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Exploration of life cycle data calculation: Lessons from a Passivhaus case study

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ABSTRACT

Executing a life cycle carbon analysis on a building has two components to consider: the *Embodied* Carbon (EC) and *In-use* Carbon, the sum of these forms 'the building carbon budget'. The *in-use* can be obtained through regulatory tools such as the Standard Assessment Procedure (SAP) in the UK. *Embodied* carbon has a loose framework with little guidance on a standardised methodology. This paper explores embodied carbon analysis using building components to enhance the understanding of the sensitivity and categorisation of measurements to propose a methodology. The exploration of differing methods on a Passivhaus case study was undertaken with the use of global warming potential identified as the correct unit of measurement. Different methods of estimating quantities and datasets used for an EC calculation are discussed. Results highlight a variation in carbon emissions for certain common building materials between the method used in the Environmental Performance Declarations (EPD) compared to current databases such as Inventory of Carbon and Energy (ICE) using Cradle to Gate data. Designers prefer simple embodied carbon calculation methods. This paper identifies a calculation method giving an acceptable accuracy with the least amount of input data required to implement regulatory standardisation within the industry.

1. Introduction

Life Cycle Analysis (LCA) has many parallels with the levels of input in quantity surveying such as the Standard Method of Measurement 7th edition, SMM7 [1]. However, the framework for a LCA is less defined, based on a systems approach on a case by case basis, often executed after works are completed as an audit process rather than at the design stage. The boundaries of a LCA study are more fluid in nature [2]. The results obtained are a direct consequence of the framing of a specific question at the commencement of analysis with each analysis a stand-alone study.

The European Union, the UK government and environmentally conscious designers are pushing towards zero carbon buildings through directives, building regulations, as well as good practice design. Unfortunately, the building industry has been more reluctant to make these methods 'business as usual'. Technological responses have largely been rejected, in preference to fabric solutions resembling the German Passivhaus standard [3] of high insulation and low infiltration rates.

An immediate consequence of their low operational energy is the higher impact of embodied energy as additional materials are required for the building construction [4]. This suggests that in the future embodied carbon of buildings will play an increasing role in the design of buildings and have a higher impact within their Life Cycle (LC). The EU in line with the International Panel on Climate Change (IPCC) has been giving attention to the Global Warming Potential (GWP) of buildings accounting for the damage caused by greenhouse gases within the atmosphere as a result of climate change. Operations past the first major refurbishment cycle are considered to be of little impact on climate change, as the major damage to the atmosphere is assumed to have already been done.

Abbreviations: BoQ, Bill of Quantities; BRE, British Research Establishment; EC, Embodied carbon aka cradle to gate; EPD, Environmental Product Declaration; FU, Functional unit; GGBS, Granulated ground blast slag cement replacement; GWP, Global Warming Potential usually measured in $kgCO_2$ equivalence; ICE, Inventory of carbon and energy; IPCC, International panel on climate change; LC, Life cycle; LCA, Life cycle analysis; PFA, Pulverised fuel ash cement replacement; RICS, Royal Institute for Chartered Surveyors; SAP, Standard Assessment Procedure, used under Part L of Building Regulations UK; SMM7, Standard Method of Measurement 7ed by RICS; WRAP, Waste and Resources Action Programme, UK organisation.

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1.1. Framework and objectives

This paper concentrates on the different methods of calculating cradle to gate impacts, accounting for the environmental impact from the extraction of raw materials until it leaves the factory gate as Embodied Carbon (EC) and quantifying its significance [5]. It further explores the significance of the measurement and the data protocol used by building designers within LCA calculations taking into account industry datasets and gross material usage including site waste and their influence on cradle to gate quantification. This can lead to a definition of a simple methodology for assessment.

An initial assessment of the Global Warming Potential of a life cycle of a Passivhaus building identifies the initial cradle to gate stage as the most significant stage of all other life stages in terms of its climate change impact. Therefore, it is relevant to focus, for a given case study, on the assessment of the EC component. This is further supported by data which can be defined, where other aspects such as end of life are predictions based on a range of future scenarios which have a great deal of uncertainty.

The LCA carbon figure can be broken down into product, construction, use and end of life stages. BS: EN 15978 [5] further breaks down these stages (Table 1) for the whole plot (the site curtilage) the building occupies. EC was analysed in depth for a case study; other stages such as maintenance and deconstruction/demolition could be derived as a percentage of the initial EC figure [6] but are not the focus of this paper in which only stages A1–A3 are analysed.

The significance of future design targets in the form of carbon allowances for buildings requires a standardised methodology to be put in place otherwise results will not be comparable (as is the case with current EC studies). This paper collects the differing methodologies of LCA and estimates the impacts of their differences on the assessment of building designs.

Any future carbon budget will be made up from the *Embodied* Carbon and *In-use* Carbon. In the drive to reduce carbon in buildings evaluation of the *in-use* carbon approach has been adopted and as a result clear regulatory protocols exist for its calculation such as Standard Assessment Procedure (SAP) within the UK building regulations [7]. Whereas SAP is a simple steady state tool, more dynamic simulation tends to result in a more accurate estimate producing a lower result [8]. Embodied carbon calculations with higher levels of refinement are investigated here to improve on the emission result obtained.

The selection of optimal methodologies is significant to the precision of the calculation made. This study explores the protocol for the method of defining the EC component as an enablement of future benchmarking of buildings by carbon allowances. No standardised simplified measurement protocol currently exists.

Measuring the EC within buildings has no fixed calculation methodology despite a range of papers identifying the depth and detail required to obtain useful results. The time required to carry out the calculation is one component of the design process and needs to be affordable to designers. The impact of the initial EC value within a building's life implies that the calculation should be carried out at an early stage when many of the design options are being explored and where the most significant carbon savings can be incorporated [9].

Currently the level of detail required depends on the user in setting the physical boundary stage of project (the certainty required) and the amount of works executed. Arguably the EC calculation for the highest accuracy should be conducted after the detailed design phase. The significance of the impact of individual material components is explored within the study.

Existing carbon data is largely based on individual product evaluations defined by specialist software packages [10]. Current approximations used in the industry are unclear, often using several sources of unreferenced data [11]. It has been previously shown by CarbonBuzz [12] that a defined metric cannot estimate the *in-use* carbon but highlights the comparative importance of elements that could provide a basis for future design decisions. A similar approach is taken to obtain results from a case study. EC can be measured with a range of units. This study adopts the units of carbon emission as kilograms of carbon dioxide equivalent ($kgCO_2eq$) in line with IPCC metrics.

From the Royal Institution of Chartered Surveyors (RICS) [11] the EC of the case study should be in the range of 250–1000 $kgCO_2eq/m^2$. The RICS figures have little background information and the methodology is undefined. The results are therefore of limited use to a designer as the quoted figure cannot be interrogated or manipulated to explore different design options. This study breaks down the individual components of a case study to show their significance.

2. Theory and method

Numerous academic studies have been conducted but due to the lack of protocol there is a variance of scope and results obtained. Table 2 presents a summary of differences identified in the literature review. These studies were selected as they addressed life cycle of buildings in Europe using scientific figures (as is proposed in this study) rather than weighted point scales.

The majority of the studies were made in dwellings. In most the energy used in the operation stage is compared to the embodied carbon one. Results are presented in terms of the time: how long does it takes for the operation phase to surpass the EC figure? Although there are a range of units and measurement protocols, their method of measurement falls within two distinct groups:

- Those which use a materials quantification of the building.
- Those that classify the buildings according to building components.

Much of the work done in this area takes a chemical view of the materials which compose a building. This approach makes it easier to break down the components to their original sources and quantify the energy required to adapt raw materials to their final uses [13,14,30,34,49]. This creates an abstract aggregation of results in which it is unclear where the materials are used. For instance, the resultant figure for the amount of steel may be a combination of multiple building components, from wash hand basin taps to steel reinforcement within structural concrete constructions.

The other approach is to quantify the building as a range of differing components [45,51]. It is more practical for a designer to have the LCA figure associated with the building element. This allows a parametric analysis to identify best solutions or a clear decision on the implications of a decision to invest in a particular element. However, this method has its drawbacks as a building may contain hundreds of products but only a small proportion of the aggregated result is presented. These studies do not define the boundary well enough nor are the quantities in which the materials are obtained, e.g. tiles are rarely brought per unit but come in specified multiples or per square metre, which may lead to a misinterpretation of results. This second approach forms the basis of the quantification of the building elements in the case study to be presented in Section 2.2 where further shortcomings are discussed.

As the case study is a Passivhaus design it is worth overviewing a standard and estimating its Global Warming Potential (GWP). A Passivhaus building is defined by very low energy consumption (15 $kWh/m^2/year$ for heating and 120 $kWh/m^2/year$ primary energy), high levels of insulation (e.g. U value for exterior walls below 0.15 $W/m^2 K$ in the UK) and air-tightness [52]. To obtain a preliminary estimate of the GWP of a Passivhaus building (see