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A Danish model of building macro-components to promote circularity

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Abstract. A better understanding of the material composition of the existing building stock is important for the development of circular economy strategies in the building sector. This paper presents a recently developed model to map the types and amounts of various materials in existing buildings in Denmark, with a high level of detail at the level of components rather than just material types. The model is meant to enable a detailed description of the building stock and a consideration of how components could be reused. Building properties are imported from the Danish national building registry (BBR) and processed into a relational database. Properties are combined with information on past construction techniques from architecture handbooks to estimate the most likely macro-components (types of wall, roof, etc) used in each building, and dimension these components. Material amount estimates from the model are compared with previous estimates as well as with material inventories from case study buildings. While the open-source model currently lacks accuracy, it is intended to be easily modifiable, and can support continuous improvements of the estimates based e.g. on new information from material passports, waste treatment facilities or remote sensing data. The paper discusses future opportunities to improve the model's accuracy and use it to help develop circularity strategies and complement on-site inspections to overcome barriers to circularity.

1. Introduction

The building sector is a major consumer of non-renewable natural resources (such as river sand), and is responsible for about 20% of global greenhouse gas emissions [1]. The global demand for buildings is expected to remain high in the coming decades [1]. Therefore, it is crucial to implement strategies to mitigate environmental impacts and resource use linked with building construction. As new buildings are steadily being constructed while older buildings are demolished, there is an opportunity to implement reuse and circularity strategies in the building sector.

An optimal circularity strategy should focus on reusing materials as far up the value chain as possible. In particular, preserving buildings (i.e. prioritising refurbishment over demolition) should be the top priority. When buildings undergo extensive refurbishment or demolition, reusing entire components (such as windows and wall panels) should be prioritised over recycling or downcycling materials. However, there is often insufficient knowledge about buildings' material composition at the component level to enable reuse at a large scale [2]. In particular, authorities need to understand the amounts of various reusable resources as well as their spatial and temporal distribution to develop reuse strategies. Similarly, developers need to know well in advance what reused products are available for purchase, since design and procurement processes happen long before the actual construction, and temporary storage of reused materials is costly [3].

The present study assumes that more precise estimates of buildings' material composition could help address these challenges and facilitate circularity strategies. For instance, Oezdemir et al. [4] claim that the creation of a cadastre of secondary resources is a prerequisite to urban mining. Material inventories in the existing building stock are often based on estimating the standing floor area for different building archetypes, and multiplying it with material intensity coefficients (MICs) representing the amounts of different types of materials per m^2 for each archetype [5–8]. While such studies provide useful information on urban stocks at the municipal and regional scales, more detailed information at the component level is needed to promote circularity [9]. A cadastre indicating for instance the amount of clay in each building is only of limited relevance for urban mining, since it doesn't indicate how much of this amount consists of bricks versus roof tiles, or whether these components can easily be deconstructed and reused. To address these issues, this paper presents a model of buildings' composition at the level of components rather than just material types. This "macro-component model" is intended to facilitate planning for component reuse and other circularity strategies in the building sector.

2. Method

The macro-component model is illustrated in Figure 1 and available in supplementary material. The model uses a catalogue of macro-components, i.e. types of walls, roofs, floor slabs, etc. used in existing buildings. Each macro-component includes a detailed product composition, as well as the time period over which it was used. These values were estimated based on Danish handbooks on building design (notably [10]). For instance, cast-in-place concrete external walls were used between 1930 and 1960 and contain ca. 460kg of concrete per m^2 of wall. Several solutions might coexist for any given year.

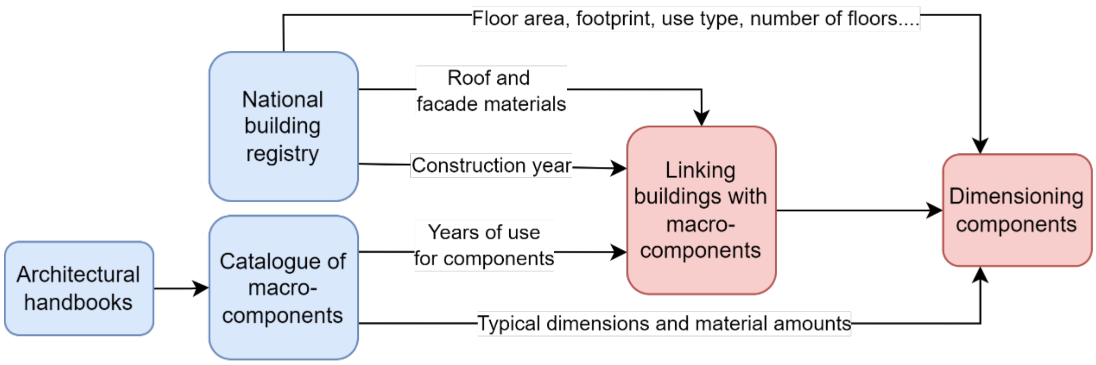

Figure 1. Overall logic of the macro-component model

Available information from the national building registry (BBR) is used to provide "best guess" estimates of which macro-components are used in each building. In this first version of the model, this estimation is only based on the façade and roof cover materials recorded in BBR, as well as the building's construction year. In future iterations of the model, more relevant BBR parameters such as the building's latest renovation year and type of use can help refine the prediction. For components for which directly relevant information is available (roof cover, roof structure and external walls), the range of possible solutions is first narrowed down based on BBR information. For instance, if the recorded façade material is "brick", the external walls could be massive brick walls, sandwich walls or curtain walls. Then, the remaining solutions are filtered further based on the building's construction year. If the construction year fits within the periods of use for several solutions, one is selected at random. In rare cases where the construction year doesn't fit the use period of any solution, a random solution is selected.

To quantify material amounts, the building and its macro-components are first dimensioned. In the absence of more precise data about building dimensions, the height of each building is estimated based on the number of floors and a standard floor height value. The roof pitch is estimated based on the type of roof cover material. Functions to dimension inner walls were extrapolated from French studies [11]. The perimeter of the building is estimated based on the footprint and a space efficiency factor (SEF) to correct for the fact that the building's footprint is not a rectangle. Finally, material amounts are estimated based on the buildings' dimensions and typical material amounts for each type of component, recorded in the macro-components catalogue.

The macro-component model is implemented using a PostgresQL relational database and a Python logic layer. The PostgresQL database stores information from the BBR registry, the macro-component catalogue, and the model's results. The links between buildings and macro-component types are stored in mapping tables in the database (e.g. a "building to roofs" table links each building with a type of roof). The Python code communicates with and modifies the PostgresQL database, and is used to perform all calculations and logic operations.

3. Model results

The macro-component model can produce a relatively detailed inventory of components for any given building. This section compares the first results from the macro-component model to actual measured values, and to results from other Danish models (the CircleBank model [12] and a model by Lanau et al. [8]). Although the model provides results as a detailed list of components, the results are presented here aggregated per material type or building part for the purpose of comparison. Data on actual building material inventories are scarce, so the type of analysis carried out depends on data availability.

3.1. Amounts per material type

The first point of comparison for model results is a set of 25 apartment buildings constructed between 1870 and 2000, for which material inventories were estimated as part of another project (CircleBank, private communication). For each building, material amounts were provided in seven material categories. CircleBank estimates are assumed to be more accurate than any other model results for these particular buildings, since estimation algorithms for the CircleBank model were developed based on building plan studies for these 25 buildings (among other data sources). Figure 2 shows the difference between model results and CircleBank estimates, for both the macro-component model and the previous model (Lanau et al). Negative values indicate that model results are lower than the CircleBank estimates.

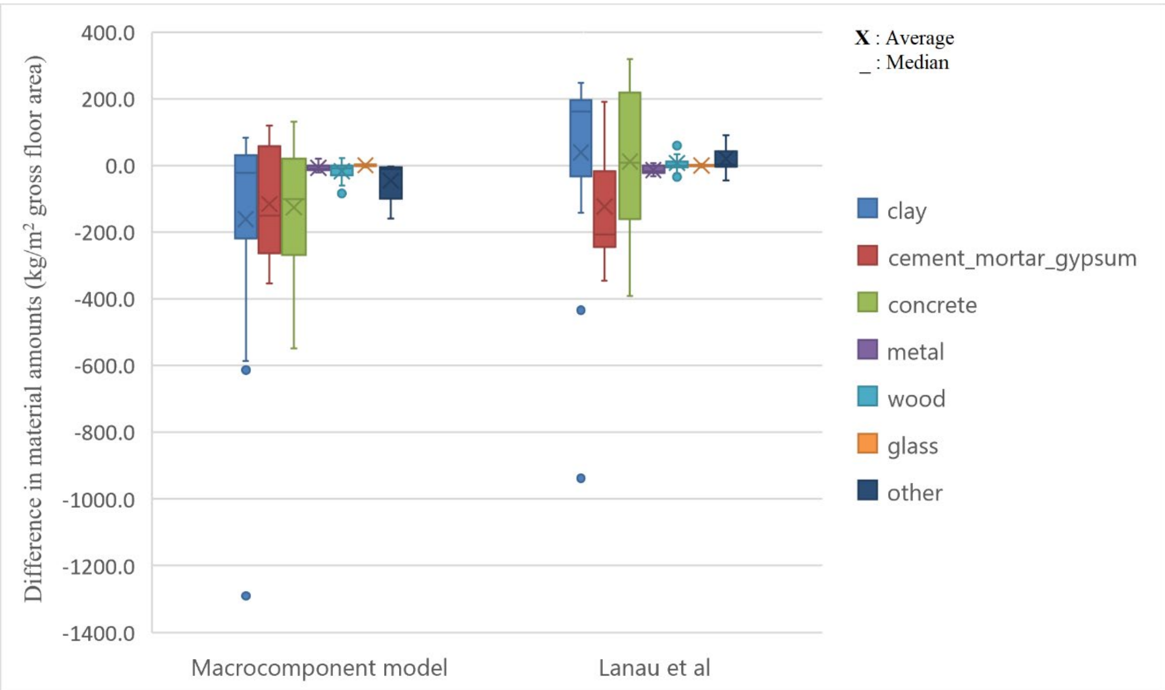

Figure 2. Comparison between model results and CircleBank estimates

The results indicate that the macro-component model often underestimate material amounts. In examples built before 1960, clay is the most important material category, due to the widespread use of brick walls and roof tiles, and this material category shows a high variability. After 1960, concrete becomes the most prominent category. Differences are also notable in other categories: for instance, for glass, both models tend to overestimate material amounts in older buildings, with the macro-component model showing the largest gap, but in recent buildings both models tend to underestimate material amounts, with no major difference in accuracy. However, material amounts in these categories are dwarfed by clay, concrete and to a lesser extent mortar and gypsum products.

In the main material categories, the Lanau et al model [8] often provides more accurate estimates than the new macro-component model, which significantly underestimates material amounts. One explanation is the bottom-up nature of the macro-component model: buildings are described as a combination of components, which is sometimes incomplete in this first version of the model. For instance, the model does not yet handle stairs, balconies or basement rooms.

3.2. Amounts per building part

A second point of comparison is offered by freely available building case studies from the Danish Knowledge Center for Sustainable Construction [13], including both residential and non-residential buildings. Here, we compare "block-wise material intensity coefficients" (BMICs) [8]. BMICs distinguish material amounts in various parts of the building, and link material amounts to a building's footprint and number of floors, rather than floor area. The over-block (resp. under-block) BMIC is calculated by dividing material amounts in the roof (resp. the foundations, basement and ground slab) by the footprint. The horizontal block BMIC is calculated by dividing material amounts in intermediate floors by the number of floors minus one. The vertical block BMIC is calculated by dividing material amounts in the walls by the number of floors. Figure 3 shows differences between model results and actual material inventories, for the macro-component model and the pre-existing Lanau et al. model.

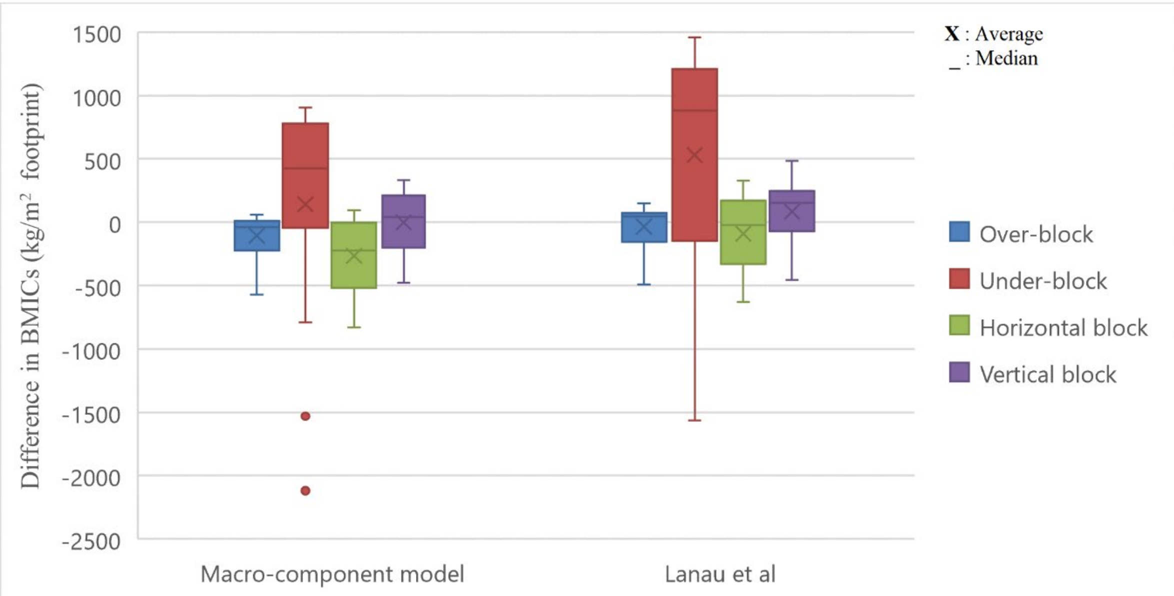

Figure 3. Comparison between model results and actual material inventories

The results indicate that both models provide good estimates of material amounts in the walls in average. The macro-component model tends to underestimate material amounts in both the roof and the floor slabs. Once again, this is due to the incompleteness of the bottom-up model. There is therefore a need to refine the model and ensure that it includes e.g. stairs, balconies and attics. However, the largest differences by far for both models are found in the under-block, where the models sometimes underestimate, sometimes overestimate material amounts. This is due to a very high variability in material amounts in building foundations, where two similar buildings might have vastly different material amounts due to the type of soil, the type of foundations, or overdesigned foundations.

4. Concluding discussion

The macro-component model offers a quick method to estimate amounts of various reusable components in Danish buildings. It can provide a useful basis to plan for reuse strategies at the municipal, regional, and national levels. The high level of detail allows for new uses compared to more conventional aggregated models. For instance, the model can help policymakers and planners assess the potential to reuse components in new construction, and to adapt construction practices to promote reuse. By linking the model with scenarios for construction and demolition [14], amounts of specific components available for reuse in any given year can be estimated. By connecting these amounts to geographical locations, the model can also support the planning of waste handling facilities (optimal location and capacity). This type of model could also be coupled with a materials exchange platform to create a marketplace for secondary materials (the intention behind the CircleBank project [12]). Finally, the model uses a similar nomenclature as the Danish national building LCA tool, LCAbyg, enabling an integration of environmental impact calculations with the model. However, while the model can provide useful guidance at a macro scale (for planners and policymakers), it is not sufficient to provide detailed information on reusable components in a specific project (for developers and contractors). On-site inspection of components will likely always be necessary to identify the specific properties of components, to guarantee their safety, quality, and match them to the specific needs of other projects. At a detailed level, macro-component models can still play a role as screening tools prior to inspections, and to support the reporting of data relevant for reuse (e.g. in combination with material passports).

Several directions have been identified for future development. Importantly, while the model provides precise descriptions of buildings, its accuracy remains low at this stage. This is partly due to its bottom-up nature, leading to underestimations of material amounts as components like stairs and balconies are not yet modelled. Such incompleteness errors are not present in conventional MIC-based models. However, the model's completeness could be improved over time, to cover all relevant macro-components. The functions used to link buildings with macro-components could also be refined to consider the building's use type, interdependencies between components (e.g. which walls are load bearing might influence which types of floor slabs are used), as well as probability distributions for various components. The latter is not yet available in Denmark, but has been used in similar models e.g. in France [15]. Deriving such functions and statistics is a high priority tasks, as these represent very valuable resources for building stock modelling. More case studies are needed to test and improve the model, including component-level validations of model predictions. However, this process is time consuming, and it is challenging to find data for older non-residential buildings. Remote sensing data such as satellite and LIDAR data offer new resources to partially automate and improve model predictions, in particular regarding the identification of building types, geometry as well as roof and façade materials [16]. Although there is much to improve, the model is built to allow for incremental improvements over time. It lays the groundwork and provides a framework and nomenclature to continuously improve the mapping of buildings' material content.

Beside quantitative improvements to the model, there is a need to better understand qualitatively in which contexts its use could help overcome barriers to circularity. Previous studies have highlighted issues of governance, logistics, traceability, quality control and data availability as some of the main challenges to circularity strategies in the building sector [2]. While better models of material content could be expected to help address some of these issues, there is no guarantee that better information leads to better decisions. The use of the model in a practical context needs to be better understood.

Supplementary material

The code used to build the model (version 1) is available at https://github.com/NFrancart/iBuildGreen

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References

[1] L.F. Cabeza, Q. Bai, P. Bertoldi, J.M. Kihila, A.F.P. Lucena, E. Mata, S. Mirasgedis, A. Novikova, Y. Saheb, Buildings, in: P.R. Shukla, J. Skea, R. Slade, A. al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2022. https://www.ipcc.ch/report/ar6/wg3/
[2] R. Tirado, A. Aublet, S. Laurenceau, G. Habert, Challenges and Opportunities for Circular Economy Promotion in the Building Sector, Sustainability (Switzerland). 14 (2022). https://doi.org/10.3390/su14031569
[3] V. Augiseau, S. Barles, Studying construction materials flows and stock: A review, Resour Conserv Recycl. 123 (2017) 153–164. https://doi.org/10.1016/j.resconrec.2016.09.002
[4] O. Oezdemir, K. Krause, A. Hafner, Creating a resource cadaster-A case study of a district in the Rhine-Ruhr metropolitan area, Buildings. 7 (2017). https://doi.org/10.3390/buildings7020045
[5] N. Heeren, T. Fishman, A database seed for a community-driven material intensity research platform, Sci Data. 6 (2019). https://doi.org/10.1038/s41597-019-0021-x
[6] D. Yang, J. Guo, L. Sun, F. Shi, J. Liu, H. Tanikawa, Urban buildings material intensity in China from 1949 to 2015, Resour Conserv Recycl. 159 (2020). https://doi.org/10.1016/j.resconrec.2020.104824
[7] B. Sprecher, T.J. Verhagen, M.L. Sauer, M. Baars, J. Heintz, T. Fishman, Material intensity database for the Dutch building stock: Towards Big Data in material stock analysis, J Ind Ecol. 26 (2022) 272–280. https://doi.org/10.1111/jiec.13143
[8] M. Lanau, G. Liu, Developing an Urban Resource Cadaster for Circular Economy: A Case of Odense, Denmark, Environ Sci Technol. 54 (2020) 4675–4685. https://doi.org/10.1021/acs.est.9b07749
[9] F. di Maria, C. Micale, A. Sordi, G. Cirulli, M. Marionni, Urban mining: Quality and quantity of recyclable and recoverable material mechanically and physically extractable from residual waste, Waste Management. 33 (2013) 2594–2599. https://doi.org/10.1016/j.wasman.2013.08.008
[10] Jesper. Engelmark, Dansk byggeskik : etagebyggeriet gennem 150 år, All Elements. (2013). https://danskbyggeskik.dk/ (accessed February 7, 2023).
[11] A. Mailhac, Contribution au développement d'une méthodologie d'évaluation environnementale aux échelles urbaines., Université de Toulouse, 2019. https://tel.archives-ouvertes.fr/tel-02889301v2
[12] Circlebank project, (2022). https://circlebank.dk/
[13] Videncenter om Bygningers Klimapåvirkninger, Case library (2023) https://byggeriogklima.dk/
[14] Q. Li, S.R.B. Gummidi, M. Lanau, B. Yu, G. Liu, Spatiotemporally Explicit Mapping of Built Environment Stocks Reveals Two Centuries of Urban Development in a Fairytale City, Odense, Denmark, Environ Sci Technol. (2022). https://doi.org/10.1021/acs.est.2c04781
[15] R. Tirado, A. Aublet, S. Laurenceau, M. Thorel, M. Louërat, G. Habert, Component-Based Model for Building Material Stock and Waste-Flow Characterization: A Case in the Île-de-France Region, Sustainability. 13 (2021) 13159. https://doi.org/10.3390/su132313159
[16] H. Arbabi, M. Lanau, X. Li, G. Meyers, M. Dai, M. Mayfield, D. Densley Tingley, A scalable data collection, characterization, and accounting framework for urban material stocks, J Ind Ecol. 26 (2022) 58–71. https://doi.org/10.1111/jiec.13198