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Towards a more circular construction sector: estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks

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Abstract

Humans are extracting and consuming unprecedented quantities of materials from the earth's crust. The construction sector and the built environment are major drivers of this consumption which is concentrated in cities.

This paper proposes a framework to quantify, spatialise and estimate future material replacement flows to maintain urban building stocks. It uses a dynamic, stock-driven, and bottom-up model applied to the City of Melbourne, Australia to evaluate the status of its current material stock as well as estimated replacements of non-structural materials from 2018 to 2030. The model offers a high level of detail and characterises individual materials within construction assemblies for each of the 13 075 buildings modelled.

Results show that plasterboard (7 175 t), carpet (7 116 t), timber (6 097 t) and ceramics (3 500 t) have the highest average annual replacement rate over the studied time period. Overall, replacing non-structural materials resulted in a significant flow at 26 kt/annum, 36 kg/(capita·annum) and 721 t/(km²·annum). These figures were found to be compatible with official waste statistics. Results include maps depicting which material quantities are estimated to be replaced in each building, as well as an age pyramid of materials, representing the accumulation of materials in the stock, according to their service lives. The proposed model can inform decision-making for a more circular construction sector.

Keywords

Material flow analysis; maintenance; Melbourne; urban mining; life cycle assessment; urban metabolism

1. Introduction

Over the last century, the global population and material consumption increased by a factor of ~4 and ~10, respectively (Krausmann *et al.*, 2009). According to the same study, the use of construction minerals increased by a factor of 42. This dramatic increase in annual material consumption per capita has resulted in the accumulation of 792 Gt of materials in in-use stocks of buildings, buildings, infrastructure and other manufactured goods in 2010. This represents a stock accumulation 23 times higher than at the start of the twentieth century (Krausmann *et al.*, 2017). Krausmann *et al.* (2017) also indicate that growth in material use and accumulation is unevenly distributed across the world, with stock growth in China accelerating exponentially over the last decades. For instance, cement production in China alone accounted for 55% of global production for the year 2010. From 2011 to 2013, China produced as much cement as the United States over the twentieth century (Smil, 2013).

The unprecedented material consumption experienced after 1945 can be associated with the creation and expansion of cities across the world as well as the rapid increase of global urban population. The latter is projected to further increase by ~3 billion people by 2050 (United Nations - Department of Economic and Social Affairs (UN), 2014), most of which in developing economies. This is expected to lead to the creation of new urban areas, and associated additional material consumption.

When aligning these figures, the material requirements of modern societies, spearheaded by cities and urban centres, become a self-evident societal, environmental and economic concern (Matthews *et al.*, 2000). In fact, current volumes and trends of global material consumption and energy use drive local and global environmental impacts, including resource depletion, climate change, and waste, among others (Prior *et al.*, 2012; Seto *et al.*, 2014). In addition, the current linear economic model further intensifies anthropogenic stress on natural resources, namely because of a very high demand for raw material extraction on one side, and a significant dumping of pollutants and discarded materials on the other, beyond the assimilative capacity of ecosystems.

The construction sector and the built environment consume the largest share of materials, globally (Schandl *et al.*, 2016), and represent the highest share of local waste production (Athanassiadis *et al.*, 2016). The significance of the construction sector in terms of material consumption is expected to further increase in the future (Fishman *et al.*, 2016).The transition towards a more circular economy where output flows could be reintegrated as secondary resources is being presented as a promising solution at the construction sector (ABN-AMRO & Circle Economy, 2014; World Economic Forum, 2016), city (City of Amsterdam, 2014; Institut d'Aménagement et d'Urbanisme de l'Ile-de-France, 2013; London Waste & Recycling Board, 2015), national (Geng *et al.*, 2012) and global level (Ellen MacArthur Foundation, 2015). Nevertheless, current figures estimate the global economy is only about 6% circular (Haas *et al.*, 2015). Hence, a mismatch between policies, political aspirations and current practices exists. In most cases, the majority of construction materials are only crushed and reused as aggregates for roads (M. Hu *et al.*, 2010). Such end-of-pipe solutions significantly downgrade the technical and economic value of construction materials, addressing only partially the demand for natural resources and waste generation and management (Cullen, 2017).

To realistically implement circular economy strategies for the built environment, such as urban mining (Krook & Baas, 2013), it is crucial to have a better understanding of the type of materials that enter, exit and are being stocked within cities. A number of studies have already assessed these flows and stocks using a mix of bottom-up, top-down, static and dynamic approaches, as well as focusing on different types of materials and spatial scales (inter alia Augiseau & Barles; D. Hu *et al.*, 2010; Kleemann *et al.*, 2016; Kral *et al.*, 2014; Pauliuk *et al.*, 2013; Tanikawa *et al.*, 2015; Van Beers & Graedel, 2003; Wiedenhofer *et al.*, 2015a). These studies successfully provide information at the targeted scale, for instance, material quantities available at a city scale. This information can identify pathways towards a more circular economy.

Yet not enough studies provide spatialised results by building, allowing industry and other urban stakeholders to localise secondary resources that become available at a certain time and estimate their potential market (Kleemann *et al.*, 2016; Tanikawa *et al.*, 2015; Tanikawa & Hashimoto, 2009). While an increasing number of authors are looking into stock spatialisation (see *inter alia*, Reyna and Chester (2015) and Mastrucci *et al.* (2017)), there is still a need for *‘improved knowledge about stock-flow dynamics […], and the spatial patterns of stock distribution’ (Krausmann et al., 2017, p. 1885)*. One of the remaining hurdles to implement circular strategies and urban mining at a local and global level is to provide more qualitative information on material flows exiting the built environment in order to understand whether it is possible to reuse these materials as entering flows (Di Maria *et al.*, 2013;

Graedel *et al.*, 2011). For instance, it is necessary to better understand from which building are estimated material flows originating, when are these flows occurring, and whether it is possible to tap into them. There is therefore a need for models that enable spatialising and estimating the occurrence of material flows for building stocks at a high level of detail.

1.1. Aim and scope

The aim of this paper is to quantify and map annual non-structural material inflows and outflows associated with the replacement of construction materials to maintain in urban building stocks in order to support decision-making for a more circular built environment and construction sector. The City of Melbourne, Australia is used as a case study.

This paper covers solely the replacement of non-structural materials over time, their magnitude, and location. This is included in module B4 (material replacement) of the life cycle stage of a building, in the European Standard 15978 (2011) on the environmental performance of buildings. Material flows resulting from new construction or demolition are not taken into account. This is because material replacement flows during the *use* life cycle stage of a building are usually understudied in urban stock and flow models, notably in a detailed bottom-up manner such as in this study. The end-of-life stage of these materials and their recyclability potential are also discussed. The scope of the paper is depicted in Figure 1.

The bottom-up approach used in this paper has been originally developed for individual buildings by Stephan (2013) and adapted to cities by Stephan and Athanassiadis (2017). Readers are referred to the latter study for information regarding the modelling approach for buildings, bill of material quantities (material inventory) estimations, embodied environmental requirements of the built environment and other aspects.

1.2. Structure

Section 2 describes the proposed bottom-up approach including data requirements, quantification algorithms, mapping tools, and its application to the City of Melbourne, Australia in order to illustrate its potential. Uncertainty is also discussed in Section 2.5. Section 3 presents the results and Section 4 discusses the modelling approach and presents its limitations and future research steps, before concluding in Section 5.

2. A dynamic and stock-driven bottom-up approach to estimate and spatialise future construction material replacement flows in cities

This section describes the method proposed to estimate and spatialise future construction material flows that enter and exit urban systems in order to maintain their building stock. The overall modelling approach is presented, followed by data requirements, algorithms used, the case study description and uncertainty in the model.

2.1. Overall modelling approach

The proposed stocks and flows model is a retrospective and prospective dynamic stock-driven bottom-up model (Augiseau & Barles, 2017; Muller *et al.*, 2014). While its dynamic nature is similar to the model proposed by B. Müller (2006), it is built up from individual materials into construction assemblies and then buildings. A construction assembly is a group of construction materials or elements that serve a particular function, e.g. an outer wall assembly providing weatherproofing and intimacy can be a brick veneer wall, made of bricks, mortar, an air gap, a waterproof layer, insulation, timber-framed wall, water vapour barrier, plasterboard and paint.

The model quantifies the bill of material quantities (material inventory) of every single building in a city, based on its geometry and constituting assemblies. The geometry of a building is typically taken or derived from the land-use database of a city or cadastral records. The specific assemblies used in a building are harder to estimate, e.g. what type of outer walls, roof, internal walls, windows, etc. They are typically assumed to be the same for every type of building in a city. This study uses the same archetypal approach (using 48 archetypes) as in Stephan and Athanassiadis (2017) and defines an archetype as a unique combination of land-use, building age and height, with associated building assemblies, specific to each archetype. For additional information, please refer to the open-access detailed lists of building archetypes (Stephan & Athanassiadis, 2016b) and assemblies (Stephan & Athanassiadis, 2016a) which are available on Figshare. Once the bill of material quantities (material inventory) of a building is generated, the building material stock of the city is calculated as the sum of all quantities in all buildings present in that city.

Input and output flows of construction materials are derived from material replacement rates (see Section 2.2). They are equal in this study since the model assumes that as soon as a material/assembly reaches its estimated service life, it is replaced by the same material/assembly. This assumes no technological change over the coming 12 years (2018-2030), which is judged as acceptable as the construction industry has been relying on similar materials and construction assemblies for years, notably in terms of internal partitions, paint, carpet, timber, steel, and other materials. The only exception would be materials in envelope assemblies, such as glass (for double glazing) and insulation. However, these two combined represent 3.7% of the estimated material replacement flow (see Table 2). Therefore, this fixed technological framework is not expected to affect the results significantly over the relatively short period of analysis. The replacement of materials at the end of their service life creates both an output flow of construction materials that have been worn off and an input flow of new construction materials. The following assumptions thus underpin the model used in this study:

- A perfect 1:1 replacement of materials at their end of life;
- No technological changes over the period of analysis;
- No modifications due to socio-economic factors over the period of analysis;
- No changes in land-use (or building archetype) over the period of analysis (e.g. conversion of a warehouse into apartments);
- No hibernating stocks (no materials are kept in buildings beyond their service life, although they do not serve any functional purpose anymore (Wallsten *et al.*, 2015)); and
- No material leaching (i.e. materials such as paint and corrosive metals do not decay across their service life).

The resulting material flows are linked to the geographical information system (GIS) for buildings and can therefore be spatialised, over time. For each year in the period of analysis, the model is able to provide a replacement flow of a given material, the buildings and assemblies where this flow is occurring, and its magnitude. Therefore, the model is able to answer the questions: What? Where? When? And How much? A capacity of spatial material stock models that is advocated for by Tanikawa and Hashimoto (2009). The overall modelling approach is depicted in Figure 1. More details on quantification steps and algorithms are provided in the next section.

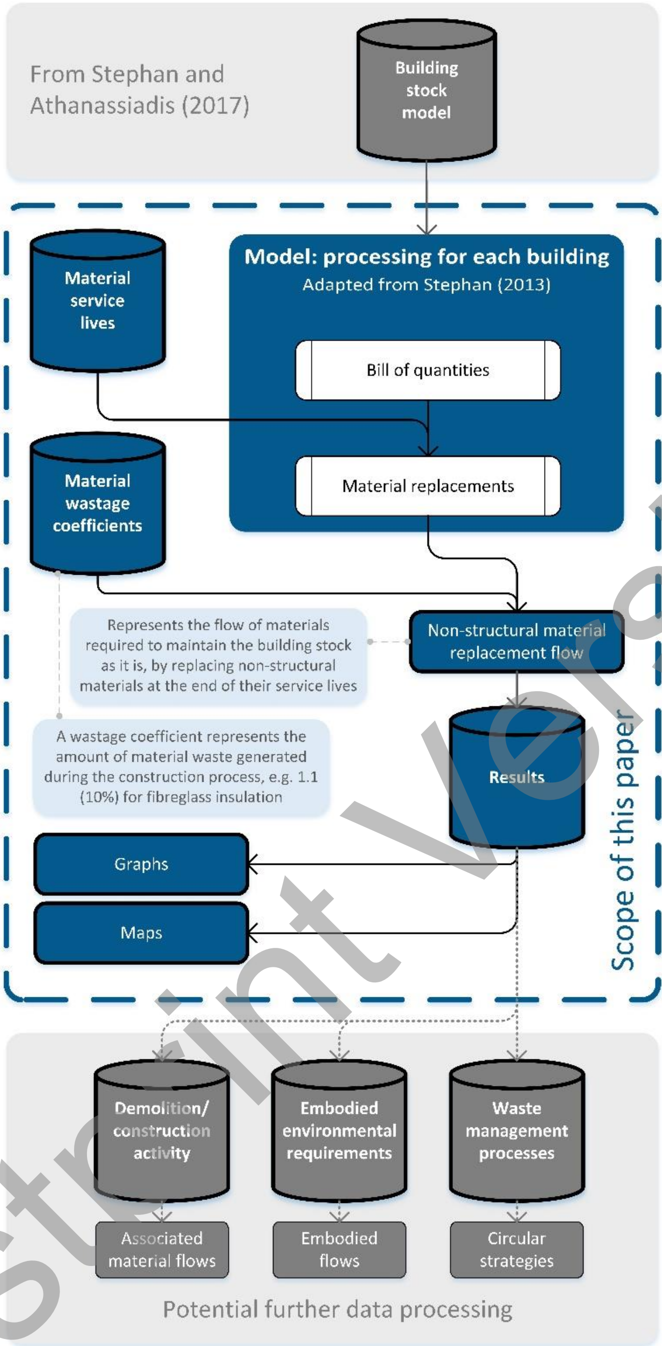

Figure 1: Overall modelling approach and scope.

2.2. Characterising construction material flows

As described in Stephan (2013), Stephan and Crawford (2014), and Stephan and Athanassiadis (2017), the model used describes each material (e.g. glass in a glazing pane) as part of a construction assembly (e.g. window). This allows the model to differentiate the service life of materials depending on their function and the assembly they belong to. For example, timber used in doors will be replaced, while structural timber will not (see Table 1). This approach is similar to the nested model that Busch *et al.* (2014) use but with a static technological model. This is because the construction industry is one of the least innovative and a minimal change in assembly composition is expected over the period of analysis (2018-2030, see Section 2.4).

In this study, the model relies on average material service lives compiled from Ding (2004), NAHB and Bank of America (2007) and Rauf and Crawford (2015), most of which have been used in previous life cycle assessment studies of buildings in Australia (e.g. Crawford *et al.* (2010) and Stephan *et al.* (2013)). Table 1 presents the average service lives of construction materials and assemblies that are used, along with other properties. Note that materials which are not replaced (e.g. Concrete), intervene in the determination of the stock, and their properties are listed for transparency. A wastage coefficient represents the percentage of material wasted during transportation from factory and construction on-site or off-site. For example, fibreglass insulation battens have a wastage coefficient of 1.1 meaning that there is a 10% additional material requirement due to wastage during transportation and installation (e.g. off-cuts).

Table 1: Properties of main construction materials used in the model.

						Used in			
Material	Type	Unit	Weight (kg/unit)	Service life (years)	Wastage coefficient (1 = no waste)	Envelope	Structure	Systems	Finishes
Aluminium	Reflective foil	m^2	0.31	30	1.1	×	×		
Aluminium	Roof coating	m^2	0.15	5	1.05	×			×
Aluminium	Interior shutters	m^2	0.34	12	1.05	×			×
Aluminium	Gutter	m	1.08	20	1.05	×			
Aluminium	Frame	m	1.66	40	1.05	×			×
Aluminium	Door handle	no.	0.229	30	1.05				×
Aluminium	Exterior shutters	m^2	0.34	40	1.05	×			×
Aluminium	Virgin	t	1000	35	1	×		×	×
Aluminium	Sill	t	1000	40	1	×		×	×
Bitumen	Plain	m^3	1020	20	1.05	×	×		×
Carpet	Wool	m^2	2.5	10	1.05				×
Carpet	Nylon	m^2	2.5	10	1.05				×
Ceramics	Clay bricks (110 mm)	m^2	158	Not replaced	1.05	×	×	×	×
Ceramics	Tiles	m^2	23.2	50	1.05		×		×
Ceramics	Terracotta roof tiles (20 mm)	m^2	38.44	50	1.1	×			
Ceramics	Fibre cement sheet (4.5 mm)	m^2	6.12	30	1.05	×			×
Ceramics	Fibre cement sheet (6 mm)	m^2	8.16	30	1.05	×			×
Ceramics	Toilet suite	no.	60	40	1.03				×
Ceramics	Basin	no.	14	35	1.03				×
Concrete	15 MPa	m^3	2400	Not replaced	1.1	×	×		×
Concrete	20 MPa	m^3	2400	Not replaced	1.1	×	×		×
Concrete	25 MPa	m^3	2400	Not replaced	1.1	×	×		×
Concrete	32 MPa	m^3	2400	Not replaced	1.1	×	×		×
Concrete	Aerated block (200 mm)	m^2	181.5	Not replaced	1.05	×			×
Concrete	Cement (structural)	t	1000	Not replaced	1.05		×		
Concrete	Cement (other)	t	1000	25	1.05		×		
Concrete	Hollow block (200 mm)	m^2	148.5	Not replaced	1.05	×	×		×
Concrete	Roof tile (20 mm)	m^2	38.44	50	1.1	×			
Concrete	Mortar	m^3	1600	Not replaced	1.3	×	×		×
Concrete	Precast	m^3	2400	Not replaced	1.01	×	×		×
Concrete	Hollow block (100 mm)	m^2	74.25	Not replaced	1.05	×			×
Concrete	Hollow block (180 mm)	m^2	133.65	Not replaced	1.05	×	×		×
Concrete	25 MPa (low waste)	m^3	2400	Not replaced	1.005	×	×		×

Material	Type	Unit	Weight (kg/unit)	Service life (years)	Wastage coefficient (1 = no waste)	Used in Envelope	Used in Structure	Used in Systems	Used in Finishes
Copper	Pipe	m	0.082	30	1.05			×	
Copper	Wire	t	1000	30	1.03			×	
Glass	Clear float (4 mm) window pane	m²	10	40	1.03	×			×
Glass	Toughened glass (6 mm)	m²	16.2	40	1.03	×			×
Glass	Toughened glass (12 mm)	m²	32.4	40	1.03	×			×
Insulation	Expanded polystyrene	m³	24	50	1.1	×	×		
Insulation	Fibreglass	m³	12	30	1.1	×	×		
Insulation	EPS (sandwich panel fill)	m³	24	50	1.1	×	×		×
Paint	oil-based	m²	0.069	10	1.05	×	×		×
Paint	water-based	m²	0.077	10	1.05	×	×		×
Plasterboard	(10 mm)	m²	12	30	1.05	×	×		×
Plasterboard	(13 mm)	m²	15.6	30	1.05	×	×		×
Plastics	General (PVC)	t	1000	30	1.05	×	×	×	×
Plastics	Laminate (1 mm)	m²	0.8	10	1.05				×
Plastics	Plastic membrane (1mm)	m²	0.8	100	1.1	×	×		
Plastics	Polystyrene (structural)	m³	240	100	1.05		×		
Plastics	PVC water pipe (20 mm)	m	0.05	25	1.05		×	×	
Plastics	UPVC pipe (100 mm)	m	1.325	25	1.05		×	×	
Plastics	UPVC pipe (100 mm slotted)	m	1.325	25	1.05		×	×	
Plastics	Vinyl flooring (2 mm)	m²	1.6	50	1.05				×
Plastics	Bath (Acrylic)	no.	20	40	1				×
Plastics	Wire coating	t	1000	30	1.03			×	
Sand and stone	Sand	m³	1600	Not replaced	1.1	×	×		×
Sand and stone	Screenings	m³	2400	Not replaced	1.3	×	×		
Steel	COLORBOND (R) steel decking	m²	4	30	1.05	×	×		
Steel	Reinforcement	t	1000	Not replaced	1.05	×	×		×
Steel	Lintel	t	1000	Not replaced	1.02	×	×		×
Steel	Stainless	t	1000	80	1.05		×		×
Steel	Steel decking	m²	10	30	1.05		×		
Steel	Gutter	t	1000	20	1.05	×	×		
Steel	Door accessories	t	1000	30	1.05	×	×		×
Steel	Stainless (sink)	no.	7.25	40	1				×
Steel	Structural	t	1000	Not replaced	1.05	×	×		×
Steel	Reinforcement (prefabricated)	t	1000	Not replaced	1.005	×	×		×
Timber	Hardwood (structural)	m³	800	Not replaced	1.05	×	×		×
Timber	Hardwood (exterior)	m³	800	30	1.05	×			
Timber	Softwood (framing)	m³	800	Not replaced	1.02	×	×		×
Timber	MDF/particleboard	m³	750	30	1.05	×	×		×
Timber	Softwood (panels)	m³	800	30	1.02	×			×
Timber	Squirting (20 x 1.8 cm)	m	2.7	50	1.1	×			×
Timber	Hardwood (window frame)	m³	800	40	1.05	×			

Material	Type	Unit	Weight (kg/unit)	Service life (years)	Wastage coefficient (1 = no waste)	Used in: Envelope	Structure	Systems	Finishes
Timber	Hardwood (poles)	m³	800	50	1.05				

Note: Service lives based on Ding (2004), NAHB and Bank of America (2007) and Rauf and Crawford (2015); wastage coefficients are sourced from Wainwright and Wood (1981) and CSIRO (1994); and weight intensities are based on each product.

For a given year *y*, the construction material replacement flow can be calculated as per Equation (1). This is achieved by multiplying the quantity of a given material in each assembly of each building by a wastage coefficient and by 1 or 0 depending the need for material replacement. The part of the equation to the right of the bracket calculates if the time lapsed since the construction of the building is a multiple of the service life of a particular material m. If it is, the fraction is an integer and the material is replaced (value of 1) if not, the material is not replaced (value of 0). For example, given a 2030 time horizon and a building constructed in 2012, carpet, with a service life of ten years will be replaced in 2022 ($(y-CY_b)/SL_{m,a,b} = 1 \mid \delta = 1$) only since δ = 0 for all other years. The δ terms acts like a modified Dirac delta survival curve distribution, which is often used in dynamic stock-driven models, alongside Weibull distributions (Muller *et al.*, 2014). The sum of all material replacements across the city is the material replacement flow for a given year *y*.

$$CRF_{m,y} = \sum_{b=1}^{B}\sum_{a=1}^{A} Q_{m,a,b} \times w_{m,a,b} \times \begin{cases} \delta = 1 \Leftrightarrow \dfrac{(y - CY_b)}{SL_{m,a,b}} \in \mathbb{Z}^+ \\ \delta = 0 \Leftrightarrow \dfrac{(y - CY_b)}{SL_{m,a,b}} \notin \mathbb{Z}^+ \end{cases} \quad \forall\, CY_b < y \leq TH \tag{1}$$

Where:

m = a given material (e.g. timber); *y* = a given year (e.g. 2020); *b* = a building; *a* = an assembly within a building (e.g. windows); $CRF_{m,y}$ = city replacement flow of material *m* for year *y*, in functional unit of material; $Q_{m,a,b}$ = design quantity of material *m* in assembly *a* of building *b*, in functional unit of material (e.g. m³ of timber); $w_{m,a,b}$ = construction waste coefficient of material *m* in assembly *a* of building *b* (e.g. 1.05); δ = a modified Dirac delta function; CY_b = construction year of building *b* (e.g. 1987); $SL_{m,a,b}$ = service life of material *m* in assembly *a* of building *b* (e.g. 30 years); $\mathbb{Z}^+$ is the set of positive integers; and *TH* = time horizon (e.g. 2030).

2.3. Data requirements

The bottom-up building stock model requires a detailed building geometry database, a land-use database (used to derive assembly archetypes for buildings), a GIS database of the building stock for spatialisation and, most importantly for material flow analysis, a detailed database of material service lives alongside the year of construction of each building. A database of wastage coefficients for construction materials can also be used to account for on-site construction waste (as in this study). These data allow the assessor to quantify and spatialise material flows associated with material replacement, across the city. Data requirements and potential extensions are summarised in Figure 1.

2.4. Application to the City of Melbourne, Australia

The City of Melbourne is used as a case study to illustrate the potential of the developed model. The City of Melbourne is chosen for the availability of detailed open data and its heterogeneous building stock of ~14 000 buildings. All details pertaining to the application of the model to the City of Melbourne are provided in Stephan and Athanassiadis (2017). Only a brief description of the case study city is given below.

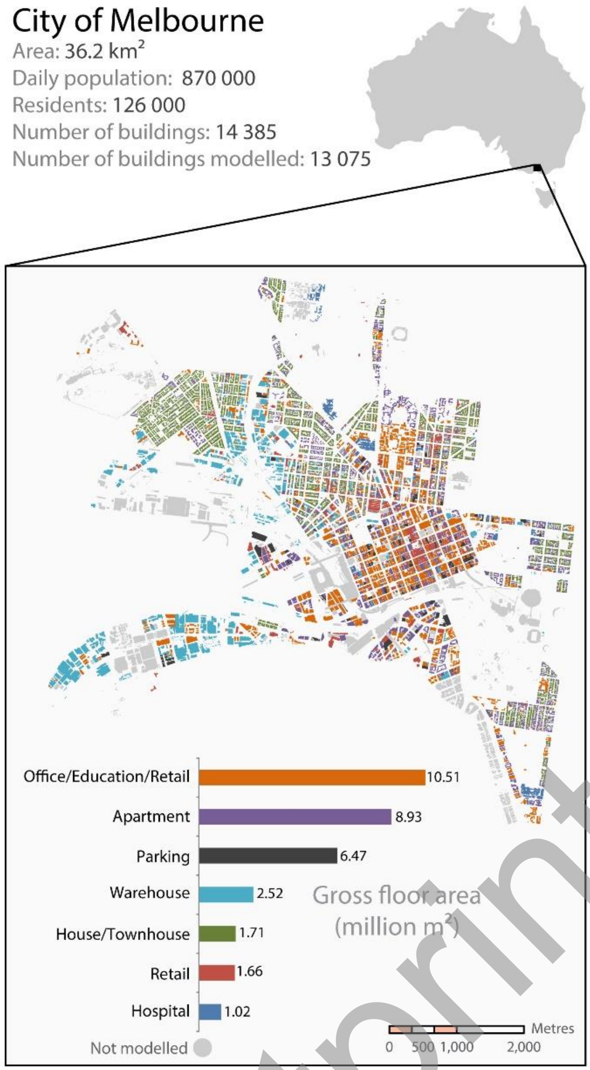

Figure 2: Location and map of the City of Melbourne with buildings differentiated by typology. Note: The City of Melbourne map and the number of buildings is based on data from City of Melbourne (2015a); population figures are as of 2015 and are based on City of Melbourne (2015b).

The City of Melbourne covers most of the inner core of Metropolitan Melbourne (or Greater Melbourne), Australia, the second most populous city after Sydney with a population of ~4.7 million inhabitants living in the metropolitan area according to the latest census (ABS, 2017). The City of Melbourne has a broad range of publically available datasets (City of Melbourne, 2017), notably the Census of Land Use and Employment (CLUE) database (City of Melbourne, 2015a) which contains the floor area by land-use, the year of construction, and the number of stories for most of the 14 385 buildings. The land-use types are diverse within the City of Melbourne, as depicted in Figure 2. This makes the application of a material flow analysis model more interesting as construction materials used in particular buildings (e.g. hospitals) are taken into account. Out of the 14 385 buildings 13 075 were retained in the model and the rest were excluded because they either had a gross floor area of less than 45 m² or they were exceptional buildings, such as sports complexes (e.g. the Melbourne Cricket Ground) or train stations (e.g. Southern Cross Train Station).

2.5. Uncertainty

While there are many sources of uncertainty affecting the model, two main categories can be identified and are expected to affect the outputs most, namely parameter uncertainty and model uncertainty. These are described in a more theoretical sense in a range of studies, such as Huijbregts (1998).

Parameter uncertainty is mostly present in the service lives of materials which are paramount for the reliability of the proposed model. Realistically estimating these service lives is extremely difficult for a given building as they depends on a broad range of factors, including the physical properties of a material, climate, construction quality and detailing, user taste and behaviour and others (Aktas & Bilec, 2012; Thomsen & van der Flier, 2011). The International Standard 15686-1 (2011) defines a set of seven different factors that can influence the service life of a construction material. The base service life of a material, based on empirical data, is multiplied by all seven factors to obtain a corrected service life, adapted to the particular material in a specific building. However, the choice of these factors can be very subjective as discussed in Hovde and Moser (2004). Therefore, the so-called 'factor method' is not considered in the model as it would further increase uncertainty and only the base service life is used. The same base material service lives are used across the stock but are expected to vary significantly between buildings in reality. This means that at a building scale, the reliability of material replacement flows for a given year is low. The level of confidence increases when quantifying the average or total material flow over a number of years. At a city scale (e.g. for the City of Melbourne and its 13075 modelled buildings), results are much more reliable in general as this variability is significantly reduced following the law of large numbers (with N= 13 075 buildings).

Another source of uncertainty is assumptions in the model itself, notably the 1:1 replacement of materials. The proposed model assumes that the input flow balances the output flow as materials are replaced, but this is not always realistic as construction assemblies could be replaced with other assemblies with different material compositions. For example, an aluminium-framed single-glazed window from the early 1980s could be replaced by a timber-framed double-glazed window today. It is however hard (if not impossible) to reliably forecast this in a model. Instead, what-if scenarios (Pesonen *et al.*, 2000) can be run to evaluate the influence of the uptake of certain construction materials or assemblies on the material flow in the city. The model does not currently account for these potential future scenarios and can be a source of uncertainty. However, it can be further extend to allow for differentiated material replacements (see Section 4.4).

To summarise, this model, like any other, suffers from uncertainty, notably from parameter and model uncertainty. Results are not expected to be very reliable for a single building in the city, and that is mostly due to variability in material service lives as well as modelling uncertainty. At the whole city level, results are expected to be reliable due a significant drop in parameters variability (law of large numbers) but would still suffer from the model uncertainties associated with the chosen assumptions (see Section 2.1).

3. Results

This section presents some of the results that can be obtained by applying the developed model to the City of Melbourne. Figure 3 presents the age pyramid of main construction materials present in the City of Melbourne's building material stock in 2015. Borrowing this graphical representation from demography can facilitate a better understanding of the state of the stock. It also offers a visual tool to estimate major replacement flows. The use of age pyramids to represent material stocks is discussed by Cabrera Serrenho and Allwood (2016) in their study of material stock demographics of cars in Great Britain.

The pyramid shows the accumulation of hard-wearing materials in the building stock, e.g. concrete, steel, timber, and how non-durable materials typically do not remain in the stock for a long time, e.g. carpet and plasterboard. It allows stock managers (construction and demolition companies) to anticipate periods of major replacements, by comparing the stock of a material with its typical service life (see carpet and plasterboard as examples). For instance, there is a significant amount of 25-years-old plasterboard (see bar A in Figure 3) that would need to be replaced in 5 years (assuming a typical service life), resulting in a large material replacement flow that should be managed in a manner to create most opportunities, for the environment, society and the economy.

The pyramid also shows years of significant construction activity. For example, in 1960 (year 55 in the pyramid), a large amount of construction materials was added to the stock due to the reported construction of three medical facilities in the CLUE database. Similarly, the spikes occurring for 1990-1992 (years 23-25 in the pyramid), are related to the construction of large office and apartment buildings in the CBD. The top 15 heaviest buildings (out of 317 constructed during that period), represent alone, 67% of the net addition to stock during those years. Large individual building projects can therefore have a notable effect on the material stock profile of a city council.

Using a pyramid to represent the stock also allows an easy comparison of the order of magnitude of material quantities. For instance, the mass of concrete alone is, on average, thirteen times more than those of all other materials combined. Overall, the mass of the estimated material stock in buildings of the City of Melbourne is 56,007 kt as of 2015. This is broken down into concrete (51,412 kt | 91.8%), steel (1,983 kt | 3.5%), ceramics (944 kt | 1.7%), timber (378 kt | 0.7%), plasterboard (243 kt | 0.4%), carpet (71 kt | 0.1%), glass (58 kt | 0.1%) and other materials (918 kt | 1.7%). For a breakdown of the 2015 material stock by construction assembly, please refer to Stephan and Athanassiadis (2017).

It is important to note that the level of uncertainty associated with the construction year of buildings and the assumed service life is compounded and increases as we move upward in the pyramid. Years close to its base contain the most reliable data. This means that stock estimates for recently constructed buildings and for easy-wearing materials is more accurate than for old buildings and hard-wearing materials.

Table 2 contains the annual estimated material flows for the City of Melbourne, by material, from 2018 to 2030 (time horizon). The largest estiamted material replacement is expected to occur in 2020 with 73 kt (Gg) of materials being replaced, followed by 2030 with 50 kt (Gg). The increase for 2030 across most materials is due to different drivers for different materials. For instance, for steel, glass and aluminium, the top 15 buildings by replacement flow represent alone, 46%, 48% and 49% of the 2030 replacement flow, respectively. Paint and timber are less concentrated, with the top 15 buildings by replacement flow representing 16% and 29% of the total. The percentage of buildings in which a material replacement is estimated to occur during 2030 is as follows: Paint 30%, Ceramics 15%, Plastics 15%, Aluminium 14%, Carpet 13%, Steel 13%, Timber 10%, Plasterboard 7%, Glass 6% and Insulation 3%. This percentage is calculated as a fraction of the total building stock. If only buildings in which the material is actually installed are considered, the share of buildings in which carpet is replaced rises to the top for 2030, at 36%.

These numbers are estimates only and rely on typical material services lives (see Table 1). However, on average, the City of Melbourne is expected to require 26 kt (Gg) of new materials per year (excluding paint calculated at 0.8 kt), to maintain its 2015 building stock over the period 2018-2030. This will also generate 26 kt (Gg) of construction material waste (not including new construction and demolitions). This equates to 721 t/(km^2·annum) or 0.5 kg per square metre of building gross floor area (excluding underground parking) per annum. The annual flow per capita for the City of Melbourne, obtained by dividing each year's material replacement flow by the projected population (residents, workers and students only based on City of Melbourne (2015a)), is 36 kg/(capita·annum).

While there are no publically available construction and demolition data for the City of Melbourne, state-side data can be used to provide some context around these material replacement flows. In 2010-2011, the state of Victoria (including Greater Melbourne and all other cities and townships) generated 4 528 kt of construction and demolition waste (DSEWPaC and Blue Environment, 2014). From these, an estimated 3 492 kt (78%) are associated with concrete (2 537 kt), bricks (622 kt) and rubble (362 kt), which are not modelled in the material replacement flows addressed in this study. An additional 427 kt are hazardous waste and other materials not covered, leaving 580 kt associated mainly with timber (146 kt), metals (97 kt) and plastics (23 kt). Using a Victorian population of 5 509 798 inhabitants in

2010-2011 (as in DSEWPaC and Blue Environment (2014)), this equates to 105 kg/capita for that year. This figure is for non-structural construction materials (except steel) that are deemed similar to those considered in this study, but would exclude some other modelled materials such as carpet. In comparison, the estimated 36 kg/(capita·annum) of material replacement flow to maintain the building stock of the City of Melbourne over 2018-2030, represents 34% of this figure. While a more thorough validation is needed (which would require data that are not currently available), this provides some confidence to the results, given that the 105 kg/capita figure also encompasses demolition activity.

When comparing the material replacement flow to the total construction and demolition waste statistics (including all materials), it represents 4.4% of the annual construction and demolition waste per capita across the state of Victoria, Australia, which is 822 kg/capita (DSEWPaC and Blue Environment, 2014). Assuming a 1.5% renewal rate of the building stock of the City of Melbourne per annum, the material replacement flow would represent 3% of the total (material replacement (26 kt) + demolition flow (840 kt)). This is also in line with the 4.4% figure above.

Figures 4a and 4b depict the spatialised accumulated construction material replacement flow, by building, for the period 2018-2030. While results are calculated per year, an accumulated value over a time period covers potential variability in the time of material replacement as the exact year of replacement is almost impossible to predict reliably (see Section 2.5). For all materials except carpets, a single replacement occurs between 2018 and 2030. Carpet is replaced twice in 17.4% of buildings and once in the rest. Such maps can be a valuable tool for decision-makers, construction and demolition companies, waste management companies, architects, urban planners and other actors of the built environment that are interested in understanding where flows are likely to occur for a given year range (and possibly for a single year, if more reliable data become available) and in what intensity.

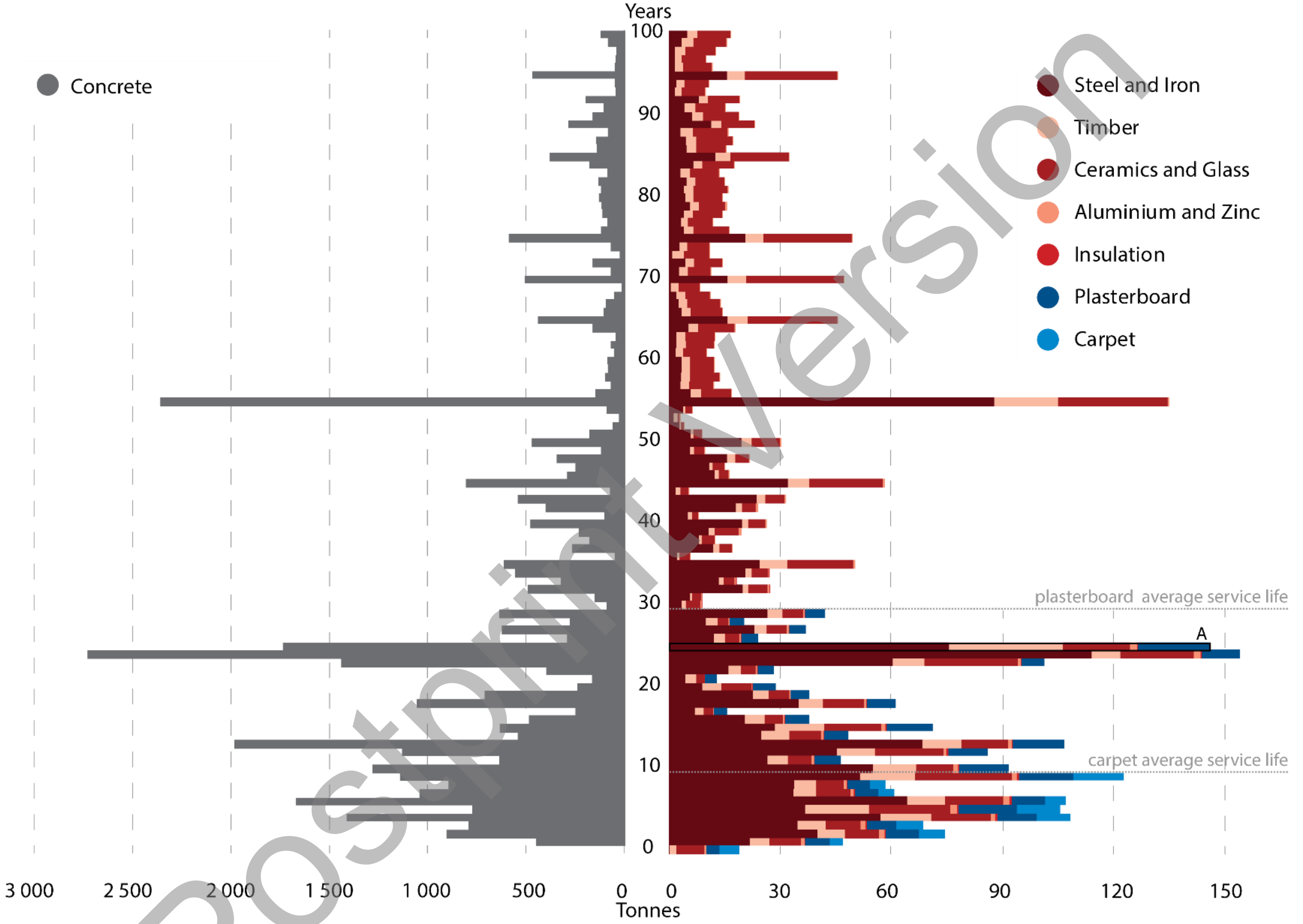

Figure 3: Estimated age pyramid of the City of Melbourne's construction material stock in 2015, for main materials, with concrete on the left and other materials on the right. Note: The mass of concrete is one order of magnitude higher than all other materials combined; original in colour.

Table 2: Estimated input flows associated with the replacement of non-structural materials to maintain the 2015 building stock of the City of Melbourne, by material, from 2018 to 2030, in tonnes (Mg).

Year	Material: Steel (non-structural)	Timber (non-structural)	Glass	Aluminium	Ceramics	Insulation	Plasterboard	Plastics	Carpet	Total
2018	94	2 470	537	326	2 791	60	4 366	164	4 217	15 026
2019	90	2 327	246	151	1 860	62	4 466	129	5 556	14 888
2020	2 503	27 359	1 812	752	8 277	226	19 279	909	11 710	72 826
2021	126	4 839	648	412	1 669	69	10 126	166	8 962	27 017
2022	169	7 078	545	413	3 010	67	6 048	240	7 116	24 686
2023	79	2 738	764	490	3 242	51	4 347	180	7 025	18 915
2024	99	2 532	352	233	1 777	54	3 199	171	3 479	11 895
2025	193	4 616	963	289	3 804	78	6 147	248	5 251	21 589
2026	99	3 376	770	541	3 510	61	5 027	209	13 698	27 289
2027	137	4 980	474	323	2 558	66	7 866	218	4 010	20 631
2028	168	2 013	829	578	2 448	67	3 490	174	4 217	13 986
2029	141	3 989	590	436	2 765	63	6 515	192	5 556	20 248
2030	1 397	10 944	3 101	1 857	7 785	242	12 404	708	11 710	50 148
Profile										
Annual Average	407	6 097	895	523	3 500	90	7 175	285	7 116	26 088
Total	5 295	79 261	11 631	6 801	45 496	1 166	93 280	3 708	92 507	339 144
Fraction of total stock[a]	0.3%	21%	20%	24%	5%	14%	38%	19%	130%	1%

Note: [a] represents the total replacement flow over 2018-230 as a fraction of the total material stock, including structural materials.

Three main observations can be drawn from Figures 4a and 4b. These are discussed below.

Firstly, the accumulated flows (input and output) of plasterboard, timber and carpet are an order of magnitude higher than those of the other materials presented. The maximum building-specific replacement flows across the building stock, are, by material: timber (3 530 t), carpet (1,457 t), plasterboard (1 168 t), ceramics (981 t), glass (223 t), steel (197 t), aluminium (148 t), plastics (79 t) and insulation (24 t). Both the quantity of material used in a building and its density affect these figures.

Insulation, with a very low density and a limited quantity is logically the least significantly flow, both at the individual building level and at the whole city level (see Table 2). Nevertheless, the flow of insulation materials is important as some insulation materials can be hard to recycle. In the case of Melbourne, the dominant majority of thermal insulation installed is fibreglass, with significant embodied energy (Crawford & Treloar, 2010), and is therefore critical to re-use or recycle, although it is very hard to do so. Recent studies (e.g. López *et al.* (2012), indicate that pyrolysis could be used to recycle fibreglass into useful products. Fibreglass could also be re-used in cement production (Dehghan *et al.*, 2017), or recycled into new construction products, typically by separating the glass fibres and using them as reinforcement, e.g. in polypropylene underfloor vents, railway sleepers (Job, 2013). There is therefore a strong incentive to find solutions to increase the circularity of fibreglass, notably in the case of Melbourne and Australia in general, where it is widely used in construction.

Secondly, it is important to interpret these maps in light of Figures 5 and 6 from Stephan and Athanassiadis (2017) which depict the total material stock as well as the stock of steel, glass and carpet for each building. While the quantities of stock and replacement flows can be very different, the comparison reveals what share of the material stock is replaced for each building, from 2018 to 2030. Across the entire building stock, 0.3% of the steel stock (including structural steel), 20% of the glass stock and 130% of the carpet stock is estimated to be replaced (see Table 2, bottom row).

Thirdly, it is important to note that some buildings do not have any replacement flow (represented in light grey). This is because either no materials are replaced during the period of analysis (the building is recent or the material service life is not reached during this time period) or because these materials are not present in the building.

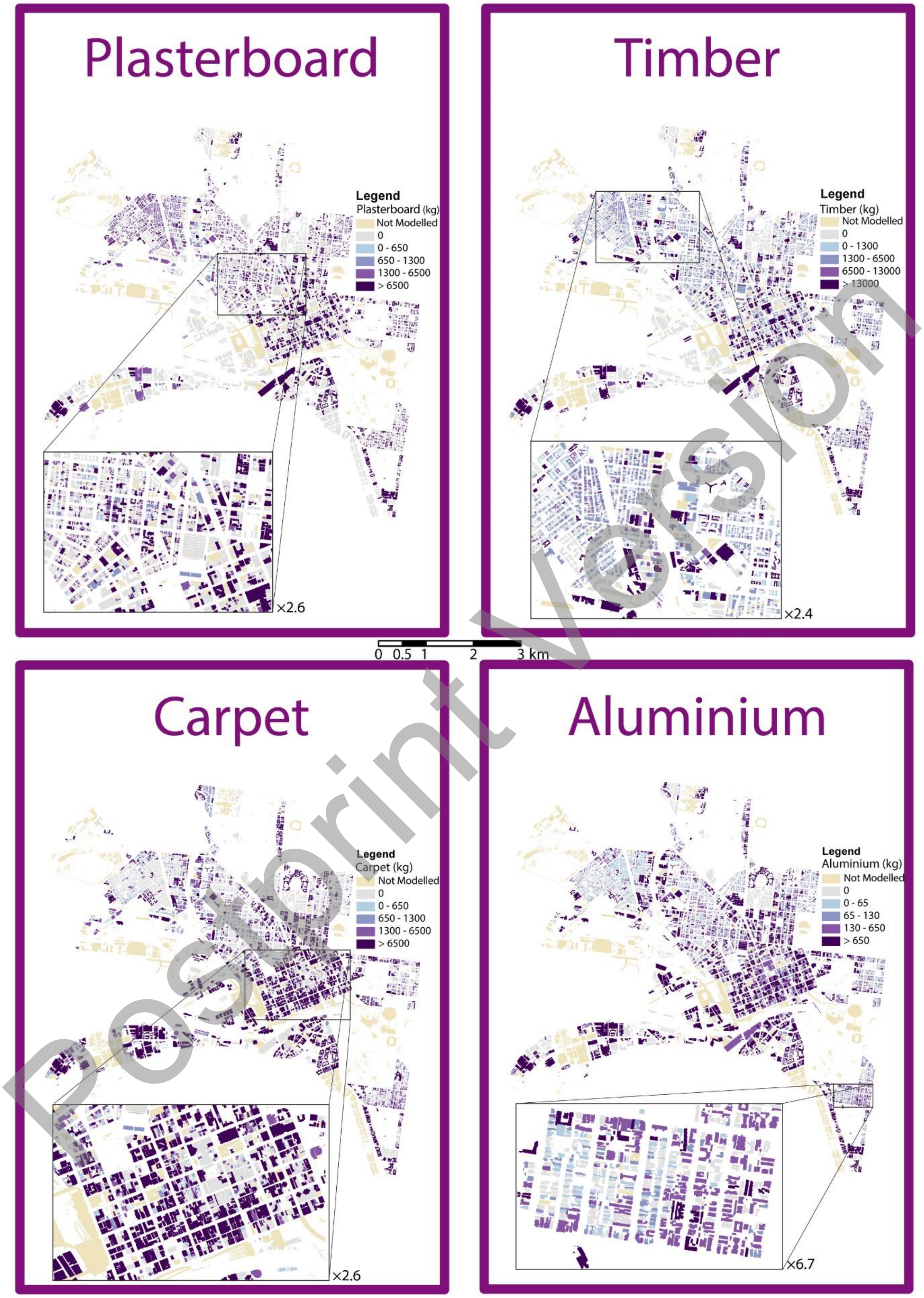

Figure 4a: Estimated accumulated building material replacement flows in the City of Melbourne, for plasterboard, timber, carpet and aluminium, from 2018 to 2030

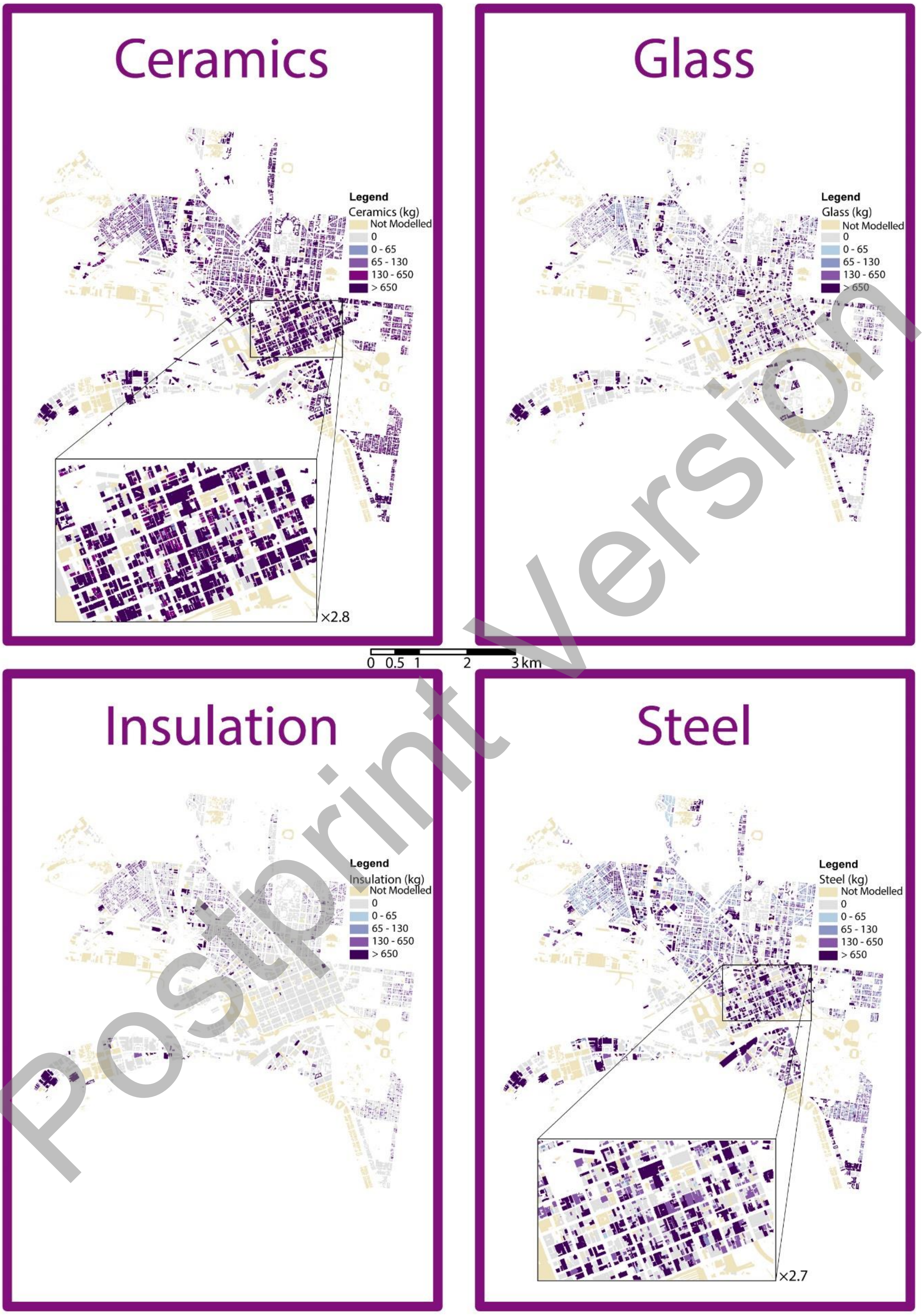

Figure 4b: Estimated accumulated building material replacement flows in the City of Melbourne, for ceramics, glass, insulation and steel, from 2018 to 2030

4. Discussion

This section discusses the model and its application to the City of Melbourne. It covers the contribution of this study to the body of knowledge and situates the model within a broader context of actions targeting a more circular economy for the construction sector. The limitations of the model and associated future research directions are also discussed.

4.1. Contribution of the developed model

This study has shown that a dynamic, stock-driven, bottom-up modelling of urban building stock can facilitate the management of material replacement flows through a detailed spatial and temporal analysis. Such models allow decision-makers to identify major flows of materials, anticipate time periods of intense material replacements or flows and better understand where these flows take place. The model is applied to the City of Melbourne (see also Stephan and Athanassiadis (2017)) but can be used in other cities, as long as necessary data are available (see Section 2.3). Two main observations can be noted.

Firstly, material flows associated with the replacement of non-structural construction materials to maintain in-use urban building stocks are not negligible. In the case of the City of Melbourne, they are estimated at 26 kt/annum, 721 t/(km²·annum), 36 kg/(capita·annum) or 0.5 kg/m² (gross floor area; excluding underground parking) on average, from 2018 to 2030. It is hard to compare these figures to others in the literature as few studies use a similar approach to quantify material flows, and specifically material replacement flows. Among these studies, Wiedenhofer *et al.* (2015b) quantify material flows associated with the maintenance and replacement of the residential building stock in European Union (63.385 million buildings) using a top-down approach. They find an average replacement flow of 3.21 t/annum per building from 2004 to 2009, compared to 1.31 t/annum for residential buildings in the City of Melbourne (9 858 residential buildings), from 2018 to 2030. In the absence of any indication about the total floor area modelled or the average dwelling size in Wiedenhofer *et al.* (2015b), this comparison only allows us to observe that the two flows are of the same order of magnitude and that replacement flows associated with maintenance cannot be neglected, notably for mature building stocks with a low construction/demolition activity.

Secondly, the application of the model to the City of Melbourne reveals that individual buildings can have a notable impact on the material replacement flow at a municipality level. The top 15 buildings in terms of annual material replacement flow, represented on average 36.8% of the total annual flow for the City of Melbourne with a minimum of 16% for paint, a maximum of 49% for aluminium, a standard deviation of 9.6% and a median of 36.5%. The simultaneous renovation of very large buildings or complexes in a city can therefore result in a spike in the material flow (see Table 2 and Figure 3) and offer significant potential for material recovery, re-use and recycling. Spatialising these average annual flows (see Figures 4a and 4b) unlocks potential synergies for material re-use between different sites and also from buildings to other sectors of the economy (see Section 4.2).

Quantifying and spatialising the replacement flows of urban building stock provides information about how much and where secondary resources are available in order to mitigate the use of new material and waste generation. However, this only represents a single step towards a more circular economy of the construction sector. Indeed, besides the recovery and recycling of replacement flows that exit the building stock, there are a number of other measures that could be implemented to make building stocks more circular.

4.2. Towards a circular economy for the construction sector

Transitioning to a more circular economy for the construction sector in the City of Melbourne requires to first understand the current rate of material recovery. Using state-wide data as a proxy for the City of Melbourne (due to the absence of statistics at this scale), 69% of construction and demolition waste was recovered in 2010 based on DSEWPaC and Blue Environment (2014). Using the raw data on which that source is compiled, this 69% recovery rate varies widely by material category, with a reported 0% for glass, 14% for plastics (PET, HDPE, PVC, LDPE, PP and PS), 18% for timber, 79% for masonry materials (Asphalt, Bricks, Concrete, Rubble and Plasterboard/Cement sheeting) and 93% for metals

(Steel, Aluminium and other non-ferrous metals). Unfortunately, the breakdown of the materials sent to landfill is not available and therefore specific recycling rates for a material within a material category, e.g. plasterboard within masonry materials, is not available. Based on these statistics, there seems to be significant scope for increased recovery of glass, plastics and timber; a moderate margin of improvement for masonry materials; and a limited margin for metals, which are almost completely recovered. There is no existing data for carpet but if data for plastics is used as a proxy, recovery rates are low. This means that glass, plastics and timber would need to be better recovered and additional processing factories would need to be set up to process them and re-inject them in the economy. The estimated annual flows of 895, 285 and 6 097 t/annum for glass, plastics, timber, respectively, from 2018-2030 and for the City of Melbourne could drive pilot recovery projects. In addition, carpets could also by recycled and are estimated at 7 116 t/annum. Recycling carpets still requires further research, but progress has been made in developing processes to turn wool carpets into fertiliser (McNeil *et al.*, 2007) and to recycle nylon carpets (Braun *et al.*, 1999; Zhang *et al.*, 1999). Such pilot projects for increased material recovery and circularity would capitalise on material flows within the Greater Melbourne Metropolitan area as well as on construction and demolition flows.

It is also important to consider the circularity of the City of Melbourne's building stock within the broader economy. The outflows of materials could be recirculated within the construction sector (e.g. concrete downcycled as crushed aggregates for roads (Wiedenhofer *et al.*, 2015b)), but also in other sectors. Similarly, the construction sector can recirculate recovered materials from other sectors, such as textiles as thermal insulation (Briga-Sá *et al.*, 2013).

Information from the model can facilitate the initiatives above, which also fit within the *Metropolitan Waste and Resource Recovery Implementation Plan* (MWRRG, 2016) for Greater Melbourne. For instance, the difference of annual replacement flows between materials (see Table 2) could encourage city officials to devise specific circular strategies for these materials given that there is a sufficient *critical mass* for companies to be involved and change their current practices. This *critical mass* is pivotal to ensure both financial and environmental benefits and avoid a *circular economy rebound* effect (Zink & Geyer, 2017). However, there are additional parameters that could influence both urban administrations and companies to transition towards more circular practices, such as the price of materials and the ease of disassembly of materials. Metals such as steel and aluminium are therefore of primary importance for construction and demolition companies due to their economic value. They are also particularly interesting from a circular economy perspective as they are more recyclable compared to other materials (e.g. fibreglass) without significant loss of mechanical properties (although this option is typically energy intensive). This is anyhow reflected in the very high rate of recycling of metal waste (93%) (DSEWPaC and Blue Environment, 2014). In summary, the current public data on construction material flows indicates that higher rates of recovery and circularity are achievable for certain material categories through a combination of intra- and inter-sectorial circularity.

At a more international level, numerous strategies can be deployed to transition to a more circular construction sector. For instance, more sustainable and durable materials, such as renewable materials manufactured using renewable energy sources, can be encouraged. These would gradually replace non-renewable and less durable materials where possible. The environmental benefits from using more 'sustainable' materials could be measured using the developed model, by using associated coefficients of embodied energy, water, emissions and other requirements.

Another step towards a circular building sector is 'design for disassembly'. As mentioned above, the calculated replacement flows exiting the City of Melbourne are not necessarily ready to be reused and/or recycled. Most of them are tangled with other materials hindering their separation, optimal reuse in other buildings, or recycling. Thus, in order to optimise the reuse of flows it is necessary that future buildings and building assemblies are designed to be better disassembled. Modular and prefabricated construction can broaden the possibilities of reuse (ARUP, 2016). This calls for a close collaboration between architects and manufacturers to conceptualise new construction details and connections between building assemblies. At this stage, the developed model does not distinguish whether building assemblies are designed specifically for disassembly, therefore the estimation of exiting flows does not necessarily represent how much could *actually* be reused. This information could be an additional qualitative indicator for each of the building assemblies available in the model.

A crucial step that would need to be implemented before building stocks become more circular is a shift of perception in the ownership of construction materials. In fact, in order to maximise reuse and recycling rates, materials could be owned by manufacturing or real estate companies over their entire period of use (which could span multiple service lives) to maintain their economic and technical values as much as possible. Thus, construction materials would be provided as services instead of products to building occupants (product service system). For instance, Philips (pay-per-lux)[1] and Desso (take-back)[2] have implemented such strategies, where only a *service* is sold to the client, such as 'square metres lit' or 'floor covered by carpet'. When the materials provided through the service do not cover the demand of the client anymore, they are taken back, repaired and replaced. This shift in ownership encourages manufacturing companies to develop recovery schemes, material and energy efficiency strategies to refurbish as effortlessly as possible their products, as well as producing components that have a longer service life. This shift would help enhance the circularity of the construction sector from a producer's perspective.

However, there are potential barriers in the way of product service systems, such as consumers being under the impression that they are not in control (Tukker, 2015). Moreover, the management of the end-of-life stage of a material within a product service system would need to consider the amount of embodied energy required to restore the material's quality compared to producing it anew, as well as the quantity of material recovered compared to the total material quantity required for primary production (Cullen, 2017). Nevertheless, there is potential for improved environmental performance should these challenges be overcome. While the model does not currently allow modelling the environmental and economic benefits of a shift in procurement and ownership, this could constitute future research.

Finally, another actor that would impact the transition towards a circular economy is local governments and administrations. For instance, all of the circular economy strategies above could be enforced through policy-making from local (or national) governments. A more immediate approach could consist of governments fixing a percentage of recovery rate from buildings to be demolished or renovated as well as the use of secondary materials in new buildings or during renovation operations within public procurement processes and public works (ABN-AMRO & Circle Economy, 2014). Different scenarios of reuse could be modelled using the proposed model in order to evaluate their potential for reducing both construction and demolition waste and the use of new construction materials (and associated embodied environmental requirements).

The systemic and complex nature of a circular economy requires change both at a company level and at the entire construction sector level. This implies that policy-making and communication between companies could help as much as engineering and design innovations to achieve the transition towards a circular economy in the construction sector and the built environment (ARUP, 2016). As established in Pomponi and Moncaster (2017), transitioning to a circular built environment will require research across economic, environmental, behavioural, societal, technological and governmental dimensions.

4.3. Limitations

The proposed model has limitations, like any other. It does not include furniture, heating, ventilation and air conditioning (HVAC) and lighting equipment, electronic appliances, and other goods contained within buildings. These flows can represent a non-negligible amount of material flow or even flows with a higher economic value per tonne or recyclability rate due to their material composition (Wallsten *et al.*, 2013; Yamasue *et al.*, 2013). In addition, this model solely focuses on buildings, omitting transportation

[1] http://www.ellenmacarthurfoundation.org/case-studies/selling-light-as-a-service

[2] http://www.desso.fr/globalaccounts/regus/take-back%E2%84%A2-programme/

infrastructure as well as water and energy grids which can be significant. For example, they represent ~15% of the total urban material stock of the Brussels Capital Region, Belgium (Institut Bruxellois de Gestion d'Environnement (IBGE), 2015). Also, the presented research does not address associated embodied requirements which were already presented in a previous study by the authors (Stephan & Athanassiadis, 2017). Furthermore, while this study uses 48 different archetypes and associated assemblies, a higher resolution would further improve the quality of the data in the model. In addition, the model uses a deterministic Dirac-delta function to replace materials based on defined service lives. Instead, probabilistic survival curves, such as those used in Miatto *et al.* (2017) could be drawn from to randomly replace a material (value of 1 in the right term of Equation 1) at its end of life. The resulting stochastic model would be more realistic but to the authors' knowledge, there is currently limited data to model the actual survival curves for materials and assemblies. The model also suffers from uncertainty, notably due to the lack of accurate data, the use of an archetypal approach and the difficulty of reliably predicting material replacements (see Section 2.5 for more details). Finally, the model focuses on material replacement flows and does not account for new construction and demolition flows which can be drastically higher although less predictable from a spatial perspective. Despite these limitations, the strength of the model lies in its adaptability and capacity for improvement. As such, these limitations could constitute the basis of future research to improve the model.

4.4. Future research

The model discussed in this paper and its application to the City of Melbourne pave the way for myriad future research. These include, expanding the scope of the model to account for new construction as well as demolition activity, quantifying embodied environmental requirements associated with material replacement flows and further detailing the model to investigate different replacement and end-of-life scenarios.

By coupling these model with future scenarios, such as city development plans and anticipated demolition activity, material flows resulting from construction and demolition can also be captured. These flows are usually much more significant than material replacement flows, as shown in Wiedenhofer *et al.* (2015b). Knowing that in many dense urban cores, industrial land with a low material intensity per square metre is typically repurposed for high-rise or high-density development with significantly higher material requirements, the material stock can be expected to increase significantly, causing 'spikes' of material stocks, both spatially (e.g. visible on maps such as Figure 4) and temporally (e.g. visible in the age pyramid, Figure 3).

Embodied environmental requirements associated with material replacements can also be quantified. For example, using hybrid embodied energy coefficients from Crawford and Treloar (2010), the embodied energy associated with material replacements from 2018 to 2030 across the City of Melbourne (~50 million m² of buildings) represents ~50 000 TJ. This is equivalent to the initial embodied energy of 3.3 million m² of new 200 m² suburban detached houses in Melbourne (based on data from Stephan and Crawford (2016)). By favouring re-use and recycling, the amount of recovered embodied energy, water, greenhouse gas emissions (or other environmental flow) can be estimated. This will enable decision makers to better understand the implications of their construction and demolition waste management strategies.

Aside from these two main areas of future research, the proposed model could allow the assessor to impose the replacement of a certain assembly by another, within certain timeframes, e.g. systematically replace single-glazed windows with double glazed windows from 2020 onwards. This would move beyond the two main assumptions in this work, which are a 1:1 replacement ratio and no technological change over the period of analysis. This feature would allow a more flexible analysis of future scenarios, although the information available to model such changes is not always available or reliable.

Another significant area of future research revolves around participatory data gathering. Encoding the actual assemblies used in a building would significantly improve the accuracy of the model, compared to using an archetypal approach. A collaborative platform where building occupants can upload assembly compositions and obtain an estimation of the quantity of materials in their building, associated embodied requirements and anticipated replacements would help collect more reliable data and reduce parameter uncertainty (see Section 2.5).

Finally, from a data representation and decision-making perspective, the age pyramid (Figure 3) could be coupled with information on material quality and the associated assembly in which each material is used. For example, glass and ceramics can be disaggregated and glass in single and double-glazed windows can be further differentiated. This could provide significant insights for energy retrofitting as well as informing policy and potential subsidised schemes for installing more thermally performant windows.

5. Conclusion

There is currently a need for models that can spatialise, quantify and estimated current and future input and output material flows of building stocks in a detailed manner in order to better assess the economic viability of implementing circular economy strategies for the construction sector. This paper described a dynamic, stock-driven and bottom-up model which was used to quantify and map the replacement flows for all buildings in the City of Melbourne, providing estimations about which materials urban authorities should focus on to establish reuse and recycling strategies. Results show that replacement flows represent, on average 26 kt/annum, 36 kg/(capita·annum) or 0.5 kg/(m^2(gross floor area)·annum). These results were found to be compatible with estimates from official waste statistics. Outputs from the model can also help construction companies to assess whether material replacements represent a sufficient and continuous flow of materials that could be integrated in their practices. Figures still suffer from uncertainty and do not include material flows entering and exiting the stock through new construction and demolition activities. Regardless, the developed model could further contribute to the implementation of a more circular economy in Melbourne and be applied to other cities around the world. This would allow actors of the built environment and public authorities to test different scenarios and strategies in order to reduce environmental requirements associated with material replacements and improve their economic value. Ultimately, this will contribute to transitioning to a more circular construction sector and built environment.

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