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Material-intensity database of residential buildings: A case-study of Sweden in the international context

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ABSTRACT

Material intensity coefficient (MIC) databases are crucial for bottom-up material stock studies. However, MIC databases are site specific and not available in many countries. For this reason, a MIC database of residential buildings in Sweden was created in this study. As these had not previously been explored, considerable attention was paid to MIC database results, variables and limitations. Next, to contextualize the results, the database was compared and discussed with other studies in other geographical scales and regions. The MIC database is based on (1) specialized architectural-data and (2) densities of construction materials. The study looked at 46 typical residential buildings in Sweden, 12 single-family (SF) and 34 multi-family (MF) structures, built within the time period 1880–2010.

The results show specific trends for material intensity and composition, but also for the mass distribution of different building elements. Additionally, it was shown that the number of floors and the footprint size of a building have a considerable impact on the MICs, especially for buildings with a low number of floors, such as SF structures. Furthermore, when compared to MIC databases from other countries, the study database, which relates to Sweden, shows a higher intensity for wood and steel. Finally, contradictory MIC results for similar geographical regions were highlighted and discussed. This showed that to achieve consistent standardized MIC databases, further analysis of MIC databases for different geographical scales and regions are needed, and this is therefore recommended.

1. Introduction

The main bulk of all materials is stocked in the built environment, in buildings and infrastructures. As a result of expansion and maintenance of the built environment, construction materials contribute the largest annual addition to this stock (Kovanda et al., 2007; Rosado et al., 2016; Wiedenhofer et al., 2015). In addition, the accumulation of materials is accelerating in many industrialised nations, due to rapid economic and demographic growth (Fishman et al., 2016). This unprecedented growth of the built environment is directly linked to multiple environmental impacts, possible future resource scarcity, and waste accumulation (Fischer-Kowalski et al., 2011). Reusing construction materials from the built environment could potentially reduce the environmental impacts, and set construction industry and local governments on a more sustainable path.

In recent years, a number of material stock studies have been conducted for the purpose of quantifying material accumulation within the built environment (Han and Xiang, 2013; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009). In addition to estimation of

accumulated materials, previous studies have also assessed: the demolition curve of buildings in time (Tanikawa and Hashimoto, 2009), material demands due to future expansion and maintenance of the stock (Wiedenhofer et al., 2015), the dynamics of material stock due to population and lifestyle variations (Müller, 2006; Hu et al., 2010), correlations between material stock dynamics and socio-economic indicators (Fishman et al., 2015), the loss of resources due to natural calamities (Tanikawa et al., 2014), etc. All these assessments are relevant for developing the circular economy concept within the built environment at the macro level (Pomponi and Moncaster, 2017).

One of several methods developed to estimate material stock is bottom-up accounting, which is also known as a coefficient-based method. This method is preferred for its ability to describe the stock accumulation through time and space (Tanikawa et al., 2015). Bottom-up studies are data demanding. Two major databases are required: (1) the physical size of the built-environment components (e.g. m, m², m³, etc.), and (2) the material intensity coefficients (MIC) specific to each component (e.g. kg/m, kg/m², kg/m³, etc.). The first database is used to estimate the size of the built environment within any given region

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(district, city, nation, etc.). The data for this database can be collected from statistical offices or geographical information centres. The second database contains the MICs, which are used to describe the material composition of different components of the built environment.

Unfortunately, MIC databases are site specific and not available in many countries. MICs are impacted by local external factors, such as: climate, geological activity (e.g. seismic activity in Japan), historic and economic development, resource availability (e.g. wood availability in the Nordic countries), architectural trends, etc. To overcome these limitations, new methods and data sources for building up MIC databases have been explored. Both residential and non-residential buildings are very sensitive to the factors listed earlier, and have received considerable attention lately (Kleemann et al., 2016; Ortlepp et al., 2015; Ortlepp et al., 2016; Schebek et al., 2016).

Ortlepp et al. (2015) have proposed a new method to produce an MIC database for non-residential buildings in Germany. The database was based on architectural data (e.g. area or volume of buildings, usage type, building element descriptions, etc.) collected from the Building Cost Information Centre of the German Chamber of Architects. 252 building samples were included and separated by construction period (7 time periods between 1975 and 2010) and building type (institutional, office, agricultural, etc.). In another similar study (Kleemann et al., 2016), the authors developed a MIC database used to estimate the material stock of buildings in Vienna, Austria. This database included data on 66 sample buildings, collected from several different sources: on-site material analysis, construction files, and lifecycle inventories. The samples were grouped into 15 building categories, classified into 3 building types (residential, commercial, and industrial), and 5 construction periods (from before 1918 until after 1997).

In the current study a MIC database of residential buildings in Sweden was created. Residential buildings were studied because they are the most numerous, making up approximately 70% of the total gross floor area in Sweden (Statistics on building permits for housing and non-residential buildings, 2017). With one exception, an MIC database for residential buildings in Europe, including Northern Europe – (Wiedenhofer et al., 2015), to the best of the authors' knowledge, no MIC database for residential buildings in Sweden has been produced before. The approach adopted in the current study is conceptually similar to those used in the previously mentioned studies (Kleemann et al., 2016; Ortlepp et al., 2015; Ortlepp et al., 2016; Schebek et al., 2016) however it is documented differently. Furthermore, the current database was populated in a systematic way based on specialized architectural data in contrast to other studies that rely on random samples of buildings. The specialized architectural data includes descriptive texts, cross-sections, and architectural plans of 12 typical single-family and 34 multi-family buildings, constructed in Sweden during the time period 1880–2010.

The main scope of this study is to focus on database formation within a case study of residential buildings in Sweden. Although a national estimate of material stock could have been made, the authors chose to further investigate the results, limitations and variables of the MIC database, mainly because these aspects had not yet been explored in the literature. To further contextualize the database results, the paper ends with a discussion on the MICs of residential buildings and the need for a standardized method to allow for an international comparison.

2. Method and materials

2.1. Method steps

The method used to compile the material intensity coefficient (MIC) database of residential buildings was divided into six different steps (Fig. 1). Each step is discussed separately in the following paragraphs.

Step 1. MIC database structure

The architectural data used to populate the MIC database was

extracted from two previous studies on architectural trends of single-family (SF) and multi-family (MF) residential buildings, erected in Sweden during the time period 1880–2010. Architectural data was collected from both urban and rural areas. 12 typical SF buildings were selected as the most representative, after analysis of more than 4000 real estate advertisements and 1000 plans, collected from over 30 municipalities in Sweden (Björk et al., 2009). Similarly, 34 typical MF buildings were selected, based on analysis of multiple plans, on-site pictures and interviews with local historian-architects, gathered from 20 municipalities in Sweden (Björk et al., 2013).

To enable better interpretation of the MIC database, the 46 typical buildings were categorised according to three features: residential building type (SF and MF), type of structure and construction period (Table 1). The same three features were also used to code the buildings selected as typical. As all the typical SF buildings were wooden structures, they were not further categorised by structure type. MF buildings, on the other hand, have diverse structures and were separated into four categories: wooden (WMF), wooden-brick (WBMF), brick (BMF), and concrete (CMF). Finally, the buildings were differentiated by the time periods in which they were most commonly built. Each typical SF building represents a single decade, and to indicate this, each building was coded with the first year of the relevant decade (e.g. SF1890). For MF buildings, some of the typical examples were representative of several decades, why the first year of the construction period was used for coding purposes (e.g. BMF1910). There were some occasions where several of the typical MF buildings overlapped within the same time period. Where this was the case, the buildings were coded using an additional numerical indicator (e.g. BMF1930.1, BMF1930.2).

Step 2. Inventory of construction materials

In the inventory step, data on the construction materials of each typical building were collected. The type and dimension (in mm for thickness and in mm² for sections) of the construction materials were tabulated (Table S1, Supplementary information). The construction materials were also inventoried by building element: foundation/basement slab, basement wall, basement ceiling, intermediate floor, top floor, internal wall, window, external wall, and roof. These inventory tables were then used to produce spreadsheets, which was where the modelling of the database took place.

The architectural data contained detailed information, such as descriptive texts, cross-sections, and plans for each of the 46 typical buildings. The descriptive text was mainly used for the inventory task.

Step 3. Volume of construction materials

In this step, the volume of each construction material was calculated using equations (1) and (2). Which equation to use was determined based on the type of construction material and its dimension type: thickness or section.

In relation to construction materials for which the thickness dimension was available in the inventory (e.g. bricks), this was multiplied with the total area (in mm²) of the construction material within a building element (e.g. external walls) and a typical building.

$$V_{i,j,l} = B_{i,j,l} \times A_{i,j,l} \quad (1)$$

where: $V_{i,j,l}$ is the volume of the construction material i , part of building element j , for typical building l ; $B_{i,j,l}$ is the thickness dimension of construction material i , part of building element j , for typical building l ; $A_{i,j,l}$ is the area of construction material i , part of building element j , for typical building l ;

In relation to construction materials for which the section dimension was available in the inventory (e.g. wooden beams), this was multiplied with the total length of the construction material (in mm) within a building element (e.g. internal wall) and a typical building.

$$V_{i,j,l} = E_{i,j,l} \times F_{i,j,l} \quad (2)$$

where: $V_{i,j,l}$ is the volume of construction material i , part of building

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