The importance of understanding the material metabolism of the built environment

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ABSTRACT

Construction materials are a crucial part of our built environment, but whilst the energy use of buildings is often discussed, rarely is their material consumption. Furthermore, with increasing populations and urbanisation, demand for these materials continues to increase, and in turn, so will the embodied environmental impacts created from the extraction, processing, transport and maintenance of these materials. Shorter building lifetimes are also becoming more prevalent, in part due to densification in urban areas. This creates both wasted materials and embodied impacts. A suggested greenhouse gas mitigation strategy is therefore to extend the lifetime of materials/components, e.g. through reuse, in order to displace the need for new materials and their associated impacts.

However, this calls for a new way of thinking about the built environment, it becomes a system of stocks and flows, where the output flows should be redirected into inputs. However, this requires a much greater understanding of this system, which is in essence the material metabolism of the built environment. To date, research in this area has largely focused on single buildings, and techniques such as design for deconstruction and reuse that seek to improve the availability of reused materials, this could be thought of as a circular economic approach. However, for a true assessment of circular economic potential, a single building is not sufficient, as it provides a limited feedstock for future buildings. To capture the full extent of flow interactions, a wider system should be investigated – that of a neighbourhood/city - enabling better identification of the interdependencies that exist and potential synergies to be made between these flows, across multiple scales. This paper presents the background literature and an initial scoping exercise of such an assessment, focusing on a neighbourhood in Sheffield, England.

Keywords: Circular Economy, Material Metabolism, Embodied Energy

1 INTRODUCTION

With the Paris agreement at COP21 there was a global consensus to act on climate change, and to mitigate greenhouse gas emissions. All countries in the agreement must regularly report on their emissions, and define their 'Nationally Determined Contribution' (NDC), with the aim that temperature rises will be kept well below a 2 degree rise (United Nations, 2006). As countries ratify the agreement and propose their NDC targets they will need to be implementing mitigation strategies that maximise all opportunities. Cities account for 75% of global greenhouse gas emissions, so will likely be the focus of these strategies (UNEP, 2016). Transport emissions and those from energy use in buildings are two commonly targeted areas. However, emissions associated with the materials that construct cities are rarely considered, these emissions are termed embodied and include all those emissions attributed to material extraction, processing, transport, manufacturing, maintenance and end of life. The carbon dioxide associated with the production of the steel and cement that goes into the built environment contributes at least 3.2 $GTCO_2$/year (estimated from Allwood et al. 2012). Thus, to maximise potential reductions, material choices and construction strategies should be a part of all countries' greenhouse gas mitigation strategies. Hand in hand with this, is a need to preserve natural resources, which the built environment has a huge draw on. If materials in the built environment are thought about as a system then there are three key components, the inputs, the stock (those materials in-use) and the outputs, which are frequently thought of as demolition waste. This system could be termed the material metabolism of the built environment and could be studied at many different scales, from neighbourhood, to city, to country. If the environmental impacts of material metabolisms are to be reduced, then a good understanding of the volume and types of materials is required throughout the system. This would also open up the opportunity to understand the potential for redirection of material flows, turning outputs into inputs. This approach has most recently been termed a circular economic approach, as championed by the Ellen MacArthur Foundation (2015), where the emphasis is on maintaining the asset value of resources. Keeping materials in circulation for as long as possible should reduce the requirement for new materials and thus their associated embodied impacts. This approach has been successfully deployed where product sharing/leasing is beneficial, such as tool sharing (Ellen MacArthur Foundation, Unknown date), products which have a relatively short life span have also been identified as a priority and studied, where examples include mobile phones. (Ellen MacArthur, 2012). However, the longer life spans in the built environment do present some challenges, particularly around traceability and evolving standards. There is also currently little understanding of the material stock in sufficient detail to understand circular economic potential.

This paper presents a summary of existing research on the application of the circular economy in the built environment, as well as an overview of analysis techniques that could be applied and adapted to understand circular economic potential at a neighbourhood scale. A pilot case study is then summarised to demonstrate the potential of the approach.

2 STATE OF THE ART

There are two key areas of existing research that contribute to this idea of understanding and optimising the material metabolism of the built environment: (1) research that explores circular economic approaches in construction – these ideas could be applied to optimise the system; and (2) material flow analysis of the built environment as these methods can be applied to quantify system inputs, outputs and stock. The following two sub-sections provide a summary of some of the key literature in these areas.

2.1 The Circular Economy in Construction

The circular economy encapsulates a series of different ideas that focus on moving away from linear waste streams to closed loop, circular systems, effectively prioritising the higher levels of the traditional waste hierarchy, such as reuse. A key distinction of the circular economy as outlined by the Ellen MacArthur Foundation (2015) is the emphasis on maintaining asset value and explicit separation between biological and technical material streams. The introduction of a 'share' resources/products to the system is also new when compared to the traditional waste hierarchy, and could be applied to the sharing or co-occupancy of space in a built environment context or potentially leasing of a product or service. The technical side of the Ellen MacArthur Foundation diagram (2015) has the following strategies in order of priority: share, maintain/prolong, reuse/redistribute, refurbish/remanufacture and recycle. These strategies aim to keep resources in circulation at a high a value as possible.

Introduction of a circular economic approach into construction can be seen at a building level, as identified in the case studies explored by Cheshire (2016). Magdani (2016) also outlines a building level approach taken at BAM Construct UK, discussing their first circular project, Brummen Town Hall in the Netherlands. This project was particularly suited to this approach as the client wanted a building that would last 20 years, but occupancy was uncertain after this time frame. This meant that the project was designed for deconstruction and material reuse, so that elements could be easily separated at tend of life, elements such as structural timber could be returned under a contract to the suppliers, retaining value (Magdani, 2016).

A broader country wide approach to introducing the circular economy in construction is suggested by Esa et al. (2016), who explore strategies to manage construction and demolition waste in Malaysia from a circular economic approach. A review of existing research on the reduction of construction and demolition waste is conducted, using this as a basis for the development of a theoretical framework to introduce a circular economy that works across scales (Esa et al., 2016).

However, whilst a circular economic approach could be introduced to simply prioritise and manage construction and demolition waste, for the opportunities to be most clearly recognised it would be useful to have a clear understanding of existing stocks of materials and to estimate the circular economic potential of these. Thus, when a decision is taken whether or not to demolish, the circular economic value would be known, which could in turn influence the demolition strategy, so for example, if a high reuse potential was identified, the building might be systematically deconstructed to facilitate maximum material/element salvage with minimal damage. Literature to date has not explored circular economic potential of neighbourhoods or cities. However, the academic fields of urban metabolism and material flow analysis are applied in order to understand material metabolisms, although this is often at high level. The next section presents an overview of research in this area.

2.2 Material Flow Analysis in the built environment

This section summarises some of the key studies that have conducted material flow analyses of the built environment in order to improve understanding of material metabolism. The global growth in demand for materials, from 1900-2005, was estimated by Krausmann et al. (2009). They show that the pace of use of materials has increased, and predict that due to the relationship between the demand for materials and economic development there will be a sharp rise in material demand from developing countries as they grow their economies. Tanikinawa et al. (2015), Ortlepp et al. (2015) Brattebo et al (2009), Wang et al. (2015), Huang et al. (2013) and Fernandez (2007) take a country level approach to assess the material metabolism (or elements of it). Whereas, Wiedenhofer et al. (2015) take a regional approach, Rosado et al. (2016) focus on the material metabolism of cities, and Marcellus-Zamora et al. (2016) take a more neighbourhood approach, exploring a 3km^2 area of Philadelphia. There are however methodological similarities across these. Tanikinawa et al. (2015) provide a comprehensive analysis of the different material flow analysis methods that have been used to assess material stocks, categorising these into bottom-up accounting, top-down accounting, demand-driven modelling and remote sensing approaches. Their definitions can be summarised as follows: bottom-up accounting is a snap-shot inventory of objects within a defined area; top-down accounting uses time series, statistical data to follow material inputs, stocks and outputs within a system; demand driven modelling explores the demand for materials for certain end uses over time, using indicators such as population to model future demand; finally, remote sensing pinpoints areas of human activity and associated stocks using satellite based data, making it particularly useful for areas with insufficient statistical data.

A bottom up approach is taken by Tanikinawa (2015) to estimate the historical material stocks in the built environment of Japan, mapping the masses of materials across the country, and highlighting the build-up in stock of construction materials such as cement and aggregate. Ortlepp et al. (2015) calculate material composition indicators, extrapolating these with a bottom up approach that estimates floor areas for non-domestic buildings in Germany, in order to estimate total material stocks in non-domestic buildings in Germany. Ortlepp do highlight 'that greater knowledge is required of the quantity and quality of materials within the built environment in order to calculate output flows accurately and thus to support resource recovery', this is indeed is key if the circular economic potential of material stocks is to be assessed. Brattebo et al. (2009) take a more top down approach, supplemented with demand modelling to explore the energy and material metabolism of the building stock in Norway, focusing on residential stock and road bridge stocks, mapping historical use and scenario modelling future options. The use phase was shown as the dominate area when life cycle energy is estimated for these residential stocks. Associated masses of concrete and wood stocks and flows are also estimated, although as this is total mass, without use type there is insufficient detail to estimate circular economic potential.

There are a series of studies that investigate the material metabolism of China, with Wang et al. (2015) estimating the iron and steel stocks throughout China's economy, including the construction sector. They combine bottom-up sampling with top down mass balancing, concluding that reinforced concrete construction was the major driver for stock growth, but only a fraction of these stocks are currently recovered at end of life. This is particularly troublesome when the circular economy is considered as the value of materials is not being maintained when buildings reach the end of their life. In reality, with current design approaches, the best circular economic outcome for reinforcement steel would be to separate from concrete contamination and recycle the scrap in electric arc furnaces. Huang et al. (2013) take a broader approach, combining top down and demand modelling to estimate the material demand of construction in China, suggesting that the demand for iron ore and limestone will begin to decrease after 2030. They also suggest that increasing building lifetimes and recycling demolition material would reduce the demand for new material. This starts to come in line with a circular economic approach, although the data resolution is insufficient for a full assessment that incorporates reuse potential. An earlier study by Fernandez (2007) also estimated the material demand of new construction in China, assessing the material intensity of three major building types and scaling to estimate demand. The circular economy is also explicitly addressed in this work, suggesting two key areas to target (1) building design and (2) urban planning. Fernandez (2007) stresses the need to analyse the metabolism of cities, and suggests that 'material and energy flows are tracked, recorded, and used to develop future targets', it is also suggested that this type of analysis should be used to inform city planning.

Wiedenhofer et al. (2015) model the material metabolism of residential buildings and transport networks in the EU25, using a dynamic bottom-up modelling strategy. They suggest that for non-metallic minerals, maintenance-related inputs are significant, varying between 34% and 58% of domestic material consumption. They also highlight the significance of recycling, suggesting that if all recycled materials are used for stock maintenance they could account for 75% of this input demand.

Rosado et al. (2016) take a city wide, top-down approach to the material metabolism, analysing historical use in three metropolitan areas in Sweden. They highlight the problem that 80% of resources consumed are non-renewable, thus requiring a circular economic approach to this material to maintain value. The role of recycling to reduce the demand for import of materials and to retain non-renewable resources is also emphasised. However, they state 'there is an imbalance between the types of materials consumed and stocked, which limits the proportion of the consumption that could potentially be recovered by recycling' (Rosado et al., 2016).

Existing material flow analysis studies have predominately focused on the recycling potential of stocks when considering end of life scenarios. This is appropriate as the majority of studies estimate masses of different materials, so recycling potential can be estimated, whereas the preferred circular economic strategies, which maintain higher value of material require a more detailed understanding of the material metabolism. To ascertain opportunities to prolong building life, or reuse elements a much more detailed understanding is required of individual buildings, for example what is the construction technique, how are elements joined together, what is the age of the building and how does this influence the former details. Creating this understanding will require multiple datasets and combined material flow analysis approaches. The next section gives an overview of a pilot study conducted in order to explore and test the validity of this approach.

3 CASE STUDY ASSESSMENT

A bottom up approach was taken to conduct a material flow analysis on Walkley, a neighbourhood of Sheffield in the UK, with an emphasis on using existing, freely available data. Two main datasets where utilised: Light detection and ranging (LiDAR) and digimap, and Geographic Information System (GIS) software was used to handle and manipulate the data. LiDAR uses a pulsed laser to measure variable distances, the dataset used from the UK Environment Agency was collected from the air, and provides terrain mapping, which is typically used for flooding analysis (Environmental Agency, 2016). By subtracting the Digital Terrain Model from the Digital Surface Model, a dataset can be created which shows all objects above ground level, including buildings and vegetation. When this data set is combined with digimap, which gives geospatial data from ordnance survey, building massing can be derived. It was found from spot surveys that LiDAR provides better height data than digimap, so combining these two datasets gives a more accurate building stock massing. An example output showing a highlighted street, which was studied in detail, is shown in Figure 1.

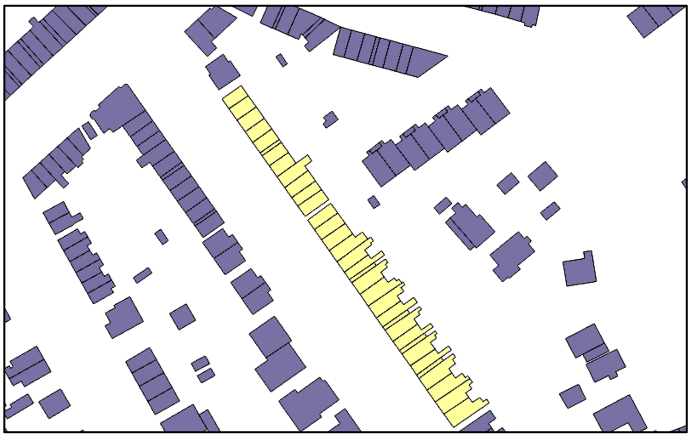

Figure 1: Example mapping output, with the street selected for detailed assessment shown in yellow.

Walkley, the case study neighbourhood, consists of largely low-rise residential buildings, the age profile of the housing in this area is shown in Figure 2. This shows that the housing stock in the area is relatively old, with 75% of the housing constructed pre-1925, 3% 1925-1955, and 22% post 1955. The street under assessment consists of brick construction. The GIS model was used to estimate the total volume of bricks in this street (see Durkin & Densley Tingley, 2016 for details of this calculation and the associated assumptions). The number of bricks in this street was estimated at 475,000. Norby et al. (2009) assess criteria for brick reusability, which is largely dependent on mortar type, Table 1 summarised their findings. If the age profile of the area is assumed to be reflective of this street, an estimated 364,800 bricks could be salvaged for reuse. Considering the value of this future resource, the price of a new brick in the UK is approximately 75p, so this asset of bricks can be valued at £273,600, and when using current embodied carbon factors, equates to an expended embodied carbon of 200,640 $kgCO_2$.

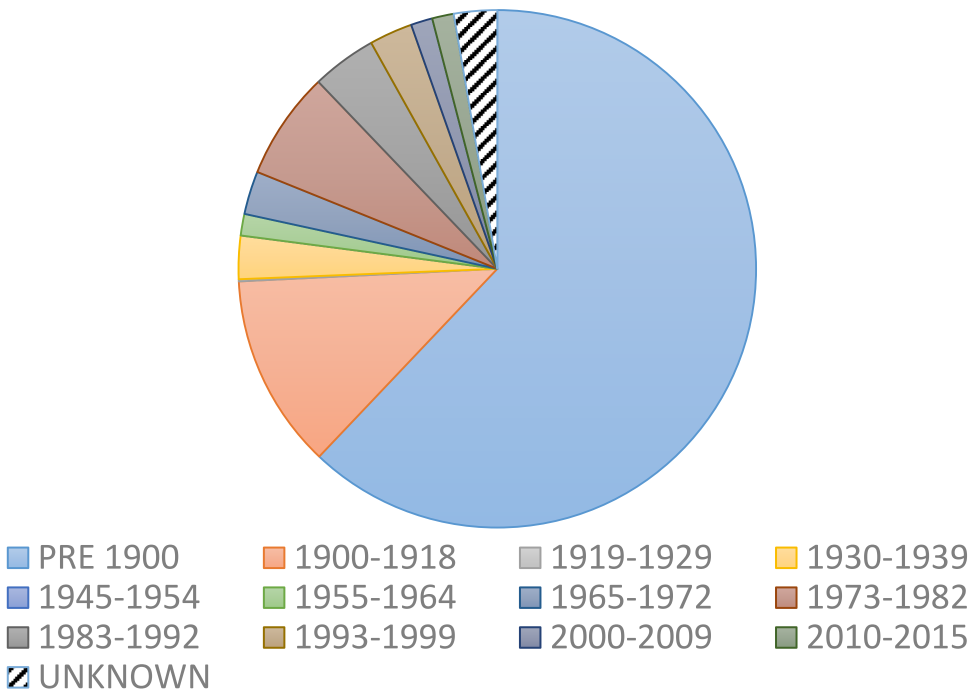

Figure 2: Housing Stock Age Profile, data taken from Consumer Data Research Centre (2016)

Age	Mortar types in Europe	% Brick Reusability
Pre-1925	Likely to be lime mortar	100%
1925-1955	Could be lime, cement, or a mixture	60%
Post-1955	Likely to be cement	0%

Table 1: Mortar Types in Europe and Brick Reusability Assumptions

4 CONCLUSIONS

This paper has summarised some of the key literature on the use of the circular economy in the construction sector, and has reviewed a range of material flow analysis techniques to ascertain the state of the art in these areas and explore their current limitations. A pilot case study on a street in Walkley, Sheffield is then conducted to test a bottom-up, remote sensing method that seeks to gather information at a high resolution. This pilot case study demonstrates the potential of this approach to develop a detailed understanding of the material metabolism of a neighbourhood, and estimate its circular economic potential. Further work will seek to develop this approach, reducing the number of assumptions required, expanding to time series data and estimating the uncertainty in results. The potential for automation of material recognition will also be explored. Furthermore, additional datasets, for example planning information will be sought, testing their use and integration into GIS to provide further detailed information on the building stocks. The current approach focuses on the façade materials, but if this is combined with material intensity estimates, such as those used by Ortlepp (2015), a greater understanding of the whole material metabolism could be developed. Although defining material use type e.g. steel reinforcement, steel I-Beam will be required so the range of circular economic potential can be assessed. By advancing techniques to develop a detailed understanding of the material metabolism of cities more strategic decisions can be made about a neighbourhood's building stock, enabling the value of resources to be maintained at the highest level possible, and environmental impacts from new resource use reduced. This paper is the first step in a piece of work to generate a detailed understanding of these material metabolisms and thus shape more strategic use of existing and new buildings.

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