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Embodied and operational energy for new-build housing: A case study of construction methods in the UK

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ABSTRACT

In this study a Building Information Model (BIM) tool is developed to simultaneously estimate embodied and operational carbon over a 60 year life span for a typical four bedroom detached house. Using the tool, four different construction scenarios are evaluated, representing a range of current construction methods used in present day UK house building. The results show that cradle-to-gate embodied carbon represents 20–26% of the total 60 year carbon emissions, with operational carbon representing 74–80% of total emissions. Construction scenarios that reduce operational carbon by improving the thermal envelope led to a 1–13% increase in embodied carbon but a 4–5% decrease in operational carbon compared to the basecase construction method. Approaches to reduce embodied carbon in new-build housing are also studied and a 24% reduction is demonstrated through building fabric changes. The study recommends that a universally robust methodology for measuring embodied carbon will enable design decisions to be taken to reduce whole life carbon emissions through improved choice of materials. Due to material changes impacting on the thermal characteristics of a dwelling, and to an extent the structural characteristics, an integrated BIM tool will be essential in quickly establishing whole life carbon impacts during the design stage.

1. Introduction

Recognition of the role of anthropogenic carbon dioxide's impact on climate change in recent years has led to the need for worldwide commitments in reducing carbon dioxide (CO_2) and other greenhouse gases. The UK government has legislated for a legally binding 80% reduction in CO_2 emissions compared to 1990 levels by 2050 as part of the 2008 Climate Change Act [1]. The built environment is a major contributor to greenhouse gas emissions as a result of construction processes, maintenance and energy associated with building use. The energy use throughout the lifetime of a building can be categorised into two distinct stages: (i) embodied energy use, the energy associated with the construction of the building; and (ii) operational energy use, the energy used post-construction once the building is commissioned and occupied. In this study embodied energy represents the energy required to source and convert raw materials into the finished product, so called cradle to gate. Emissions from buildings accounted for 35% of total UK greenhouse gas emissions in 2011 [2]. Thus great attention has been placed on the building sector with regard to achieving energy reduction measures that will aid the achievement of the stringent targets of the 2008 Climate Change Act. Such measures include insulation of all lofts and cavity walls by 2015, insulation of 2.3 million solid walls by 2022, replacement of 12.6 million old inefficient boilers by 2022 [2].

Policy, through the form of Building Regulations, is the vehicle through which change is currently being instigated with the aim to reduce the operational energy demand of new buildings. This legislative drive is resulting in buildings designed to be more energy efficient, in particular for space heating energy demand through reduced fabric heat losses and reduced infiltration heat losses [3]. The targets currently require net zero operational carbon emissions for all domestic buildings after 2016 and net zero operational carbon emissions for all new non-domestic buildings after 2019 [4]. As this operational energy use decreases, embodied energy use (the energy consumed during the construction phase) will become a greater proportion of the house life cycle carbon emissions. Currently there is no legislation in place to regulate the amount of embodied carbon during the construction of a building, including the carbon required to produce, transport and install the building components. Nonetheless, the recent Government Construction Strategy and Government Response to the Low Carbon Construction Innovation and Growth Team identifies embodied carbon as an issue that requires further investigation

Abbreviations: CO_2e, embodied carbon dioxide equivalent emissions; BIM, building information model; OSB, orientated strand board; SIP, structural insulated panels; SAP, standard assessment procedure; ICE, inventory of carbon and energy; IFC, industry foundation classes; NHBC, national house-building council.

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with regards to regulation and measurement [5]. Presently, with policy driving lower operational energy, there is the potential, if unchecked, for building material production and transportation to result in increased greenhouse gas emissions, which would be counter-productive.

A recent study by the NHBC Foundation which analysed the proportion of embodied carbon over 60 and 120 year lifespans for a typical detached and terraced house concluded that the proportion of embodied carbon, as a product of life cycle carbon emissions, increases as house designs meet future operational carbon reduction targets of 25%, 31% and 40% relative to Part L1A 2010 when considering a cradle to grave scenario [6]. The study showed that embodied carbon over a 60 year lifespan was a significant proportion of total (embodied and operational) carbon emissions (with calculated results between 31% and 44%) and the proportion of embodied carbon increased when designs aiming to reduce operational carbon were applied.

With embodied carbon playing a more significant role to the life cycle carbon emissions associated with a house, attention has begun to be focussed on how different construction materials might affect both embodied and operational carbon emissions. Monahan and Powell [7] determined the embodied carbon of a 3 bed semi-detached house and emphasised the point that the embodied carbon of a timber frame construction, using a modern method of construction, was 34% less than a comparable traditional masonry home. In both cases concrete was the most significant material in embodied carbon terms. The study involved the comparison of equivalent houses in terms of thermal envelope performance and it was determined that further life cycle carbon reductions could be achieved by a reduction in embodied carbon as operational energy was proposed to be similar. In contrast to the perceived benefits of a low thermal mass, timber framed construction the work of Hacker et al. [8] justifies the benefits of high thermal mass construction over lightweight structures in terms of overall life cycle carbon usage. Despite the higher embodied energy in a high thermal mass building, by considering a life cycle of 100 years a dynamic model was used to predict the operational carbon usage of the dwelling using weather data for a medium to high emissions climate change scenario weather data. An additional assumption with regard to a requirement for artificial cooling was also introduced and the study concluded that a high thermal mass building performed better in terms of reduced overall carbon emissions in comparison to an equivalent lightweight solution. This benefit was primarily due to the dynamic thermal storage provided by the thermal mass which results in reduced heating load as more solar and internal heat gains are stored thus reducing the heat load as well as delaying the onset of cooling requirement as the thermal mass can be cooled by night purging.

It is such discrepancies with regard to the benefit of one form of construction over another that Dixit et al. [9] point to the need for an approved and standardised measurement protocol for embodied carbon and reported on 17 studies in the literature. This study identified differences in the way that embodied energy is defined and measured in different reports with a number of these studies having used the ISO 14040 LCA (Life Cycle Assessment) methodology [10] whilst others have no mention as to the methodology employed. The LCA was originally developed for manufactured products and often do not meet the requirements of measuring embodied carbon in a building that can be large in size, complex and unique in nature and construction [9]. Buildings also have a greater lifespan compared to many manufactured materials and may undergo changes, alterations and renovation during the building life. Therefore there is a lack of reliable information in developing a clear LCA for a building. Likewise there is also variability in the embodied carbon data, often with relatively large standard deviations, for example in the ICE database values for the embodied energy of cement are 5.2 MJ/kg with a standard deviation of 2.7 MJ/kg [11]. Dixit et al. [9] suggest that a possible approach is to develop international guidelines for embodied energy measurement that will pave the way to an embodied energy and therefore embodied carbon protocol.

Throughout the life of a building, (conception, design, planning, use, maintenance, demolition) large amounts of data are used and collected. During the design and construction phases this information is added to, amended and utilised in a variety of ways with a variety of tools. Due to this nature, the information is often reformatted or re-input into a multiplicity of models; geometric, financial, structural, programme, thermal models. All sharing commonalities of data and thus the idea of creating a common data model emerged and the solution was termed 'Building Product Modelling' [12].

Now termed BIM or Building Information Management and Howard et al. carried out a recent study to assess the views and experience of experts and practitioners in the field of BIM which demonstrated that there is a general agreement that knowledge about building requirements should be modelled in a way that integrates as much data as possible as it accumulates through all stages of the design process [13]. However there is not a uniformly recognised definition of BIM, the reasons for this are probably due to the sheer scale of available information and a lack of consensus about what information is or should form the BIM. Nevertheless, there is the potential for a 'cloud' of building information to enable concurrent prediction of embodied and operational carbon emissions and aid design decisions to minimise both. The usefulness of a 'cloud' of data depends upon how the data is represented and shared [14]. Semantics is the potential downfall of model sharing such information resulting in data exchanges that are incomplete or error prone due to the lack of sematic definitions within Industry Foundation Classes (IFC) and are an issue the industry should take seriously [15]. Mah et al. [16] have utilised a BIM approach to measure the carbon footprint of the construction phase of the building lifecycle by assigning carbon values they calculated, using on site transportation analysis, to construction materials. By customising Virtual Construction Suite 2008, a programme developed by Vico Software (2008) the study was able to associate their observed CO_2 emissions data to various building construction fabric elements allowing the software to generate a prediction for the carbon dioxide emissions associated with construction of the building.

This study will use the principles of a central database of technical data that will be used to create a simplistic BIM tool that is able to concurrently compare operational and embodied carbon for new-build UK housing based on a standard geometry. Selection of construction materials from the database will automatically calculate and populate relevant inputs into a SAP based spreadsheet to calculate operational carbon, whilst simultaneously calculating embodied carbon. These two separate, but simultaneous calculations, derive their data inputs from the central database containing all pertinent material technical data, thereby fulfilling the BIM principle, see Section 2.3.

A case study of a typical modern four bedroom detached house is chosen to demonstrate the tool. Four construction scenarios, representing various alternative modern construction methods, are investigated to evaluate the impact on embodied and operational carbon emissions. The four construction scenarios are: (i) traditional masonry; (ii) heavyweight construction; (iii) closed timber frame; and (iv) structural insulated panels (SIP). Cross-comparison of the findings are then used as a basis for further detailed analysis of embodied carbon with respect to reducing embodied carbon in new-build housing through material selection. These findings suggest the use of 30% PFA concrete, timber framed glazing and alternatives to outer skin brick walls can result in 24% reduction