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Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system

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ABSTRACT

Life Cycle Assessment (LCA) is increasingly used as an early-stage design-decision tool to support choices of structural system. However LCA modellers must first make numerous methodological decisions, and the resultant wide variations in approach are often inadequately described by the modellers.

This paper identifies, and quantifies, the three major areas of methodological variation. These are: temporal differences in the stages considered; spatial differences in the material boundaries; and physical disparities in the data coefficients. The effects are then demonstrated through a case study of a student residential building in Cambridge. The cross-laminated timber (CLT) structure is compared with concrete frame, steel frame and load-bearing masonry, considering the influence that varying the temporal boundaries, the data coefficients, and the spatial boundaries has on the choice.

While for this building CLT is confirmed as the lowest impact material, the paper demonstrates that varying the methodological choices can change the results by an alarming factor of 10 or even more. The findings confirm the need for the utmost clarity and transparency with all LCA calculations. Making wider industry or policy decisions based on LCA results should be undertaken with extreme caution.

1. Introduction

The significance of the built environment on anthropogenic climate change is well-known. For many years now national regulations have focused on reducing the operational impacts of buildings. However with improvements in energy efficiency being achieved, both academic research and industry practice are becoming increasingly interested in measuring and reducing the embodied, as well as operational, impacts. The last two decades, and in particular the last five years, have therefore seen a rapid increase in the calculation of whole life (operational plus embodied) environmental impacts of buildings.

Life Cycle Assessment (LCA) is the most common approach to measurement [1], with three different methodological approaches used: process, input-output, and hybrids which incorporate elements of the previous two [2–4]. As well as these three main variations, all three methods are open to interpretation, particularly in the analysis of something as complex as a building. Without a closer look at the methodological choices being made, drawing clear conclusions from the multiple published detailed LCAs of individual case study buildings is highly problematic.

Nonetheless there are some broad conclusions that can be drawn. One of these is the widespread agreement that it is the materials used in a building that have the major impact on the total embodied carbon and this is therefore the most frequently identified mitigation strategy within the academic literature [5]. Of the high number of materials included in a building, the structural frame and foundation elements are frequently the major component both in terms of mass and embodied impacts, and the structural material is often identified as one of the most obvious routes to reduction of environmental impacts [6,7].

While academic work on increasing accuracy and understanding of LCA of buildings is important, industry practice is clearly where major savings could be being made right now, with the right approach and advice. It is therefore important to understand both what is currently being calculated in practice, and how this could be better informed by academic research.

This paper therefore considers three questions: What are the key variations within the academic literature? What are the current industry approaches to reducing embodied impacts of buildings? And, What impact do both academic and industry method-

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ological choices have on the choice of structural material in practice?

In the following section the paper reviews the existing literature to identify three key areas where there are methodological variations, the temporal boundaries provided by the choice of life cycle stages, the choice of coefficients used for materials and different life cycle stages, and the material boundaries of the physical elements included in assessment. An analysis of recent case studies is used to demonstrate the reported ranges within each of the three areas.

The focus then turns to look at how real world calculations are being conducted within industry. Section 4 describes a new building recently completed for a Cambridge University college. Rather than a detailed academic LCA of the building, this is offered as a case of how calculations are being carried out on the ground. For this building a simplified LCA was carried out at early design stage for four alternative structural solutions in order to identify the lowest impact solution. In Section 5 this original calculation is then repeated using published data ranges to show how the three identified areas of methodological variation could affect the choice made of structural material. Section 6 offers concluding remarks with implications for policy, industry and academia are offered in the final section.

2. Identifying three key methodological variations

The academic literature shows a wide variation in published results for both embodied energy and embodied greenhouse gases of buildings. Early reviews such as those by Ding [8] and Sartori and Hestnes [9] published the range of embodied energy values found in multiple previous articles, but did not distinguish between the effects of differences in the buildings and the effects of differences in the analysis methods used. A few years later Dixit et al. [10] identified some of the methodological issues which contribute to the variation in results, including the system boundaries, the life cycle stages included, the consideration of either primary or delivered energy and inclusion or not of feedstock energy, and the age, source and completeness of data. This latter was also demonstrated in the range of values found by Hammond and Jones [11] in their development of the Inventory of Carbon and Energy at the University of Bath.

By 2012 academics were calling for uniformity of data and methodologies. Dixit et al. [12, p.3741] noted that 'the current state of research is plagued by a lack of accurate and consistent data and standard methodology'. Through a review of the literature up to 2010, with a particular focus on that published since the updated ISO standards on LCA in 2006, they noted the variation in system boundaries, methods of measurement, geographic location, consideration of primary/ delivered/ feedstock energy, source and completeness of data, manufacturing technologies, etc., and called for guidelines, followed by standards and a robust database. In the same year Moncaster and Song [13] reviewed the data and methodologies used in both academic and industry calculations, and identified the three main causes for the wide range of results as: diverse and non-comparable product data; different methodologies; and differences in building design.

Arguably we have come a long way since 2012, in particular in Europe with the publication of the CEN TC 350 standards [14,15]. These define the life cycle of a construction product or project, including buildings, and set out product category rules for the development of Environmental Product Declarations. Following a process LCA approach they define four principal life cycle stages, A, B, C and D, as shown in Fig. 1. The impacts related to the operational energy use are defined by stage B6 and those to the operational water use by stage B7, with the other 14 sub-stages together making up the 'embodied' impacts. This is now the most common basis for calculating embodied impacts of buildings within academic studies from Europe.

In 2013 Moncaster and Symons [16] developed a tool which applied the newly published method to an assessment at an early design stage, such as could be carried out by a designer making initial decisions about structural materials. However they highlighted both the difficulties posed by applying the detailed method to the lack of detailed information at the early stage of a project, and once again reiterated the call for better data for all life cycle stages.

Both national and commercial databases have since been developed in line with the standards, but the picture remains unclear. Calculations continue to vary both for buildings [17] and individual materials [18,19]. Frischknecht et al. [20, p.421], in an overview of the 57th LCA forum held in Zurich in 2015, concluded that 'unifying life cycle inventory methodology, environmental indicators and life cycle inventory background databases is most important'.

In a 2017 review Säynäjoki et al. [21] found methodological variations due to material boundaries, the inclusion of sequestered carbon, end of life assumptions and data sources. While their paper covered case studies drawn from the last thirty years, reviews of more recent case studies find similar results [22–24]. Anand and Amor [23] identify numerous areas of current uncertainty and discrepancy which they suggest warrant future research, including impact category, functional unit, service life of building products, assumed life of the building (also known as reference study period), system boundaries, accuracy of material inventory, rebound effect, the time value of carbon, biogenic carbon emissions and other variations. Rasmussen et al. [24] identified 'multiple interacting methodological parameters' causing a range in results of up to a factor of 20 in embodied energy and a factor of 27 in embodied carbon. Collected as part of the International Energy Agency Annex 57, the authors found multiple differences in the system boundaries, including both within the life cycle stages considered, and within the building components included, and differences in both building and component service life assumptions.

Some papers have considered the impacts of specific methodological variations on results. For instance a review by Chau et al. [25] considers the variation in results due to the choice of impact factor, comparing full Life Cycle Assessment, Energy only and CO2 only. Säynäjoki et al. [4] apply both process-based (PB) and input–output (I–O) methodologies to the same building to assess the relative and absolute impacts of 8 key building systems. While the total (cradle to gate) impact for the I–O calculation is almost twice that for the PB, as also found by Crawford et al. [2], they also show that the proportion of the initial impacts for the main superstructure frame and roof is just over 50% for both methods. The impact of the mechanical systems is shown to be considerably lower for the PB methodology (5% as opposed to 11% for I–O), while that of the foundations was much more significant for the PB (10% of the total) than the I–O methodology (3%).

With the TC350 standards suggesting that only the product stage (A1–3) is mandatory, the choice of which life cycle stages to include within process-based analyses also varies considerably between authors. Pomponi and Moncaster [5] demonstrated the variation in included life cycle stages through a review of 77 published LCAs, while Birgisdottir et al. [26] conducted a similar analysis in a study of over 60 international cases. Häfliger et al. [27] considered the effects of changing the life cycle system boundary in an analysis of four multi-occupancy residential buildings in Switzerland, with varying frame materials including reinforced concrete, cement-based masonry and timber.

Häfliger et al. [27] also conducted a sensitivity analysis using three alternative data sources, a database of EPDs, the KBOB [28] database and the commercially available Ecoinvent. Considerable discrepancies for the timber and insulation products in par-