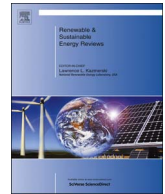




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Scrutinising embodied carbon in buildings: The next performance gap made manifest

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ABSTRACT

Life cycle assessment (LCA) is becoming increasingly mainstream as an early-stage design-decision tool for buildings. Still, there are considerable variations in how the method is currently used, leading to limitations in comparing the results and the conclusions that can be drawn. These variations are due to several factors and LCA modellers must make multiple methodological decisions during an assessment. This has resulted, unsurprisingly, in a variety of approaches, and a wide range of outcomes. Academics have produced numerous case studies on particular buildings, aiming towards a detailed understanding of the energy and carbon impacts. However, very few case studies are detailed enough to allow for an in-depth comparison. This article investigates in detail these embodied carbon assessments, considering the data used and the methodological assumptions made. An in-depth analysis shows that there are still considerable variations in how the methodology is applied, leading to substantial limitations in comparing results and drawing conclusions. Results may differ by two orders of magnitude, thus limiting the understanding of how real mitigation might best be achieved. Without immediate action, embodied carbon will become a 'second wave' of performance gap in environmental assessments of buildings. Both greater transparency and greater conformity must be embraced by the LCA community and enforced by policymakers and professional bodies.

1. Introduction

The importance of the impacts of the built environment on global greenhouse gas emissions is undisputed. The impacts of buildings in particular can be considered in two distinct but inter-related divisions; those due to the operation of the building (lighting, heating and so on), and those due to the physical construction of the buildings (including processing of materials and material waste and their transport, assembly and disassembly).

Since the start of this century there has been a considerable political focus on reducing the first of these, the operational energy and carbon of buildings, through for instance the enacting of the EU Energy Performance of Buildings Directive [1] and its enforcement via national building regulations. This has led to the encouragement of specific design measures including higher levels of fabric insulation and increasing uptake of on-site low carbon energy technologies. The

impact on the building industry has been significant, with new processes and materials and even new professions emerging as a result.

While operational impacts have indeed reduced, however a significant 'performance gap' between the modelled and the actual values from occupied buildings has become apparent. The extent of this gap was one of the most important findings in built environment research at the start of this century see, for instance, [2] and its discovery has resulted in expanded efforts to identify the reasons behind it. The application of the now well-known concept of the 'rebound effect' to the energy performance of buildings [3], later followed by the development of the idea of the 'prebound effect' [4], demonstrate the developing maturity of academic research in this area, which is helping the move towards increased actual reductions in operational energy.

The original regulatory focus on operational impacts was justified by the assumption that they were highly dominant; however, increasingly detailed calculations over the last decade have shown that

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embodied carbon¹ and energy make up a significant proportion of whole life impacts of buildings e.g. [5–12]. With the increasing move towards nearly zero energy buildings (NZEBS), both the relative and the actual extent of these impacts is likely to increase [13]. It is becoming increasingly obvious, therefore, that attention must now turn to first calculating, and then reducing the embodied impacts of buildings. As a first step towards this end, the European Committee for Standardisation (CEN) published three key standards in 2011 and 2012 (Fig. 1) [14–16] formalising the methodology for calculating whole life impacts of buildings and other construction works.

However although the new standards provide a rigorous methodology they do not dictate its use. An international assessment of 80 recent building case studies from around the world [17–19] has demonstrated the continuing variability in approach. Developed for different purposes, conducted by authors from different disciplinary backgrounds, and using different data and assumptions, drawing coherent conclusions from multiple studies remains extremely difficult. Furthermore the calculations carried out at design stage are often very different to the actual embodied impacts of the building. This second performance gap appears to be significant, and should be of grave concern.

Industry is keen to see embodied impacts included in building regulations (see for example the UK Green Building Council activities [20,21] in this area). The recognition of a gap between modelled and actual embodied impacts should serve as a catalyst to develop increasing research to support this desire as it has with operational impacts. Instead, the variation in and complexity of the calculations, and the subsequent plethora of results, seems to have had the opposite effect. No building regulations in Europe yet require reduction of embodied energy or carbon, and the variation in the calculations is used as an excuse for their continued exclusion [22].

It is crucial for the academic community to work together to produce a detailed understanding of this area, and of the multiple reasons for the gap between embodied carbon modelled at the design stage and that emitted in reality. To this end this paper provides a meta analysis of studies published since the publication of the TC350 standards in 2011. By comparing both the approaches and data used by the different authors for different phases of the life cycle of the buildings, the paper reveals the wide variation in methodological choices, and sheds light on the reasons behind the various results.

With increased knowledge it is hoped that Governments will be encouraged to support appropriate regulations for an effective design-stage approach, not currently offered by the TC350 standards, which will both reduce the gap between calculated and actual embodied emissions, and produce the rapid increase in reduction needed.

2. Previous studies

Life cycle assessments of conventional, low-energy and low-carbon buildings have been subjected to academic reviews on several occasions over the last decade.

Sartori and Hestnes [23] reviewed 60 cases from nine countries, and found a quasi-perfect linear correlation (i.e. an R^2 coefficient close to 1) between operational energy and whole life energy, which was valid across climates and other contextual differences. At the time of their review, however, embodied energy and carbon were seldom assessed and generally disregarded under the belief that their share of the whole

life figures would be negligible. It was also noted that measures targeted at reducing operational side have often a negative impact (increase of emissions) on the embodied side [23]. This particular aspect resurfaced more recently e.g. [13,24] and it is growingly becoming of great concern – especially since the focus of current regulations remains on operational energy and carbon of buildings. Ramesh et al. [25] also undertook a review of case studies, totalling 73 cases from 13 countries. Their work is also solely focused on energy, and not carbon, of buildings, and – similarly to Sartori and Hestnes [23] – they also found that operational energy accounts for 80–90% of the whole life energy, and that measures aimed at its reduction might be counterproductive from a whole life perspective [25].

The review from Dixit et al. [26] also focused on embodied energy, embodied carbon being not yet a widespread concept in 2010. They reviewed the then available scientific literature, highlighting the inaccuracy and unreliability of energy data that led to incomplete and incomparable assessments. Their work identified a set of parameters that, if addressed and adopted by scholars, could reduce variability or at least harmonise terms and definitions within the field [26]. Such focus on parameters was also part of a follow-on work of the authors [27] two years later, which updated the list of parameters and, again, called for harmonisation, and globally accepted protocols and guidelines. Though the sector has certainly moved forward, harmonised global approaches are yet to be reached [28].

It was Moncaster and Song [29] who first reviewed in detail existing data and methodologies in terms of embodied carbon and not just embodied energy. Their study coincided with the final stages of the development of the new standards produced by the European Committee for Standardisation Technical Committee 350 (CEN/TC 350), which perhaps are the most comprehensive set of tools to calculate and evaluate sustainability of buildings [15,16,30]. Moncaster and Song [29] found for embodied carbon issues similar to those identified for embodied energy, such as variability and unreliability of data, incomparability of results, and the need for consistent and transparent databases and methodologies. Cabeza et al. [31] also focused on embodied carbon in their literature review, though their focus was at the material level and not concerned with whole buildings. Their study drew attention on the still very debated field of low carbon materials since it included cement, concrete and bricks as well as wood and rammed earth [31]. Their review looked at how the embodied energy and carbon of such materials can be reduced but ignored the great variability, and the potential reason for it, of the numbers utilised in the assessments.

Pomponi and Moncaster [28] systematically reviewed the literature on embodied carbon in buildings from the past ten years in order to identify mitigation strategies and to conduct a ‘health check’ of LCAs of buildings. They found that the vast majority of LCAs show an incomplete and short-sighted approach to life cycle studies. Over 90% of the LCA studies reviewed only look at the manufacturing stage whereas just over 50% go up to the end of the construction stage, with future activities and impacts mostly neglected – in particular the embodied impacts related to the use stage [28]. Their review highlights the importance that various actors of the built environment, and their mutual collaboration, play in ensuring that knowledge on embodied carbon can be rapidly advanced. Lately, Anand and Amor [32] have reviewed recent developments and future challenges in LCAs of buildings based on the decennial environmental management and life cycle standards of the 14,000 series [33,34]. They have found that the main issues still lie with the comparability of the studies, the system boundaries, and the data used in the assessment both in terms of sources and collection procedures used [32]. Similar to Pomponi and Moncaster [28], Anand and Amor [32] also call for further developments of industry/academia collaborations to address the gaps in many of the areas identified.

While most of these existing studies offer valuable insights into the current issues of embodied carbon and explain the potential reasons

¹ Embodied carbon is a shorthand for embodied greenhouse gas emissions, calculated as ‘embodied carbon equivalent’ and measured in kgCO_{2e}, which includes carbon dioxide emissions plus all other greenhouse gases normalised to the equivalent amount of carbon dioxide which would produce the same global warming potential over a 100-year period. The term ‘carbon’ is used throughout the paper to mean embodied carbon equivalent. Clearly, greenhouse gas emissions form just one of the many environmental impacts of the built environment. However they are undoubtedly one of the critical issues the world is facing at the moment. Their calculation, and subsequent reduction, is critical to the future of the global climate.

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