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RESEARCH AND ANALYSIS

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Quantifying urban mass gain and loss by a GIS-based material stocks and flows analysis

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Abstract

Rapid urbanization generates substantial demand, use, and demolition waste of construction materials. However, the existing top-down or bottom-up frameworks combining material flow analysis (MFA) and geographic information system (GIS) tend to underestimate both input and output of construction material flows due to insufficient descriptions of key processes in building construction and demolition. To address this limitation, this study identifies four important and complementary processes—construction, demolition, replacement, and maintenance, and integrates them into an improved framework to capture all material flows. We take Xiamen, a rapidly urbanizing city, as a case study to verify this framework. The results show that ~40% of material inputs and ~65% of outputs are underestimated by previous frameworks because they fail to capture material inputs in building maintenance and outputs in construction. These findings indicate a better estimation of such key flows in the modeling framework helps to accurately characterize building material metabolism. Based on systematic counting of material stocks and flows, the improved framework can help design effective policies for urban resource management by explicitly recognizing the spatiotemporal patterns and processes of material metabolism.

KEYWORDS
geographic information systems (GIS), high-resolution urban grids (HUGs), industrial ecology, material flow analysis, urbanization

1 | INTRODUCTION

Cities are continually resulting in the exchange of materials, water, and energy between natural and artificial environments (Chini & Stillwell, 2019; Haberl et al., 2019). When the material inputs of a city exceed its outputs, an imbalance occurs and contributes to the city's mass gain and vice versa (Tanikawa & Hashimoto, 2009; Tanikawa et al., 2015). Many studies have been conducted to quantify urban material inputs and outputs dynamically to understand how a city's mass has changed over time (Augiseau & Barles, 2017; Canning, 1998; Chen, Graedel, et al., 2016; Chen, Shi, et al., 2016; Han & Xiang, 2013; Lanau et al., 2019). For example, China's rapid urbanization over the past three decades has caused massive material inputs in new buildings and infrastructure, and led to significant urban mass gain (Yang & Kohler, 2008). In addition to new buildings, a substantial amount of material inputs has been used to renovate in-use buildings and infrastructures (Wiedenhofer et al., 2015). These retrospective analyses could

TABLE 1 The comparison of material flow quantification by a stock-driven MFA-GIS approach in previous studies and this study

	Construction		Demolition		Replacement		Maintenance	
Construction activities	Input	Output	Input	Output	Input	Output	Input	Output
Tanikawa & Hashimoto, 2009	◯		–	◯				
Han et al., 2018	◯		–	◯				
Miatto et al., 2019	◯		–	◯	△	△		
Heeren & Hellweg, 2019	◯		–	◯	◯	◯	△	△
Guo et al., 2021	◯		–	◯	◯	◯		
This study	◯	◯	–	◯	◯	◯	◯	◯

Note: ◯ Completely considered; △ partly considered; – none in reality.

be combined with socioeconomic drivers (e.g., population growth and lifestyle change) to forecast material demands and urban weight changes in the future under various development scenarios (Bergsdal et al., 2007; Hu, Bergsdal, et al., 2010; Müller, 2006). Changes in urban mass have been shown to significantly affect energy consumption (Buffat et al., 2017), greenhouse gas emissions (Pauliuk & Müller, 2014), and other environmental and socioeconomic issues (Forman & Wu, 2016).

Studies on the spatial distribution of urban mass gain and loss are important to understand the environmental and socioeconomic consequences of urbanization because the content and magnitude of material flows vary geographically. Many popular frameworks that have been developed in recent years leverage geographic information system (GIS), coupled with bottom-up data, to estimate material stocks and flows and map their spatiotemporal patterns (for details, see Table 1). These frameworks usually start at building material stock quantification and then estimate material flows based on the difference of material stocks by process-based assumptions, which belong to the "bottom-up and stock-driven approach" (Augiseau & Barles, 2017). The finest objects in these studies were based on communities/streets (Han et al., 2018; Liu et al., 2022; Reyna & Chester, 2014), individual buildings (Breunig et al., 2018; Kleemann et al., 2017; Tanikawa et al., 2015; Tanikawa & Hashimoto, 2009), and even building's components (Stephan & Athanassiadis, 2018).

However, some available assumptions and theories on material stock and flow quantification at macro scales (e.g., region, country, and city) cannot be directly used at microscales (e.g., individual building and building component) for the following reasons. First, material use in new construction activity was considered as an input flow in previous studies (Han et al., 2018; Heeren & Hellweg, 2019; Reyna & Chester, 2014; Tanikawa & Hashimoto, 2009) but waste generation in this process was usually omitted. Second, the maintenance of in-use buildings would generate both material input and output instead of the net flow before and after the refurbishment (Heeren & Hellweg, 2019). Third, buildings' demolition usually followed a lognormal (Miatto et al., 2017) or a logistic growth (Tanikawa & Hashimoto, 2009) with regard to building's age and the demolition rate can be used to estimate material output for a community (Han et al., 2018), a city (Hu, Voet, et al., 2010), or even a country (Bergsdal et al., 2007; Huang et al., 2017; Müller, 2006; Yang & Kohler, 2008). However, this assumption cannot be adapted to material output quantification at the individual building level because the demolition of an individual building not only is correlated to building's age but also depends on urban planning, building's status, cost-benefit in economy, and residents' willingness (Kohler & Hassler, 2002; Pomponi & Moncaster, 2017; Wuyts et al., 2019, 2020). These various drivers can determine building demolition through complex socioeconomic interactions and therefore lead to nonlinear relationships and feedbacks (Caduff et al., 2014; Kohler & Hassler, 2002). That is why Kohler and Hassler (2002, p. 232) suggested: "There is no relation between the age or condition of an individual building and the probability that it will be demolished."

To fill these gaps, we (1) proposed an improved framework to characterize material metabolism and avoid the underestimation of material flow, especially at the individual building level, (2) took Xiamen, a rapidly urbanizing city in China, as a case study to verify this framework, and (3) examined both the benefits and challenges of combining spatial analysis with material flow analysis (MFA).

2 | METHODS

2.1 | An improved framework for estimating building material metabolism

Our improved framework coupling GIS and stock-driven MFA was built on previous work (Guo et al., 2021; Han et al., 2018; Heeren & Hellweg, 2019; Miatto et al., 2019; Tanikawa et al., 2015) (Table 1). It can systematically describe material flows and thus presents a comprehensive picture of material inputs and outputs (Figure 1). In this framework, GIS was not only used as a data container (e.g., building information, land cover/use changes, remote sensing data, historical images, surveys, and statistics) but also used for data processing and material stocks and flows quantification (Figure 1). Total material stocks were calculated based on total floor area of buildings and material intensities (Section 2.1.1).

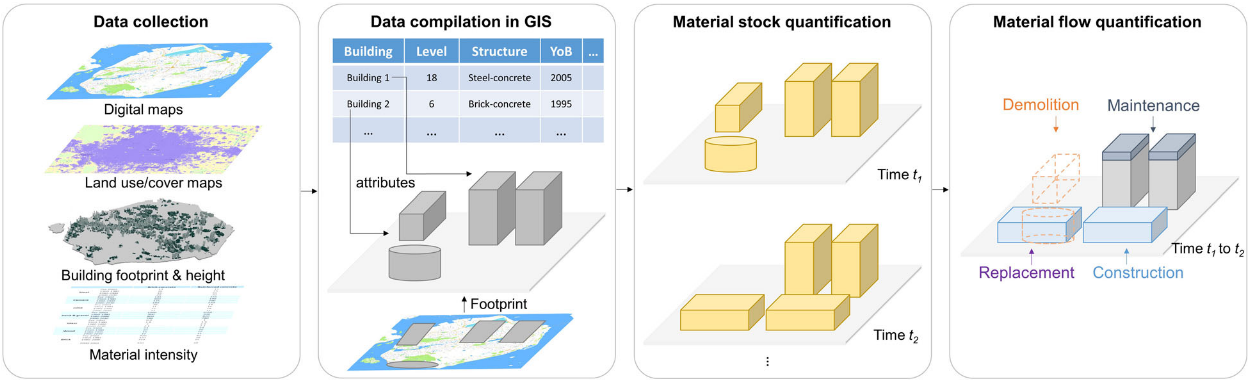

FIGURE 1 A framework combining stock-driven material flow analysis (MFA) and geographical information system (GIS) to simulate material metabolism. This improved framework highlights four typical activities that generate material flows, namely, construction, demolition, replacement, and maintenance

Four complementary processes (construction, demolition, replacement, and maintenance) were used to estimate material inputs and outputs (Section 2.1.2).

2.1.1 | Material stocks

Total material stock is estimated by multiplying total floor area by material intensity:

$$\mathrm{MS}_m^t = \sum Q_{i,s,n}^t \times \mathrm{MI}_{s,m,n}^t \tag{1}$$

where MS is total stock of material m at year t, Q is the total floor area (footprint $\times$ level) of building i with structure s and year of build n, and MI represents the intensity of material m with structure s and year of build n (Table 2).

2.1.2 | Material flows

The difference of material stocks between two time periods equals the material net flow and the difference between total input and output:

$$\mathrm{MS}_m^{t+1} - \mathrm{MS}_m^t = \mathrm{NetFlow} = \mathrm{MIF}_m^{t+1} - \mathrm{MOF}_m^{t+1} \tag{2}$$

where MIF is the total input of material m from year t to $t+1$; MOF is the total output of material m from year t to $t+1$. Four complementary construction activities (construction, demolition, replacement, and maintenance) generate material inputs and outputs. Therefore, total material input (or output) equals the sum of these subinputs (or suboutputs) from the four complementary processes:

$$\mathrm{MIF}_m^{t+1} = \mathrm{MIF}_{i,m,s1}^{t+1} + \mathrm{MIF}_{i,m,s3}^{t+1} + \mathrm{MIF}_{i,m,s4}^{t+1} \tag{3}$$

$$\mathrm{MOF}_m^{t+1} = \mathrm{MOF}_{i,m,s1}^{t+1} + \mathrm{MOF}_{j,m,s2}^{t+1} + \mathrm{MOF}_{j,m,s3}^{t+1} + \mathrm{MOF}_{i,m,s4}^{t+1} \tag{4}$$

where $s1$, $s2$, $s3$, and $s4$ represent the four complementary construction activities, respectively.

Construction

The construction process represents new construction activities on the ground with no buildings (e.g., built-up area instead of farmland) and its net flow of materials equals the total material input for constructing new buildings minus construction waste generation in this process, thus:

$$\mathrm{NetFlow}_{m,s1}^{t+1} = \sum_i \mathrm{MIF}_{i,m,s1}^{t+1} - \sum_i \mathrm{MOF}_{i,m,s1}^{t+1} \tag{5}$$

TABLE 2 Material intensity (MI) for residential building in Xiamen, China

Material	Time	Structure: Brick concrete (kg/m^2)	Structure: Reinforced concrete (kg/m^2)
Steel	Pre-1960	14	15
	1960–1980	16	25
	1980–2000	18	65
	2000–present	20	70
Cement	Pre-1960	145	155
	1960–1980	160	190
	1980–2000	175	200
	2000–present	180	220
Lime	Pre-1960	30	14
	1960–1980	31	16
	1980–2000	32	28
	2000–present	33	32
Sand and gravel	Pre-1960	1000	1020
	1960–1980	900	930
	1980–2000	800	820
	2000-present	740	780
Glass	Pre-1960	0.9	1
	1960–1980	1.8	1.9
	1980–2000	2	2.1
	2000–present	2.1	2.2
Wood	Pre-1960	24	24
	1960–1980	20	20
	1980–2000	16	16
	2000–present	12	12
Brick	Pre-1960	420	40
	1960–1980	370	30
	1980–2000	350	15
	2000–present	320	10

where MIF_{s1} is material input for constructing new buildings *i* and these input materials are converted to material stocks (MS) in the next time period $t + 1$. Meanwhile, new construction also generates construction waste and thus results in material output (MOF_{s1}) (e.g., ~50 kg/m^2 in China) (Chen et al., 2006; Hu, You, et al., 2010; Wang et al., 2014).

Demolition

The demolition process represents the demolishing of in-use buildings (e.g., to increase green space or open space within a city) and thus only generates output flow:

$$\text{NetFlow}_{m,s2}^{t+1} = -\sum_j \text{MOF}_{j,m,s2}^{t+1} \tag{6}$$

where MOF_{s2} is material output and its value equals the material stock in the demolished building *j*.

Replacement

In contrast to the demolition process, the replacement represents the process of constructing new buildings on the site where old buildings were demolished right after (e.g., urban renewal), and therefore includes both in-use buildings demolition and new construction that occur at the same geographic location during t to $t+1$ period, thus:

$$\text{NetFlow}_{m,s3}^{t+1} = \sum_i \text{MIF}_{i,m,s3}^{t+1} - \sum_j \text{MOF}_{j,m,s3}^{t+1} - \sum_i \text{MOF}_{i,m,s3}^{t+1} \tag{7}$$

where MIF_{s3} is material input for constructing new building i (equation refers to the construction process) and MOF_{s3} includes both material output from demolished building j (equation refers to the demolition process) and construction waste generated by the new construction (equation refers to the construction process). The difference between the replacement process and the construction process (or demolition process) is that the latter only has construction (or demolition) activity in the same geographic location but the former has both. It is important to include such a process into the improved framework to reduce the underestimation of material flow during t to $t+1$ period by retrieving the total magnitude of input and output instead of their "net" effect.

Maintenance

The maintenance process represents the renovation of building components when certain components rather than the entire building reach the end of their service lives. Therefore, it generates both material input and output. Here, a demolition rate of components is used to estimate the magnitude of material output (Reyna & Chester, 2014; Tanikawa & Hashimoto, 2009) with the following assumptions:

- The demolition rate here does not represent how many buildings are demolished within a community or a city (Han et al., 2018; Reyna & Chester, 2014; Tanikawa & Hashimoto, 2009), but represents the broken components (e.g., roof, outwall) of each building. The demolition rate is estimated according to construction structure (e.g., brick-concrete and reinforced-concrete).
- We assume that buildings would use similar types of components instead of broken ones during t to $t+1$ period, thus a replacement of materials at the end of life by new ones (Stephan & Athanassiadis, 2018).

Therefore, we have:

$$\text{MOF}_{m,s4}^{t+1} = \sum_i Q_{i,m} \times \left(D_i^{t+1} - D_i^t\right) \times \text{MI}_{i,m}^{n} \tag{8}$$

$$\text{MIF}_{m,s4}^{t+1} = \sum_i Q_{i,m} \times \left(D_i^{t+1} - D_i^t\right) \times \text{MI}_{i,m}^{t+1} \tag{9}$$

$$D_i{}^t = \frac{1}{(t-n)\text{SD}_i\sqrt{2\pi}} \cdot e\left(-\frac{\left[\ln(t-n) - \text{Mean}_i\right]^2}{2\text{SD}_i{}^2}\right) \tag{10}$$

where MS^n is the material stock in the building i at the year of build n, and $D_i{}^t$ is the demolition rate of building i at the year t. Its value is related to the average lifespan (mean) and standard deviation (SD) of building i. The average lifespan of building i is given by surveys (e.g., 30-year for brick-concrete structure and 50-year for reinforced-concrete structure (Han & Xiang, 2013; Hu, Bergsdal, et al., 2010; Huang et al., 2017; Yang & Kohler, 2008) or the year when the ratio of remaining-to-demolished parts is 50:50 (Han et al., 2018; Komatsu, 1992).

2.2 | Study area and data compilation

Xiamen, a city formerly known as Amoy, is one of the most livable cities in China with lengthy seaside, Buddhist temples, art galleries, and beautiful parks. It is comprised of several islands, of which the Xiamen Island is the largest and also where the downtown is located. This island has a total of ~150 km^2 area and houses more than 2 million residents, resulting in a high density of ~13,000 person/km^2 (higher than Shenzhen, Singapore, and Hong Kong). Large-scale construction activities, renovation of old cities, and maintenance of in-use buildings lead to demands for large amounts of construction materials and generate a substantial volume of construction and demolition waste (CDW), which poses considerable pressure on the environment and human health if not managed properly. However, the construction and CDW treatment require official permission from the Xiamen Construction Bureau (XCB) but less information is known on waste flows.

To understand material metabolism in Xiamen Island, we digitalized footprints of buildings as vector polygons in the ArcGIS (version 10.2) based on historical atlases (1960–2018) downloaded from Google Earth (version 6.2) (Figure 1). A unified attribute table was further created based on these building polygons to calculate footprint area. We checked building levels on the street view in Baidu Map and vintage in real-estate websites (www.Fang.com and www.lianjia.com) and finally recorded them in the attribute table of building polygons (Figure 1). Field surveys were conducted between March 2018 and October 2019 for data filling (e.g., missing footprint and floor number of new buildings) and cleaning (e.g., vintage information for the buildings with a long history). After the data preparation and compilation in the vector datasets, we accounted for material stocks

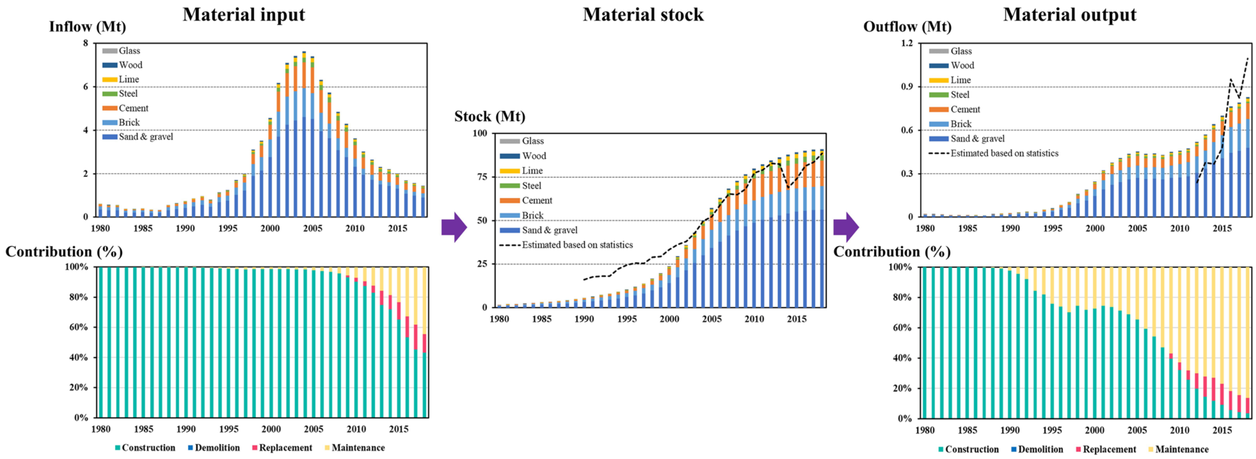

FIGURE 2 Material metabolism of residential buildings in the Xiamen Island, China (1980–2018). Dotted lines represent material stocks and construction and demolition waste generation in statistics (see Section 2.2). Underlying data for this figure are available in Supporting Information S1

and flows in 250 m × 250 m grids. We collected the residential area per capita and total population from statistics (XBS, 2019) and multiplied them to estimate total residential building stock in Xiamen to validate the simulated results. We also collected total amount of CDW generation during 2012–2018 in Xiamen from XCB. We excluded the proportion of excavated soil generated from building construction (Chen & Liu, 2021) and on the mainland part of Xiamen (because we only selected the Xiamen Island, the downtown area of Xiamen, as the study area) from the statistic CDW data and finally used the rest of the values to compare with the output flow simulated by our model.

3 | RESULTS

3.1 | Temporal changes of material stocks and flows

Total in-use stock of building materials in Xiamen grew rapidly from 1.58 million metric tonnes (Mt) in 1980 to 91.13 Mt in 2018, with an average annual growth rate at ~11% (Figure 2). During this period, material stocks first experienced a steady growth in the 1980s and hit 20 Mt at the beginning of the new century; then grew rapidly during 2000–2010 and increased to ~60 Mt; and finally reached 91 Mt in 2018 (Figure 2), which equals to ~45 t per capita.

Material inputs showed a reversed U-shaped tendency during 1980–2018. More specifically, material inputs increased from the 1980s, peaked in 2003 (~8 Mt/year), and then declined (Figure 2). New construction activities dominated material inputs before 2005 because of the rapid urbanization in Xiamen (Figure 2). After 2005, material inputs generated from the maintenance and replacement activities increased rapidly and accounted for ~45% and ~12% in 2018, respectively (Figure 2). Material outputs generally kept growing since the 1980s and hit ~0.8 Mt until 2018 (Figure 2). Before 2005, solid waste generated from new construction activities dominated material outputs (Figure 2). After that, the maintenance and replacement activities had generated more and more wastes and finally contributed to ~85% and ~10% in 2018, respectively (Figure 2). The substantial contributions of waste generation (material output) from construction and maintenance activities indicated that it is necessary to identify such activities for material flow quantification (see more in Section 4.1).

3.2 | Spatial patterns of material stocks and flows

Material stocks kept increasing in both spatial extent and density on Xiamen Island (Figure 3). In the 1980s, only the downtown area, located in the southwest corner of the island, had materials stocks (Figure 3). From 1990 to 2000, more material stocks were accumulated in the suburban area (the east and middle parts of the island) than in the downtown area due to the rapid development of new economic and technological districts (e.g., Xiamen Hi-tech Industrial Development Zone was established in the 1990s) (Figure 3). After 2000, material stocks not only kept increasing in the downtown area but also proliferated in almost the whole island (Figure 3).

Continuous material inputs led to increased accumulation of material stocks (Figure 3). The spatial hotpots of material inputs occurred at the downtown area (the southwest corner of the island) in the 1980s, then moved to the suburban area (the east and middle parts of the island) during 1990–2000, and finally concentrated at the northeast corner (e.g., Wuyuanwan new city) in the 2010s. The spatial extent of CDW generation

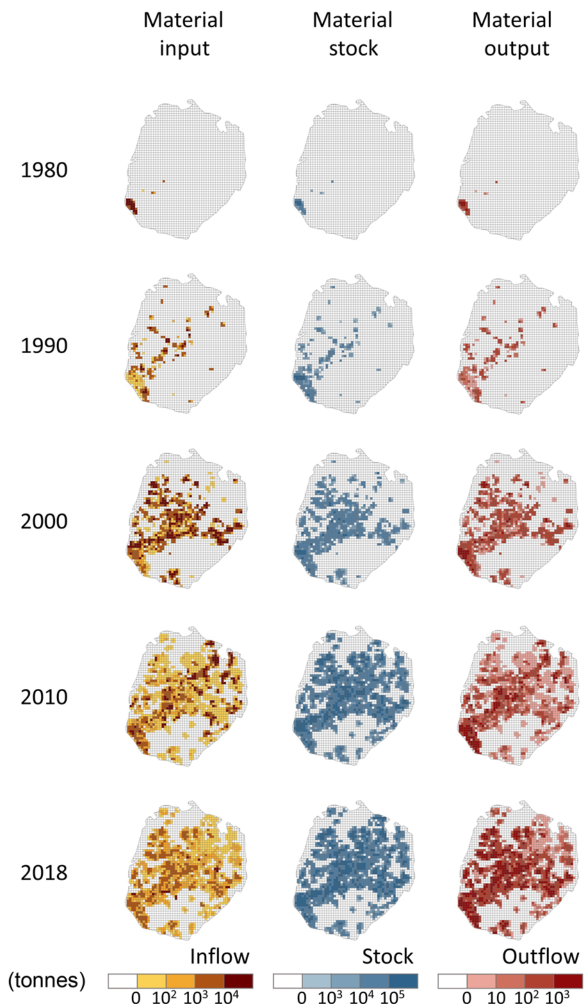

FIGURE 3 Spatial patterns of material metabolism in residential buildings of the Xiamen Island, China (1980–2018). Underlying data for this figure are available in Supporting Information S2

(materials outputs) kept pace with material inputs but the magnitude varied (Figure 3). Before 2005, new construction activities dominated CDW, leading to a similar pattern between the material inputs and outputs (Figure 3). After 2005, the demolition and maintenance of buildings contributed to more and more CDW due to a relatively short lifetime of Chinese residential buildings (Figure 3) (relative to those in Europe) (Wiedenhofer et al., 2015).

4 | DISCUSSION

4.1 | Advances and uncertainties of the improved MFA-GIS framework on material flow quantification

The improved stock-driven MFA-GIS framework developed in this study can systematically identify key processes in building construction, demolition, and refurbishment, and therefore can present a complete picture of material inputs and outputs instead of "net" flows estimated by the difference between the stocks at different time frames (Equation 1). Specifically, this framework can not only quantify the material input by new construction activity and waste output by building demolition (Han et al., 2018; Tanikawa & Hashimoto, 2009) but also characterize substantial contributions of material input and output from building replacement (Guo et al., 2021) and maintenance (Heeren & Hellweg, 2019; Miatto et al., 2019) (Table 1). The replacement activity is one of the main parts that was ignored, which potentially led to the underestimation of total material flow in previous frameworks. A new assumption was made to avoid the underestimation of material inputs and outputs generated from building maintenance and related refurbishment (Table 1). Besides, the CDW generated in new construction activity was usually omitted by previous stock-driven GIS-MFA frameworks (Table 1) and could contribute to a certain amount of CDW, especially in areas experiencing rapid urban expansion (see Figure 3).

The high accuracy in building stock simulation and CDW prediction proved that this MFA-GIS framework performed well in material stock and flow quantification (Figure 2). The decreasing gap between simulated and in-situ building stock, from −28% in 2000 to +3% in 2018, and ~89% of accuracy in CDW generation prediction during 2012–2018 was mainly due to data gaps or high uncertainty for those buildings with long history. The missing or inaccurate data on old buildings, which usually are low-rise brick-concrete buildings and have been demolished and replaced by new buildings (Liu, Chen, et al., 2020), would lead to an underestimation of material stocks and flows (Figure 2). For those identified buildings, the total floor area quantified by multiplying building footprint and level could potentially be overestimated because sometimes, the floor area of upper stories is smaller than the bottom's, resulting in <9% of uncertainty.

Besides, GIS has shown great potential for characterizing spatiotemporal patterns of material stocks and flows by coupling with MFA, yet these prevalence frameworks, including our's, are still quasi-spatial in nature due to a lack of one or more variables that are a function of space, or can be related to other spatial variables (e.g., materials exchanges between neighbors). Based on the improved MFA-GIS framework, we could systematically quantify the temporal flows of materials for each grid or building typology but it is still difficult to describe spatial flows within them (e.g., transportation of CDW from a demolishing building to a landfill), because these spatial flows or processes usually occur at daily or monthly scales, mismatching those estimated by frameworks at annual or decadal scales (e.g., Miatto et al., 2019). This limitation not only obscures spatial flow characterization but also hinders the development of MFA from a quasi- into spatially explicit framework. Therefore, comprehensively and accurately describing both spatial and temporal flows is the key to developing the next generation of MFA framework and better understanding material metabolism in space and across time.

4.2 | Policy implications for urban management

The spatial features of material stock and potential CDW (output flow) generation simulated based on the updated framework are key information to design recycling facilities planning and optimize the waste management system. In Xiamen, many spatial hotspots of CDW generation have been revealed in Figure 2. For example, the Siming district, as the old city and downtown area of Xiamen, had the highest rate of CDW generation (>1000 tonnes/km^2·yr). After 2010, many local hotspots occurred in the Huli district (100–1000 tonnes/km^2·yr), where a new economic and high-tech district was developed in the 1990s. These hotspots are potentially key areas for planning local recycling facilities or logistic centers. Meanwhile, a potential quantity of CDW generated in the next few years could further be predicted by the updated framework, which provides temporal information to help plan corresponding recycle or treatment capacity. Both these spatial and temporal dynamics of CDW can certainly support a city-level management planning.

The MFA-GIS framework developed in this study improves the characterization of urban material metabolism and provides spatiotemporal maps of material stocks and flows during urbanization and infrastructure construction. In China, urbanization and infrastructure construction usually cause large amounts of material inputs and substantial environmental effects in the surrounding areas due to the pollution-intensive materials (e.g., steel) and short-distance transportation (e.g., cement) (Liu, Chen, et al., 2020; Pauliuk & Müller, 2014). Therefore, spatiotemporal hotspots of material inputs are key to understanding embodied environmental burdens across space and time (Stephan & Athanassiadis, 2017). In-use material stocks are usually correlated to socioeconomic development (Han et al., 2018) and service suppliers (Pauliuk & Müller, 2014), and therefore could be used to indicate levels of urbanization (Liu, Li, et al., 2020), human welfare or well-being (Lanau et al., 2019), and sustainability (Haberl et al., 2019). At the end of service lives, spatiotemporal maps of material outputs provide hotspots of CDW generation and can thus help to design the effective planning of reuse, recycle, and landfill facilities. It can also help to optimize transportation systems according to the trade-off between transportation cost and treatment subsidy and this optimization could change the current territory-based and self-sufficient scheme (PGBM, 2020) to a cross-regional one (Chen & Liu, 2021).

5 | CONCLUSIONS

Spatiotemporal dynamics of material stocks and flows are important to understand the environmental and socioeconomic consequences of urbanization. In this study, we identified four important and complementary processes—urban construction, demolition, replacement, and maintenance, which can significantly affect material stocks and flows, and integrated them into a new framework based on the bottom-up approach combining material flow analysis (MFA) and geographic information system (GIS). We took Xiamen, a rapidly urbanizing city, as a case study to verify this framework and the results showed that the previous bottom-up frameworks tended to underestimate both input and output of construction material flows due to insufficient descriptions of key processes in building construction and demolition. These findings indicate a better estimation of such key flows in the modeling framework helps to accurately characterize material metabolism and effectively design urban policies for resource management by explicitly recognizing the spatiotemporal patterns and processes of materials.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article and its supporting information files.

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