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An analysis to understand how the shape of a concrete residential building influences its embodied energy and embodied carbon

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ABSTRACT

The built environment is recognized as a major hotspot of resource use and environmental impacts. Life Cycle Assessment (LCA) has been increasingly used to assess the environmental impacts of construction products and buildings and a new trend is characterized by the application of LCA to larger systems such as neighborhoods during early design phases. Assessing urban development projects at the master-planning stage raises the issue of inventory data collection, especially for building materials which are reported to account for about 20% of primary energy consumption in buildings, and up to 45% of associated greenhouse gas emissions. Urban planners focus on the urban morphology and little information is known about the buildings characteristics apart from their general shape. This paper proposes a simplified model for the assessment of buildings embodied energy and embodied carbon in relation with urban planners' design levers. The model relies on the decomposition of buildings into functional elements in order to be sensitive to the shape of the buildings. A detailed sensitivity analysis and contribution analysis of the model is conducted on two types of generic building forms, in order to investigate the influence of parameters relating to shape on the embodied energy and embodied carbon of a building. The sensitivity analysis shows that the parameters relating to shape (such as the dimension of the buildings) are more influential on the embodied energy and embodied carbon per square meter of building than the ones relating to the elements themselves (such as the wall thickness). The contribution analysis also brings evidence of the relation between the compactness factor and the embodied energy and embodied carbon of a building.

1. Introduction

By 2015 fifty-four percent of the world's population lived in urban areas [1] and the building sector is a major hotspot of resource use and environmental impacts. For instance, it accounts for about 20% of the total delivered energy consumed worldwide [2]. In industrialized countries, buildings are responsible for 42% of the final energy consumption, 35% of greenhouse gas emissions and more than 50% of all extracted materials [3].

The analysis of environmental impacts of the built environment is addressed through a variety of methodologies depending on the scale of study. At the construction material scale and at the individual building scale, life cycle assessment (LCA) is the clearly accepted scientific methodology for quantitative assessment of materials/buildings over their entire lifespan accounting for upstream impacts [4]. Several reviews have been conducted on LCA in the construction industry [5–8]. These reviews all point to the fact that case studies found in literature are difficult to compare because of their specificities like building type, climate, comfort requirements, local regulations, etc. Nevertheless trends can be identified such as the dominance of the use phase (especially due to energy consumption for heating and cooling) and the increase of the share and absolute value of the building materials embodied energy in the context of low-energy buildings.

In the field of urban sustainability assessment, there is a growing interest for the neighborhood scale [9–11]. It is indeed a typical operational scale for urban development projects and integrates key levers for urban eco-design. This change of scale, from building scale to neighborhood scale, is driven by the need to address key

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issues such as bioclimatic design, shared equipment (e.g. district heating), urban density or mobility issues.

As an answer to this growing interest, a new trend stems in the application of LCA to neighborhood projects. In a critical review of LCA application at the neighborhood scale Lotteau et al. [11] highlighted the major challenges related to the application of LCA at the neighborhood scale, among which the question of the collection or production of life cycle inventory (LCI) data for buildings. Two main approaches are encountered to produce LCI datasets for buildings at the district scale [11]. (1) A top-down approach that relies on average data for building archetypes (in this case, only the gross floor areas (GFA) of each building type are collected, and corresponding generic LCI data are used). It is often advocated in the case of really large districts or for an assessment performed at an early stage in the urban planning process, i.e. when the buildings have not yet been designed, but only their GFAs are available. (2) A bottom-up approach that is the summation of the detailed LCI of each building composing the district. This second approach is only possible later on in the urban development process, when the buildings have been designed by architects.

Both approaches show limitations to the assessment of masterplans of urban development projects, although this stage is critical when considering the overall energy performance of a district. The first approach is not sensitive to the urban morphology and especially to the shape of the buildings. The second approach is not aligned with the data available, and requires significant time and resources which are seldom available.

The influence of the building shape (general outline, height, horizontal dimensions, etc.) on the embodied energy (EE) and embodied carbon (EC) of buildings has rarely been investigated as such. From a systematic literature review, Pomponi and Moncaster [12] have compiled a list of very diverse strategies for mitigation and reduction of buildings EC, and none of them explicitly refers to the shape of the buildings. In fact only a few studies address this particular topic, and most of them focus on the influence of building height. Treloar et al. [13] propose an EE analysis of five real office buildings varying in height from a few storeys to over 50 storeys, with the aim of studying the dependence to buildings' height. Results show that high-rise buildings have approximately 60% more EE per GFA unit than low-rise buildings, which is mainly due to the need for energy intensive materials to meet structural requirements and wind load. The same kind of study has been conducted by Aye et al. [14] on generic low-rise commercial buildings. It also reveals a correlation between EE and height, and highlights the combined influence of compactness improvement (surface area to volume ratio) leading to an EE decrease with height for low-rise buildings, and of a premium for height leading to an EE increase as the number of storeys approaches ten. More recently, Foraboschi et al. [15] carried out a detailed study of EE of tall buildings structures. The authors have defined a reference structure for buildings ranging from 20 to 70 storeys, and for different floor types. To allow for comparison between buildings, each configuration is dimensioned to fulfill the exact same performance in terms of structural behavior. Results show that the floors almost always consume the majority of the EE (compared to the other elements of the structure; columns, core and beams), and also highlight the existence of a premium for height. Waldron et al. [16] also point out significant differences between building typologies (low-rise, mid-rise and high-rise buildings) in terms of envelope EE. Based on a literature review, the authors also show that EE associated to the building structure vary by a factor of three between the different building typologies.

A few papers have proposed models for the production of LCI datasets for buildings (materials) that are compatible with the application of LCA to early stage building or neighborhood design. Applications of these models on case studies provide additional insights on the influence of the shape of the buildings on their embodied impacts, even if their primary focus is to study the influence of building materials and their thickness. Basbagill et al. [17] propose a model for buildings' EE assessment at the neighborhood scale based on the description of a group of identical buildings thanks to a few input parameters: number of buildings, number of floors, dimensions of the building footprint, window-to-wall ratio. EE calculation is automated in a simplified building information model (BIM). For a fixed gross floor area, the model is run on thousands of admissible buildings configurations in terms of shape, materials, and materials thicknesses to provide designers with the EE reduction potential associated to decisions such as nature of materials and thicknesses for each building component. Although the methodology relies on exploring variations in the shape of the buildings, no analysis on its influence is provided by the authors. Davila and Reinhart [18] propose a CAD-based model for the EE assessment of a group of buildings based on 3D massing plans. Buildings are decomposed into construction assemblies (roof, external walls, ground floor, etc.) whose quantities are extracted from the 3D model. Assemblies' quantities are then combined with a database of embodied energy factors. An application of this model on three urban scenarios differing in surface occupation ratio (SOR), shows that the lower the SOR, the lower the EE. Trigaux et al. [19] present another model to assess the environmental impact of building clusters, together with the required road infrastructure. The system boundaries include the entire lifecycle of buildings and roads. A case study is conducted on four abstract neighborhoods composed of individual houses, semi-detached houses, terraced houses and apartment blocks. Results (single score) for the building materials contributor show that individual houses have 50% more impacts than terraced houses and 30% more impacts than apartment blocks. Gardezi et al. [20] propose a prediction tool for the EC of houses in Malaysia. Several types of houses have been evaluated by adoption of a partial life cycle assessment (LCA) framework. Multi-variable regression analysis is used to issue a predictive model based on the building's GFA, the ratio length/width, the volume and the weight of the building. This model highlights the fact that for buildings of similar constructive system, the EC highly depends on shape parameters. However no detailed analysis of the specific effect of each input parameters is provided.

None of the reviewed studies proposes a detailed analysis of the influence of a building shape parameters on EE and EC. In this context, the objective of this study is twofold; (1) proposing a simplified model for the assessment of a building's EE and EC that is suitable for assessments performed at the master-planning stage of an urban development project or at the sketch design stage of a construction project, and (2). study the influence of a building shape parameters on its EE and EC. The simplified model proposed in this paper is at building scale although it is meant to be used in the context of an urban development assessment. It means that it has to be applied on every building of the development. This model allows for a hybrid approach between bottom-up and top-down approaches. It makes the most of the data available at the master-planning stage of a development project; the actual shape of each building is taken into account and not only its gross floor area (bottom-up approach), and generic data related to construction methods and building materials are used (top-down approach).

We first present the conceptual model and associated data for assessing the embodied energy and embodied carbon of buildings at early design stages. Then we show the methodologies used to conduct a sensitivity and a contribution analysis for two types of generic building forms assessed with the model. The results allow to understand the relative influence and contribution of the different shape parameters. Although it could be repeated for any other type of buildings, construction systems, and national contexts, it