Using spatially explicit commodity flow and truck activity data to map urban material flows

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Abstract
To analyze and promote resource efficiency in urban areas, it is important to characterize urban metabolism and particularly, material flows. Material flow analysis (MFA) offers a means to capture the dynamism of cities and their activities. Urban-scale MFAs have been conducted in many cities, usually employing variants of the Eurostat methodology. However, current methodologies generally reduce the study area into a “black box,” masking details of the complex processes within the city’s metabolism. Therefore, besides the aggregated stocks and flows of materials, the movement of materials—often embedded in goods or commodities—should also be highlighted. Understanding the movement and dispersion of goods and commodities can allow for more detailed analysis of material flows. We highlight the potential benefits of using high-resolution urban commodity flows in the context of understanding material resource use and opportunities for conservation. Through the use of geographic information systems and visualizations, we analyze two spatially explicit datasets: (1) commodity flow data in the United States, and (2) Global Positioning System-based commercial vehicle (truck) driver activity data in Singapore. In the age of “big data,” we bring advancements in freight data collection to the field of urban metabolism, uncovering the secondary sourcing of materials that would otherwise have been masked in typical MFA studies. This brings us closer to a consumption-based, finer-resolution approach to MFA, which more effectively captures human activities and its impact on urban environments.

KEYWORDS
big data, geographic information systems, industrial ecology, truck driver activity survey, urban metabolism

1 | INTRODUCTION

1.1 | Literature review

The study of urban metabolism (UM) began with Abel Wolman’s 1965 pioneering work in The Metabolism of Cities (Wolman, 1965). Kennedy, Cuddihy, and Engel–Yan (2007) defined UM as “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste.” Within the field of UM is the method of material flow analysis (MFA), which considers the flows and stocks of materials within a predefined system by balancing the system’s inputs and outputs (Brunner & Rechberger, 2016). Due to its compatibility with the units that “local government officials would use, recognize, and understand,” MFA has been considered to be “the approach of the mainstream school of urban metabolism” (Kennedy, Pincetl, & Bunje, 2011). For a list of UM and MFA studies conducted around the world, we recommend Kennedy et al. (2007; 2011) who provided a review of UM studies, and Bao et al. (2010) who focused on MFA studies. One significant contribution to the field of MFA is the Eurostat methodology, which was published as a guide in 2001 (Eurostat, 2001). The guide established a
standardized and comprehensive methodology for practitioners to conduct their own economy-wide MFA studies and has since been modified and adapted to conduct MFA studies at the city scale (Voskamp et al., 2017).

While MFA is a useful tool for a systematic assessment of UM, a drawback is in the reduction of the study area to a “black box,” where the internal flows are often ignored (Bao et al., 2010; Eurostat, 2001). Also known as the “black boxing of urban processes,” this drawback was listed as one of the critiques of the industrial ecology approach (Newell & Cousins, 2015). By focusing only on inputs and outputs, this “black box” approach draws attention away from the internal processes of the city and “fails to theorize the process of urbanization as a social process of transforming and reconfiguring nature” (Swyngedouw, 2006). Voskamp et al. (2017) also noted that this method of analysis “effectively exclu[des] the “sourcing of secondary resources,” losing valuable insights toward a more circular metabolism. We concur that it is no longer sufficient to conduct MFA studies in a “black box” manner. Future studies must acknowledge that a city’s metabolism has both a “physical spatiality” and an element of time (Pincetl, Bunje, & Holmes, 2012) which should be highlighted and better understood.

Several UM studies have been conducted at higher spatial resolutions and at different spatial scales. To address the issues raised by Newell and Cousins (2015) above, the pair developed and applied a political–industrial ecology approach to the water supply of Los Angeles using life cycle assessment (LCA) and geographic information systems (GIS) (Cousins & Newell, 2015). The earliest study that spanned across different spatial scales was conducted by Barles (2009), who studied the metabolism of Paris starting from its large peripheral areas down to its dense city center. Pincetl et al. (2012) extended the UM framework by including “geographic specificity,” in addition to other factors such as political ecology and ecosystem services. Finally, to integrate MFA into spatial planning policies, Roy, Curry, and Ellis (2015) introduced a spatial allocation of material flow analysis (SAMFA) model and used it to visualize construction material flows in Kildare County, Ireland at the level of electoral divisions. SAMFA was then used to construct alternative scenarios and determine their outcomes.

Another issue of urban MFA studies is in its “overly broad categorization of materials” (Rosado, Niza, & Ferrão, 2014), such as fossil fuels, minerals, and biomass in the Eurostat methodology (Eurostat, 2001). Although improvements have been made to record material flows in finer detail, such as in the 2013 Economy-wide Material Flow Accounts (EW-MFA) questionnaire (Eurostat, 2013), urban MFA studies typically summarize their results in a few broad categories. This summarization hides the type of material (e.g., aluminum or copper) and the form they are in (e.g., raw, semifinished or finished product). Understanding the form they are in is valuable in making decisions on local sourcing and the potential reuse of secondary materials which contribute to a circular metabolism (Kalmykova & Rosado, 2015). Rosado et al. (2014) addressed this issue by developing the urban metabolism analyst (UMAn) model which widened the number of material categories to 28. Voskamp et al. (2017) also acknowledged this issue and proposed an enhanced urban Eurostat method involving 32 material categories.

Compounding the issues that MFA faces is its high dependency on appropriate data of material flows across time and space, as well as the lack of said data (Decker, Elliott, Smith, Blake, & Rowland, 2000; Kennedy et al., 2007; Minx, Creutzig, Medinger, & Ziegler, 2011; Pincetl et al., 2012; Shahrokni, Lazarevic, & Brandt, 2015a). Because of this, studies have resorted to using “top-down scaling and estimation” (Baynes & Wiedmann, 2012). While national data sources are preferred in the economy-wide MFA methodology (Eurostat, 2013), these data sources are diverse and vary widely across territories. For example, a 2012 MFA study in Amsterdam conducted by Voskamp et al. (2017) involved 32 databases providing data on local extraction, imports and exports, waste treatment, and flows to nature. In another case, an MFA study in Lisbon from 2003 to 2009 conducted by Rosado et al. (2014) involved 16 databases providing data on transportation, trade, production, and waste. In the case of foreign trade, the MFA methodology makes use of existing goods classification systems such as the Standard International Trade Classification (SITC) or the Combined Nomenclature (CN) in the European Union. MFA studies in Singapore conducted by Schulz (2007) and Chertow, Choi, and Lee (2011) use the United Nations International Trade Statistics Database (UN COMTRADE) which offers foreign trade data by SITC codes.

However, beyond the usual data sources of aggregated national accounts, the community has put forth new sources of information as indicators of urban metabolism. Hubacek, Feng, Minx, Pfister, and Zhou (2014) suggested building “spatially explicit footprint models” upon “the big data agenda” such as using social media to determine consumer consumption patterns. Shahrokni et al. (2015a) identified potential data sources for developing a smart urban metabolism such as using road vehicle Global Positioning System (GPS) traces to inform transportation flows and even credit card statements to inform the consumption of food, goods, and services. With these new sources of spatially explicit data, the methods of analysis will also have to be updated. Li and Kwan (2018) addressed the urgent methodological needs of UM research by proposing “3D geovisualization,” which combines GIS and visualization techniques to understand “complex metabolic processes and patterns in space-time.” The suggested examples of 3D geovisualization in UM research are kernel density estimation (KDE), the space-time aquarium, and thematic layering. Given the limitations of aggregated national accounts and the developments in gathering and analyzing data, the time is ripe for an update of data sources and methodologies in UM research.

The domain of transportation, particularly of freight, is closely related to UM and contributes to our understanding of it. Keeping with the metaphor, just as the city’s metabolism is likened to a human body’s metabolism, the freight transportation system is likened to our circulatory system. The freight transportation system carries goods for the city to function, just like how our blood carries oxygen and nutrients to different parts of the body for its metabolism. Fischer-Kowalski, Krausmann, and Smetschka (2004), Fischer-Kowalski, Gaube, and Rainer (2006) earlier identified the link between freight transportation and the material flows of an area. They then modeled the relation between material inputs and freight transport statistics and applied it to both modern cities and historical societies. There has also been much development in data availability.
within the freight transportation domain, which is attributed to the proliferation of vehicle and smartphone-based GPS devices for navigation and location services. These devices can precisely capture material and goods movement in high resolution.

1.2 | Motivations and objectives

Considering the issues and opportunities discussed above, we bring together advancements in freight data collection and UM, demonstrating the use of freight data to better inform MFA and address its gaps. We achieve this by exploring two freight transportation-related data sources that are spatially explicit and of high resolution. First, we conduct MFA at the subnational scale of the United States using commodity flow data and its derivative products. Subsequently, we apply the method of spatial aggregation in a hexagonal grid to analyze GPS-based truck driver activity data in the city-state of Singapore. Through our explorations, we aim to uncover the internal processes of the city to better understand material and goods movement. This knowledge will aid in identifying opportunities for material reuse and recycling to achieve greater circularity, and bring us closer to a consumption-based, finer-resolution approach to MFA that more effectively captures human activities and its impact on urban environments.

2 | COMMODITY FLOWS

2.1 | Introducing commodity flow data and its derivative products

Commodity flow surveys (CFS) have been conducted within the freight transportation domain to help city and transport planners better understand the exchange and movements of goods or commodities within the economy. CFS have been conducted regularly in several countries, like the United States, Norway (Statistics Norway, 2016), and Sweden (Petterson, 2018; Transport Analysis, 2017), and at the metropolitan level, like in the Tokyo Metropolitan Freight Survey (Hyodo, Kuse, Hagino, Takebayashi, & Endo, 2007; Shimizu, Hyodo, Takebayashi, Kuse, & Hagino, 2007).

The U.S. CFS is conducted every five years, with the latest being in 2017. Through questionnaires sent to business establishments, information about individual shipments such as weight, commodity codes, modes, origins, and destinations are obtained (United States Census Bureau, 2015). The locations of establishments and shipment destinations are collected in the form of postal (zip) codes, but the full dataset containing these postal codes is not made publicly available in order to protect the privacy of business establishments.

Even though the U.S. CFS is already a large undertaking, it alone does not give a complete picture of freight movements. For example, it does not capture imports with foreign origins and materials transported by pipelines. Building upon the U.S. CFS, the Freight Analysis Framework (FAF) provides greater detail of freight movements by integrating data from a wide variety of sources across multiple industries such as agriculture, municipal waste, and oil and gas. Foreign trade data is also accounted for with data from the U.S. Census Bureau. The FAF then estimates missing or suppressed data using models and imputation techniques, such as iterative proportional fitting (IPF), log-linear, and spatial interaction models (Hwang et al., 2016). There have been multiple versions of the FAF. The latest publicly available FAF is in its fourth version (FAF4) and is based on the 2012 U.S. CFS. Another similar product which provides details of commodity flows in the United States is the commercially available TRANSEARCH database, developed by IHS-Global Insight (IHS-Global Insight, 2018). Compared to the FAF, TRANSEARCH is based on county-level economic models which is then supplemented by other public and proprietary datasets. Some proprietary datasets include data from Reebie Associates’ Motor Carrier Data Exchange Program, which “provides information on actual market-to-market trucking industry movement activity” (Cohen, Horowitz, & Pendyala, 2008), and data from other IHS-Global Insight divisions, such as agriculture, chemical plants, and automotive plants (Stinson, Hill, & Palmer, 2015).

There is a strong link between current MFA methodologies and commodity flows in terms of the classification of materials, making commodity flow data compatible with MFA studies, which typically obtain material flow data at the commodity level. This link between materials and commodities has been formalized in the Eurostat methodology (Eurostat, 2001) which relates Harmonized System (HS) or Standard International Trade Classification (SITC) codes to its main material components.

2.2 | Data and methods

To apply commodity flow data in MFA, we first make use of the FAF4 database to conduct MFA at the subnational scale of the United States. The online FAF4 Data Extraction Tool (Center for Transportation Analysis, 2017) provides public access to the value and tonnage of freight movements in the United States to the level of 2-digit Standard Classification Transported Goods (SCTG) commodity codes. The domestic, import, and export flows in U.S. tons of each commodity code originating and ending at each FAF region in the year 2016 were obtained from the FAF4 Data Extraction Tool user interface. In the case of FAF4, domestic flows have origins and destinations within the United States, while import and export flows have origins and destinations outside of the United States, respectively. In implementing the U.S. CFS, the country is divided into 132 CFS areas which form the geographical strata in the survey sampling (United States Census Bureau, 2015). As the FAF is based on the U.S. CFS, FAF regions closely follow these CFS areas (Hwang et al., 2016). In order to make a
Net national material accumulation: +4.67 Mt

**FIGURE 1** Net accumulation and removal of construction materials per FAF4 region in the United States, 2016 (in U.S. megatons). The data is from the Freight Analysis Framework Version 4 (FAF4) Data Extraction Tool. One U.S. ton = 0.907184 metric tons

Note. Figure 1 created with the ggplot2 package in R.

comparison against a typical "black box" MFA study, we also obtained the national import and export flows for each commodity code from FAF4.

Using the R programming language, the net flow of material for each FAF region and commodity code was calculated by taking the total inputs to the region (all domestic shipments ending in the region and all imports to the region) and subtracting the total outputs from the region (all domestic shipments originating from the region and all exports from the region). This calculation can be expressed by Equation (1):

\[
\text{Net flow}_i = \sum_{j \in J} d_{ij} + \sum_{k \in K} f_{ik} - \sum_{j \in J} d_{ij} - \sum_{k \in K} f_{ik}
\]

where \(\text{Net flow}_i\) is the net flow of material for an FAF region \(i\); \(J\) and \(K\) are the sets of regions and foreign countries respectively; \(d_{ij}\) is the domestic flow from region \(i\) to region \(j\); and \(f_{ik}\) is the foreign flow from region \(i\) to country \(k\).

These net flows were visualized by obtaining geospatial data of the FAF regions in the shapefile format from the FAF4 website. While FAF4 data exists for all SCTG commodity codes, such as live animals and fish (SCTG code 1), coal (15) and wood products (26), the following results will focus only on construction materials: namely building stones (10), natural sands (11), and gravel (12).

### 2.3 Results

Figure 1 is a map showing the net accumulation and removal of construction materials by mass. The map shows these values per FAF region in the United States, for the entire year of 2016. At the national level, 6.14 U.S. megatons (Mt) of construction materials were imported while 1.47 Mt were exported, resulting in a net national material accumulation of +4.67 Mt. At the subnational level, a large net removal of materials is observed in the northeastern region of the United States in the state of Michigan, and in the southeastern region of the state of Florida. A large net accumulation of materials is observed in the southern region in the state of Texas and Louisiana. The top five regions of net accumulation and removal of construction materials are annotated in Figure 1.

The individual flows of a particular material—natural sands (SCTG Code 11)—were mapped to uncover local flow patterns. As the flows of natural sands are most pronounced in the state of Florida, we focus our analysis on that area. Figure 2 shows the flows between and within the FAF4 regions in the state of Florida. The remainder of Florida contributes to some of the largest flows, with 54.4 Mt flowing within the region, and a total of 26.6 Mt flowing to Orlando–Deltona–Daytona Beach. The flows between regions generally leave the remainder of Florida toward the other regions. On the other hand, Orlando–Deltona–Daytona Beach has the highest net accumulation of +25.0 Mt, with the remainder of Florida being its only source of natural sands. Apart from the significant flow within Miami-Fort Lauderdale-Port St. Lucie (11.2 Mt), the region imports virtually all its
natural sands (98.6%) from the remainder of Florida. All these observations cement the remainder of Florida as an important supplier of natural sand within the state.

3 TRUCK DRIVER ACTIVITY SURVEYS

3.1 Introducing truck GPS data and truck driver activity surveys

Within the freight transportation domain, vehicle surveys and driver surveys are conducted to better understand truck trajectories and activities. Through global navigation satellite systems (GNSS), truck geo-spatial data are also collected by businesses to track and manage their fleets’ operations. Eventually, transport researchers utilize this data to improve the models of freight transportation (Kuppam et al., 2014). When analyzed at scale, this data is valuable for transport planners to assess the usage of the transportation network and prioritize infrastructure upgrades. For example, the American Transportation Research Institute (ATRI) has access to a large amount of truck GPS information (approximately 1 billion latitude-longitude positions over spans of 1–2 weeks at 30-second intervals) and analyzes it to identify costly bottlenecks and measure truck flows across the United States Interstate Highway System (Short, 2014).

However, GPS data alone gives no information of the type and volume of goods transported. Increasingly, using sensing technologies and more sophisticated survey instruments, the freight research community is able combine “both freight vehicle tracking as well as a follow-on driver activity survey” (Alho et al., 2018) to validate truck stop activities with truck drivers, including the type and volume of commodities handled (Teo et al., 2015). This allows us to form a more complete picture of goods movements in an urban area. One example is the future mobility sensing (FMS) survey platform developed by the Singapore-MIT Alliance for Research and Technology (Zhao, Ghorpade, Pereira, Zegras, & Ben-Akiva, 2015). Combining raw GPS data and contextual information, the survey platform uses machine-learning algorithms to infer the truck’s stops and activities (Teo et al., 2015; Zhao et al., 2015). The inferred information is then presented to the truck driver for validation through an online interface (Figure 3). This process is less burdensome than traditional survey methods and allows for data validation at scale. Altogether, these developments can now capture material and goods movements in a way that is both spatially explicit and at high resolution, facilitating a more detailed approach to MFA.
FIGURE 3 Online user interface of the truck driver activity survey. Truck drivers can enter details of the activity at each stop, such as pickup, delivery, or resting

TABLE 1 Outline of the truck driver activity survey dataset

| Field                                | Details                                                                 |
|--------------------------------------|-------------------------------------------------------------------------|
| Tour and vehicle specific            |                                                                         |
| Vehicle type                         | For example, articulated vehicle, tipper truck, detachable trailer      |
| Stops                                | Number of stops in the tour                                            |
| TourID                               | A unique identifier of each tour                                       |
| Stop specific                        |                                                                         |
| Latitude, longitude                  | Latitude and longitude of the stop location                            |
| Date and time                        | Provides date and time of the start and end of the stop                |
| Activity                             | For example, pickup, delivery, refueling, queuing, mealtime, resting    |
| Place type                           | For example, construction, retail, warehouse, vehicle park             |
| Pickup/delivery specific (only applicable to pickups or deliveries) |                                                                 |
| Pickup volume                        | Volume of goods picked up (e.g., ½ truck, ¾ truck, full truck)         |
| Pickup type                          | Type of good picked up (e.g., construction, minerals, metals)          |
| Delivery volume                      | Volume of goods delivered (e.g., ½ truck, ¾ truck, full truck)         |
| Delivery type                        | Type of good picked up (e.g., construction, minerals, metals)          |

3.2 Data and methods

Using the aforementioned FMS survey platform, we utilize GPS-based truck driver activity survey data obtained from a sample of trucks over five consecutive days in the period of 2017–2018 in Singapore. The trucks were surveyed in multiple batches over the survey period. The dataset consists of stop locations of trucks validated by their respective drivers, as well as the nature of activity conducted at the stop (pickup, delivery, refueling, or resting), and the type (construction, minerals, metals, etc.) and volume of goods picked up or delivered (if any). Table 1 outlines the information contained in the dataset. For more details on the data collection methods, refer to Alho et al. (2018).

Using the R programming language, a subset of the data was extracted to facilitate subsequent analysis. Only tours involving the pickup and delivery of construction materials and minerals, and tours that reported pickup and delivery volumes in truckloads were considered. The resulting subset consisted of 749 tours involving 173 vehicles. Loose construction materials, such as sand, are most often transported using dump (tipper) trucks. With an estimated capacity of 15 m$^3$/truckload based on manufacturer specifications (Mitsubishi Fuso Truck & Bus Corporation, 2016), a total of 58,695 m$^3$ of construction material was hauled. By measuring the length of the route taken according to the reported GPS locations, the vehicles in the dataset travelled a total distance of 153,269 km.

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1 The estimation was done based on a typical tipper truck in our dataset—in this case a Mitsubishi Fuso FV51 series 25-foot truck—which accounts for 35.8% of the trucks in our dataset. Based on specifications of the model published by Mitsubishi (Mitsubishi Fuso Truck & Bus Corporation 2016), which included a technical drawing of the vehicle, we arrived at a volume of about 15 m$^3$. 
Of the selected tours, a separate dataset was created which only contained stops that involved pickups and deliveries. This new dataset will be used to conduct the spatially explicit urban MFA. The pickup and delivery volumes were recoded from a vehicle-centric one to a location-centric one. For example, a pickup of “1/2 truckload” recorded by a driver at a given location is recoded as a removal of “−0.5” truckloads. On the other hand, a delivery of “3/4 truckload” at a location is recoded as an addition of “+0.75” truckloads.

After recoding the pickup and delivery volumes to numerical values, the locations and volumes of pickups and deliveries were spatially aggregated into a hexagonal grid. The distance between two parallel edges of each hexagon in the grid is 1.8 km (see Figure 4a). For each hexagonal cell in the grid, the value of each pickup and delivery volume was totaled to give a value denoting the net accumulation within, or removal of goods from the cell. A hexagonal grid was chosen as it reduces the edge effects of rectangular grids and can better represent spatial patterns in data like connectivity and movement paths (ArcGIS Pro, 2017; Birch, Oom, & Beecham, 2007). This process is automatically done using the “stat_summary_hex” function in the “ggplot2” R package.
Due to the sensitivity of information, the values of net accumulation and removal were normalized, allowing material flows to be depicted without revealing actual quantities. The normalization step is expressed in Equation (2):

\[
x_i^{\text{normalized}} = \frac{x_i^{\text{actual}}}{\max_i \left\{ \text{abs} \left( x_i^{\text{actual}} \right) \right\}}, \quad x_i^{\text{normalized}} \in [-1, 1]
\]

where \(x_i^{\text{normalized}}, x_i^{\text{actual}}\) are the normalized and actual values of net accumulation (positive) or removal (negative) in hexagon \(i\) respectively; and \(\max_i \left\{ \text{abs} \left( x_i^{\text{actual}} \right) \right\}\) denotes the maximum absolute actual value across all hexagons. \(x_i^{\text{normalized}}\) takes values between -1 and +1.

To illustrate the material flows, further analysis was conducted for the specific set of flows heading toward Location A. This location was chosen because it had the largest magnitude of net removal or accumulation within the sample dataset (see Figure 4a). Following the data processing detailed above, the dataset was filtered to only consider pickups that immediately preceded a delivery at Location A. This dataset was then normalized and visualized in the same way as in Figure 4a. Arrows denoting the direction of flow were drawn for flows that were above 0.3 units.

To provide contextual information, locations of construction-related landmarks in Singapore, such as aggregate terminals, staging grounds, and major construction sites, are overlaid in both Figures 4a,b. This will aid in interpreting the results.

3.3 Results

Figure 4a shows a net removal of construction materials and minerals from major construction sites that involve excavations, followed by a corresponding net accumulation of the material at staging grounds. Net accumulation is generally observed at aggregate material staging grounds in the eastern end of Singapore and at Location A. Net removal is observed at two major construction sites in the north and east of Singapore, and at the terminal for construction aggregate material along the northeastern coast. Location A has the largest magnitudes of flow, with its net accumulation taking the maximum value of +1.0 units.

Figure 4b shows the origins of flows toward Location A. The largest flows come from Location B and from a major construction site in the east. Moderate flows also originate from the immediate area surrounding the staging ground. These areas have low values of net removal or accumulation and do not show up in Figure 4a.

4 DISCUSSION

4.1 Commodity flows

Figure 1 demonstrates the use of disaggregate information of commodity flows in informing the spatial distribution of material use. This is especially valuable in the case of construction materials in the United States, where variation in material accumulation and removal between regions is large.

We observe that the imports and exports are an order of magnitude smaller than the material accumulation and removal of the most significant regions (labeled in Figure 1). This implies that the observed material accumulation and removal is mainly attributed to domestic flows rather than foreign trade.

Further disaggregation into the individual materials gave more interesting results (Figure 2). Focusing on the flows of natural sands brought attention to the state of Florida, which then gave a better understanding of the situation at the local scale. The major flow within the remainder of Florida could be a result of its large geographical area masking its internal flows. Nevertheless, the remainder of Florida is an important source of natural sands in the state, with some regions relying solely on it for sand. The role of natural sands is crucial for the function of the region. Not only is it used for maintaining the beaches that Florida is renowned for, but natural sand is also a key ingredient for the construction industry, such as the production of concrete and glass. The rising costs and uncertain quality of sand obtained by offshore dredging—the usual method for replenishing eroded beaches—are forcing communities to turn to inland sources for sand, which then requires transportation by trucks (Mills & Staats, 2017). It is unknown if this phenomenon is a key driver behind our observations and more research is required in this area.

However, apart from the commodity of natural sands, the analysis uses FAF4 data, which is limited to the level of 2-digit SCTG codes. As a result, there is insufficient detail to further investigate the possible reasons that might explain our observations of other commodities. For example, the SCTG code 10 corresponding to monumental or building stone contains two subcategories: (1) calcareous (containing calcium carbonate) monumental or building stone, and (2) monumental or building stone, other, including slate (U.S. Census Bureau, 2018). Due to the different mineral compositions, items in the two subcategories might have differences in extraction and processing. Therefore, given only SCTG codes to the 2-digit level, it is difficult to fully ascertain the activities and processes that give rise to the material flows that are observed.

As previously mentioned in the introduction, understanding the type of material and the form they are in is valuable in making decisions on local sourcing and potential reuse of secondary materials. We argue that keeping the analysis at the disaggregated commodity level retains this information, which is useful for analysts and practitioners who are keen to know where and in what form the secondary material resides. Commodity flow data enables this disaggregated, and spatially explicit MFA, and is a potential source to be further explored in this field.
Although this analysis was conducted at the subnational level of the United States and does not yet constitute an urban metabolism study, the use of commodity flow data demonstrates the potential of examining commodity movements and precise accumulation on an urban, or even zonal, scale. The full dataset of the U.S. CFS provides information up to the postal (zip) code level, which would be sufficient in generating meaningful insights within cities and harmonizes well with other studies conducted at similar spatial scales, such as those that analyze energy use at high spatial resolutions in New York (Howard et al., 2012) and Los Angeles (Pincetl, Graham, Murphy, & Sivaraman, 2015). Harmonization is crucial for future studies that seek to fuse data to gain a fuller picture of a city’s metabolism, such as examining a building’s energy and water consumption as well as its freight deliveries.

### 4.2 Truck driver activity surveys

By the principle of material balance, the construction material picked up by a truck must be deposited somewhere else, although it was possible that the truck began or ended the data collection period with some construction material on board. Nevertheless, the sum of net accumulation and removal of materials across all hexagons should therefore equal to zero. In Figure 4a, this sum was about 0.67% of the magnitude of the total net accumulation and total net removal across all hexagons. While this is still a small discrepancy when viewed in proportion to the total amount of material moved, it highlights a drawback of truck driver activity surveys which require drivers to self-declare and enter data directly. Another source of uncertainty in the reported volume is the different ways aggregates are packed onto the truck. For example, loose gravel would occupy more volume than fine sand, and a full truck could possibly refer to a truck filled to the brim or a truck that has reached its maximum laden weight. Vehicle technologies like on-board truck weight sensors could overcome these issues by providing real-time information of the truck’s weight as it goes about its deliveries, eliminating the need for drivers to report the amount of material loaded or unloaded and removing the uncertainty of volumetric measurements. However, there are issues in implementation that need to be overcome, like cost, calibration across different vehicle types and manufacturers, and mandating the use of such technologies (Oehry, Haas, & van Driel, 2013).

More work is needed to bring the use of such high-resolution freight data into the mainstream. Even though the survey instruments used in this truck driver activity survey have assisted in automating some parts of the process, such as by prefilling the relevant fields, truck drivers and surveyors still have to spend time responding to and administering the surveys. Participating drivers found the daily verification “tedious,” and a considerable proportion of respondents (45.20%) drop out of the survey (Alho et al., 2018). While there are ongoing efforts to develop more sophisticated freight surveys and improve data quality, practitioners and researchers should consider these survey limitations, especially when expanding the scale of studies to year-long or fleet-wide projects.

The analysis conducted sheds light on the relation between freight transport and material flows. The use of freight transport data allows us to examine the distances traversed by the materials that are embedded in goods or commodities, something that the MFA methodology does not explicitly address (Fischer-Kowalski et al., 2006). While Fischer-Kowalski et al. (2006) examine freight transportation as manifesting from material flows, we have explored the link between freight transport and material flows from a different perspective—using freight transport data to inform the nature of material flows. The transportation impacts of material flows can also be examined, as performed by Kennedy et al. (2007). By incorporating vehicle fuel consumption and emissions modeling, the sustainability of material movements can be measured and ways to reduce its impacts explored. Examining these emissions allows us to better understand the extent of scope 3 emissions, which “occur from sources owned or controlled by other entities in the value chain” (WRI and WBCSD, 2011). In this case, scope 3 emissions would be the emissions from freight transport that support a business’ functions.

The study of the flows of construction materials and minerals reveals the reuse of materials for land reclamation in Singapore. Land reclamation is a material-intensive process. Studies of Singapore’s metabolism by Schulz (2007) and Chertow et al. (2011) show that the domestic material consumption of construction materials dominates Singapore’s material flows. Most of these materials are imported and received at aggregate terminals or seaports (Building and Construction Authority, 2018; Jurong Port, 2018). Materials from major construction sites are also observed to be moved by dump trucks into staging grounds. This material can either be stored temporarily at the staging grounds or loaded onto barges that bring the material out to sea for land reclamation (Ministry of National Development, Singapore, 2012), which explains the locations of staging grounds along the coast. We see one example of this occurring in Figure 4b, with a flow of about 0.77 units from a major construction site in the east to Location A.

### 4.3 Toward high-resolution urban material flow analysis

Our examination of construction materials and minerals in the United States and Singapore serve as case studies to demonstrate the potential benefits of using high-resolution commodity flow and freight transport data respectively to inform MFA. In the case of construction materials and minerals in Singapore, we uncovered the secondary sourcing of materials for land reclamation, which would otherwise be hidden in national-level or urban-scale MFAs. This finding supports the proposal by Voskamp et al. (2017) to incorporate locally sourced resources in the Eurostat MFA.

In the analysis of truck survey data, aggregating material flows to a hexagonal grid offers consistency in the analyses conducted in different areas. Apart from selecting a fixed set of parameters like the diameter of the hexagons, the software-generated hexagonal grid is independent of political and administrative boundaries (such as the census areas in the U.S. CFS), circumventing the problem of standardizing system boundaries in MFA.
studies (Kennedy, Stewart, Ibrahim, Facchini, & Mele, 2014; Voskamp et al., 2017). However, such boundaries still make the process of freight data collection tricky in many cities with porous urban boundaries and a mixed environment of vehicles freely moving between urban, rural, national, and international levels. Singapore, being an island city-state with clear, physical boundaries (Abou-Abdo, Davis, Krones, Welling, & Fernández, 2011; Chertow et al., 2011), is a special case which does not face this problem.

While we have analyzed the spatiality of material flows, these flows also have a temporal dimension. The use of freight transport data in MFA studies opens opportunities for a higher spatiotemporal resolution. Urban MFA studies are typically conducted across years at a yearly resolution and are limited by the frequency of national accounts. In contrast, with real-time GPS tracking, the movement of materials can be recorded in much shorter time increments. The increased spatiotemporal resolution can enhance the potential for material recovery, reuse, or recycling, especially for goods or commodities that have short life spans, and better capture the transformations these goods or commodities go through in its life cycle.

However, reaping the benefits of high-resolution data in urban metabolism studies relies heavily upon having access to such data, or if they are even available in the first place. The case studies we have analyzed make use of data which required a significant amount of resources and effort to collect, something which only entities like wealthy governments can afford. Furthermore, privacy concerns hinder the use of high-resolution data. The full dataset of the U.S. CFS which contains postal codes is not made publicly available in order to protect the privacy of business establishments. Truck GPS data are often held by businesses as proprietary information and businesses will naturally avoid releasing such data to remain competitive. Therefore, researchers must take these concerns into account as accessing and integrating data from multiple stakeholders is reported to be one of the greatest barriers to data-driven urban metabolism studies (Shahrokni, Årman, Lazarevic, Nilsson, & Brandt, 2015b).

5 | CONCLUSION

Through a series of maps and GIS techniques, we have demonstrated the potential benefits of incorporating high-resolution commodity flows and freight transport data to achieve a spatially explicit MFA. In doing so, we have addressed a criticism of confining MFA within a “black box.” By opening the “black box,” we can understand the internal process of secondary material sourcing, which would have otherwise been hidden in usual MFA studies. Furthermore, our techniques offer a way to conduct analyses that are independent of political or administrative boundaries. As data sources with higher spatiotemporal resolution become more available, we can sharpen our understanding of the life cycle of materials embedded in goods or commodities. However, with more disaggregation, we must strive to present information sensibly while keeping in mind the privacy of other stakeholders.

In the age of “big data,” we hope that these explorations encourage MFA researchers and practitioners to incorporate new data sources for studying the city’s metabolism, and for the wider community to increase efforts in improving data collection and privacy. As the stream of data grows and diversifies, future work could look at fusing them meaningfully to form a full picture of the material flows within an urban area. Such high-resolution geospatial datasets could be of population density, land use, or the distribution of water, gas, or other resource consumption. This “thematic layering” (Li & Kwan, 2018) of data will eventually bring us closer to understanding the “people, places, and uses” that drive the material flows in our cities (Pincetl et al., 2012), enabling us to make well-informed decisions toward more sustainable cities.

6 | CODE AND DATA ACCESSIBILITY

The code (in the R programming language) and data used in the analysis of construction material in the United States are available in the Figshare repository via the following link: https://figshare.com/articles/Intotheblackbox2018_zip/6854246.

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CONFLICTS OF INTEREST

The authors have no conflict to declare.

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