boundary.

The AS-MFA can be applied on any dataset that has the following critical components:

- a list of actors that have material output or material input;
- links between those actors, meaning that it is known whose output becomes which actor's input;
- content and quantity of the material input/output.

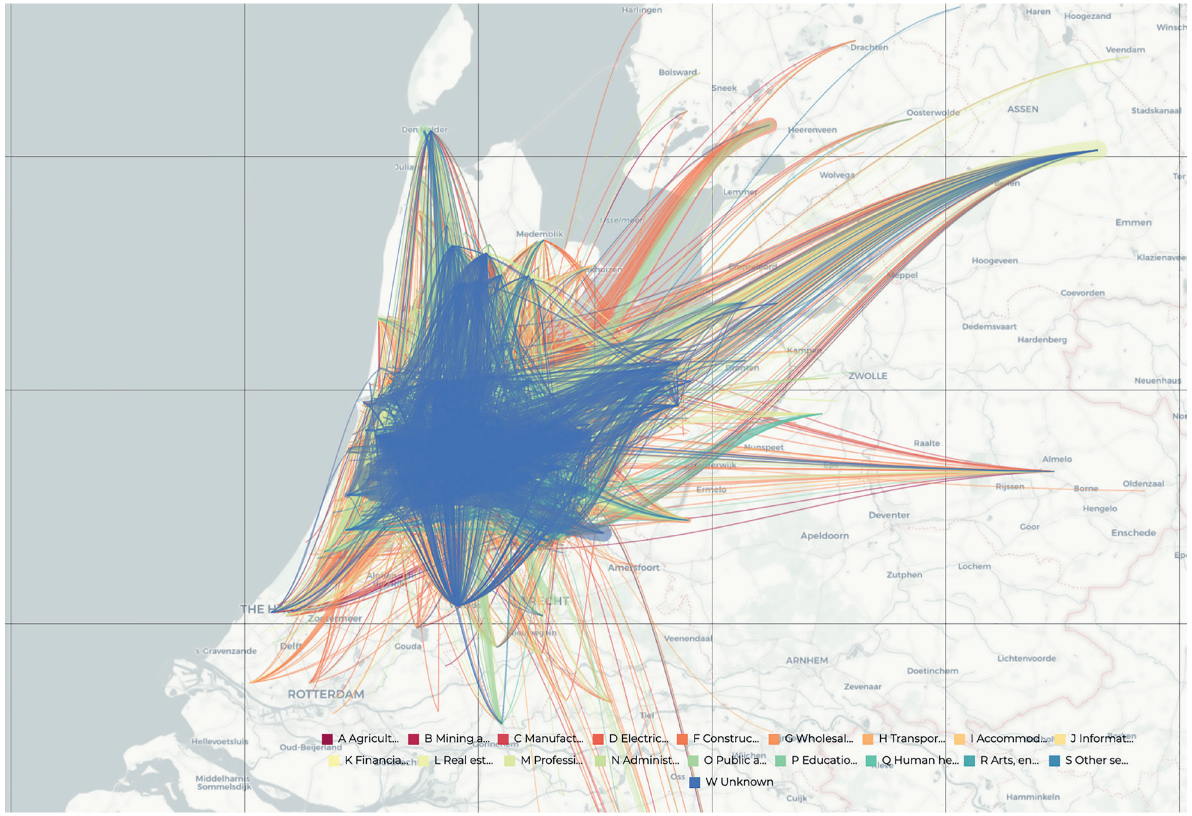
If the three components above are known, data can be enriched using the AS-MFA approach to create detailed maps and Sankey diagrams for any chosen geographical region, material or economic activity scope.

The AS-MFA consists of the following steps:

1. Data cleaning;
2. Geolocation of data points;
3. Matching actors with their economic activities using geospatial similarity check;
4. Semantic classification of material content;
5. Interactive visualisation.

NACE: section level	Description	CDW (tonnes)	Share of total (%)
A	Agriculture, forestry and fishing	23,728	0.06
B	Mining and quarrying	5,109	0.01
C	Manufacturing	2,039,225	5.31
D	Electricity, gas, steam and air conditioning supply	53,902	0.14
E	Water supply; sewerage; waste management and remediation activities	3,687,576	9.61
F	Construction	3,803,254	9.91
G	Wholesale and retail trade; repair of motor vehicles and motorcycles	353,221	0.92
H	Transporting and storage	332,479	0.87
I	Accommodation and food service activities	5,957	0.02
J	Information and communication	10,083	0.03
K	Financial and insurance activities	214,126	0.56
L	Real estate activities	1,327,325	3.46
M	Professional, scientific and technical activities	1,402,586	3.65
N	Administrative and support service activities	63,565	0.17
O	Public administration and defence; compulsory social security	14,078,384	36.68
P	Education	35,407	0.09
Q	Human health and social work activities	124,217	0.32
R	Arts, entertainment and recreation	13,164	0.03
S	Other services activities	9,668	0.03
W	Unmatched	10,801,257	28.14
Grand Total	-	**38,384,233**	**100.00**

Amount of construction & demolition waste produced in AMA 2013-2018, aggregated per economic sector
Table 1



Once all these steps are completed, the result of the AS-MFA is a digital model that can be kept in any relational database that supports geographic objects. The model is then used to generate a series of different visualisations to extract specific information:

- Reveal dominant material categories and flows in a defined territory, region or country;
- Quantify and compare material flows;
- Reveal economic activities and actors that are involved in the material flow system;
- Analyse magnitudes of contributions to the negative and positive impacts of the different activities and/or actors;
- Connect data of different material flows within a specific territory;
- Lay grounds for the assessment of environmental, social, spatial, and economic impacts caused by transportation and treatment of the (waste) materials;
- Reveal how territories relate with each other in terms of (waste) material exchange;
- Enable dynamic analysis that allows aggregating and disaggregating the data in multiple ways instead of generating a single analysis result.

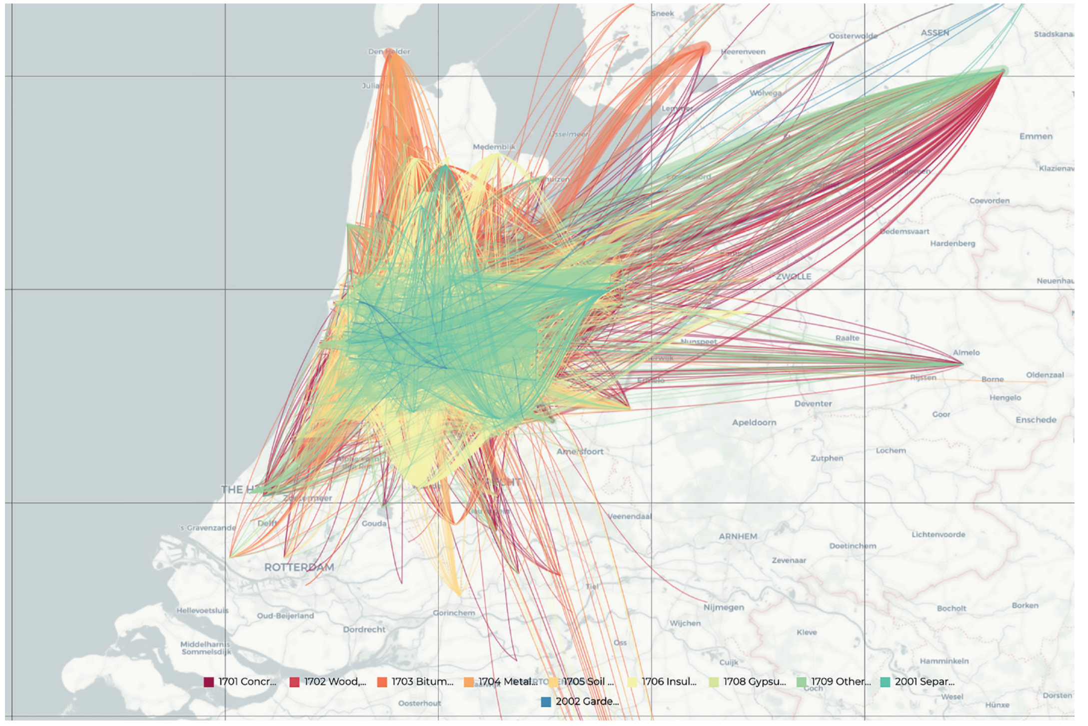
Economic activities of outwards flows from the AMA, relative to the year 2016
Fig. 1
Data and graphic Sileryte et al., 2020; (image out of scale)

In conclusion, the AS-MFA method enables the identification of key activities and actors, which reveals where responsibilities lie and therefore lays concrete points for policy or business (case) interventions. Mapping of the actors discloses their spatial location, thereby providing a spatial understanding of the regional actor-network, its spatial extent, clusters of specific activities and geographical scale of flows related to the different materials. Analysing these links and patterns allows designers, policymakers, investors and urban planners to seek optimum solutions (Moffatt and Kohler, 2008) and this way literally and figuratively provide more space for eco-innovation and circularity.

Data set and requirement
The AS-MFA provides a systematic way of analysing material flows within regions using the components: activities, materials, and actors and their interrelations. Concerning Data and databases, AS-MFA as much as possible adheres to EU-wide classification systems, ensuring the interoperability and possibility to compare different countries and regions (at least within EU). The Nomenclature des Activités économiques dans la Communauté Européenne (NACE) is used to classify the economic activities, the European Waste Catalogue (EWC) is used for the classification of waste and ORBIS[1] database due to its global coverage is used to related company names and addresses with their specific economic activities.
In order to enrich the AS-MFA model with additional information, a range of information-sources needs to be tapped concerning data on, for example, mass, energy, emissions, land use, monetary values, or social standards. The data collection specifications are then defined concerning the selected scope and key flows of materials. In general, the following data-sourcing steps should be followed, always starting from the highest level of data quality:

1. Obtain primary/company or actor specific (bottom-up) data;
2. Work with proxy data by e.g. disaggregating secondary data;
3. Use assumptions based on experts' interviews.

UM, studies on material flows typically use both top-down and bottom-up data (dis)aggregation. The level of data aggregation can significantly affect the representativeness of the mass flow simulation, and therefore, different aggregation options should be considered and, subsequently, compared (Beloin-Saint Pierre, 2017). While a model driven by data on a higher (e.g. national) aggregation level can be reliable, it loses reliability when scaled down. Contrary, a model based on bottom-up data is more reliable on a local level but will



Outwards flows from the AMA coloured according to the EWC codes, relative to the year 2016

Fig. 2
Data and graphic Sileryte et al., 2020
(image out of scale)

lose representativeness and reliability when scaled up (Roy et al., 2015). This observation suggests that if the primary goal of the study is to understand (spatial) patterns and flow specifics rather than construct the big picture, a bottom-up highly spatially disaggregated approach is more suitable than downscaling top-down/national data. The former method, however, is usually very resource-intensive as it requires extensive data collection efforts. Applying a hybrid system, using both top-down and bottom-up data, could mitigate some of the problems with the incompleteness or inaccessibility of detailed data.
The proposed AS-MFA method has been tested on the construction and demolition waste flow dataset for the Amsterdam Metropolitan Area (AMA).

Data and the Case-Study: Amsterdam Metropolitan Area
The Amsterdam Metropolitan Area (AMA) is a collaboration of 32 municipalities, two provinces (North Holland and Flevoland) and the Transport Authority Amsterdam. Around 2.4 million people live within the AMA. Moreover, Schiphol International Airport, the Port of Amsterdam, the Royal FloraHolland flower fair and the Tata Steelworks in Ijmuiden make the AMA the economic powerhouse of the Netherlands.

The waste dataset that has been used for the case study of AMA has been provided by the Division of Waste Management within the Dutch Ministry of Infrastructure and Public Works (Rijkswaterstaat). The dataset consists of reports submitted to the national online waste registration system (https://amice.lma.nl/Amice.WebAppHome/). The reports contain information about the waste pickup location, waste producer, collector, broker, processor, including their addresses, timestamp, waste quantity, collection method, EWC code and description of waste contents. These characteristics make the dataset ideal for the AS-MFA method.
For this paper, it has been filtered with the following criteria:

- The waste is either produced or treated in the AMA;
- The waste is classified according to EWC 17 as construction waste;
- The waste was reported within one calendar year.

Results
This section presents the results of the AS-MFA applied to the AMA.
The above-described selection of the national waste data set resulted in 64,905 individual data entries accounting in total for 42,108,577 metric ton of waste. See Table 1 for details about which economic sector contributes to which part of this amount.
The application of the AS-MFA resulted in flow maps, which are presented in Fig. 1 and Fig. 2. The flow map is a significant data-based network representation of a part of the urban metabolism of the region. Therefore, the map allows adding a spatial dimension to the discussion of the results. Some of these spatial questions are discussed as exemplary in the following subsection.

Discussion
This section discusses exemplary spatial questions that are relevant for policy making, working specifically in the field of Circular Economy (CE), aiming to demonstrate the added value of the AS-MFA. Furthermore, the advantage of a method that is both territorially extended but also precise in location is demonstrated.
In the Netherlands, the main actors of CE policies are municipalities and metropolitan regions administrations. Therefore, the question is, are the territories, which are the spaces of policymaking, the same or at least similar to the extent of the flow network, which are the spaces of urban metabolism and related economic activities? The flow map presented above gives a clear answer to the question. The network space is much larger than the territory of the AMA. For instance,

Comparison of waste flow movement within a portion of AMA between 2013 (top) and 2018 (bottom)
Fig. 3
Data and graphic Sileryte et al., 2020
(image out of scale)

the waste flow network of the construction sector alone exceeds not only the AMA but also the Netherlands, expanding across the country into several European countries and even beyond. For policymaking, this can be interpreted two-fold, either policy on CE have to be integrated at territorial governance level in which waste is travelling now, or policies and spatial plans need to facilitate the definition of optimal scales and amount of land necessary to develop CE strategies.
The latter leads to the spatial questions, which role in the network of urban metabolism do the economic activities in one specific sub-area play, be it neighbourhood, district or municipality? The question of localisation of the economy is of particular interest considering the redevelopment of an area, which often coincides with a significant programmatic change, in the context of the AMA mostly a shift towards residential and service-economy related land-uses (Gemeente Amsterdam, 2017). Alternatively, the (re)development of an area may take into consideration the use of nearby resources to reduce transportation costs and associated environmental impacts. In this case, two types of flows are considered:
1)one-off occurrences that convert an end-of-pipe flow into a stock, e.g. by reusing materials for construction;
2)constant occurrences that turn a constant end-of-pipe flow into a circular flow, e.g. by introducing a function which uses secondary materials for its economic activities.
We have a closer look at the development of the northern IJ-riverfront in Amsterdam to demonstrate the advantage of the AS-FMA. Circular area development is one of the fundamental principles here. For example, the neighbourhood of Buiksloterham, and most notably the 'De Ceuvel' location, has become a best practice of circular area development, widely known in the Netherlands and beyond. What if we look at this area from a network perspective?
Fig. 3 compares the situation of 2013 (top) with 2018 (bottom). Maps on the left show the relation between production on the treatment of CDW on a regional scale. The maps on the right provide insight into the production of CDW on the local scale.
Figure 3 and the data behind it demonstrate two aspects: (i) the amount of generated CDW nearly doubled, and (ii) there has been a shift in the locations of treatment. The first is an expected result in an area where in the same period, the number of dwellings doubled, while the number of companies shrank by around 25%(van Bakel, 2020). The second shows that the network space of CDW treatment became more local and followed in this sense the regional CE policy. Whether this shift leads to a higher rate of circularity, is, of course, dependent on changes in the treatment and recycling of the CDW. This question, as well as questions on how far policy changes had a direct influence on the spatial transformationsof the CDW network, goes beyond the scope of this paper.

Conclusion

Detailed data on material flows concerning urban territories is, by definition, big data - not only because of the extensive amounts of flows but also because of the complexity of the flow networks. This paper has explored Constructions & Demolition material flows, after becoming waste, by focusing on the AMA across five years. The proposed AS-MFA method allows constructing a digital model of flows on given space and juxtaposing with spatial components, such as infrastructural networks and landscape systems. Moreover, this method helps to reduce the complexity of interpreting big data, by selecting: territorial portions, temporal extent, economic activities and materials of interest. Lastly, the AS-MFA permits to explore each type of data separately from the system, and it works well with a single homogenous dataset. However, nowadays, it only includes waste materials. Although the AS-MFA method refined the current UM approach by adding a flow mapping through extended data analysis, it opens new future challenges and questions. The first one refers to the integration of a mass balance calculation in the current AS-MFA process and consequently, the necessary data required. However, the inclusion of material input and throughput pose a related challenge of data integration. For instance, if the datasets do not have the same granularity, taxonomy and semantics, then connecting input, throughput and output network nodes would require iterative mass balancing and semantic matching of material contents. This would also imply extensive and intensive manual efforts. The second challenge relates to connecting the AS-MFA outcome with more common environmental, socio-economic indicators and assessment methods. Lastly, reflections on the AS-MFA through the lens of big data pose the question on how territories could better benefit from big data analysis and in particular, how stakeholders could integrate flow mapping in urban planning policies.

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Note

[1] https://www.bvdinfo.com/en-gb/our-products/data/international/orbis

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