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RESEARCH ARTICLE

# Life cycle carbon emissions and comparative evaluation of selected open source UK embodied carbon counting tools

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## Abstract

Life cycle carbon emissions ($LCO_2$), made up of operational and embodied carbon, have become a major metric of building environmental performance and energy efficiency. Whilst there are now standard methods for operational carbon assessment due to its significance in $LCO_2$, there is still less emphasis on embodied carbon counting. However, the relative contribution of embodied carbon is on the rise as buildings become increasingly energy efficient. Following the rule that only something which is measurable is manageable, it is essential that we are able to accurately count embodied carbon. This study therefore reviews the concept of $LCO_2$ in buildings and further investigates the open source UK tools for embodied carbon counting. A comparative evaluation case study, which validates an earlier review, showed that there is no logic and consistency in the carbon figures produced by embodied carbon counting tools. This is mainly due to different system boundaries, varying underlying assumptions and methodological differences in calculation. The findings suggest that an industry-agreed data structure and common methodology is needed for embodied carbon counting. Generally, the study provides insights into the use and capabilities of the



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identified open source UK embodied carbon counting tools and is relevant to the on-going debate about carbon regulation.

## Keywords

**carbon counting tools, embodied carbon, life cycle carbon emissions, operational carbon, system boundaries, UK**

## Introduction

Climate change is one of the greatest environmental threats facing our civilization today the world over (Khalfan, 2006; Dias et al., 2007; Dimoudi and Tompa, 2008; Ürge-Vorsatz and Novikova, 2008; Kenny, Law and Pearce, 2010; Sayigh, 2014). Given that 86% of the greenhouse gases (GHGs) causing climate change are carbon ($CO_2$) related, a carbon equivalent ($CO_2e$) has been developed for the remaining 14% composed of methane ($CH_4$), nitrous oxide ($N_2O$) and refrigerant gases to enhance uniformity of measurement (DECC, DEFRA and DfT, 2008; Ekundayo et al., 2011; RICS, 2012; Du et al., 2019). The building industry is one of the largest contributors to the world's greenhouse gases. In the UK, carbon related to buildings amounts to around 47% of all greenhouse gas emissions (BIS, 2010). The introduction of the Climate Change Act 2008 resulted in a legal obligation in the UK to reduce carbon and several initiatives have been put in place to achieve this (Sturgis and Roberts, 2010; Monahan and Powell, 2011). According to DECC, DEFRA and DfT (2008) and BIS (2010), about 30 per cent reduction must be achieved by 2020 and at least 80 per cent by 2050 in relation to the 1990 baseline. The need to fulfil this commitment of reducing carbon in the built environment is changing industry's behaviour towards carbon accountability and increasing the awareness of carbon counting.

Carbon is increasingly seen as a metric of building environmental performance and energy efficiency in advanced economies such as the UK, USA, Australia etc(Pandey, Agrawal and Pandey, 2010; Pellegrini-Masini et al., 2010; Van de Wetering and Wyatt, 2010; Mah et al., 2011; RS Means, 2011). Carbon emissions are now being used as a benchmark for building performance in the UK construction industry (Boardman, 2007; Hammond and Jones, 2008a; Anderson, Shiers and Steel, 2009; Fieldson et al., 2009) and in direct response to the Energy Performance of Buildings Directive (2002) and UK Building regulations Approved Document Part L 2006 (BIS, 2010). For example, carbon emissions have since been controlled by the EU Emissions Trading Scheme. Consequently, Voorspools (2006) claimed that carbon aspect is now part of power tariffs in the UK. It is ever more important that we are able to accurately count carbon (Hitchin and Pout, 2002; Grant et al., 2009). In other words, there is a need to measure things better as the carbon market takes off and carbon becomes more expensive. Indeed, the science of measurement will be vital in underpinning the transition to a low carbon economy (Sterner, 2002). Furthermore, carbon counting can help to determine what and where significant carbon emissions are being produced during the life cycle of a building and can reveal the carbon implications in units of the various design options. This can in turn help to maximise potential for reduction and facilitate opportunities for environmental improvement (Lowe, 2000; Atkinson et al., 2009; Luo, Yang and Liu, 2016; Kiss and Szalay, 2018).

The carbon associated with a building over its entire life, i.e. life cycle carbon emissions ($LCO_2$),can be divided into embodied and operational emissions with approximate contributions of 30% and 70% respectively(RIBA, 2007; Hammond and Jones, 2008a; BIS, 2010). Industry attention and Government regulatory focus have been on operational carbon reduction through the use of energy efficient measures due to its significant contribution to life cycle carbon emissions. Embodied carbon's contribution is however becoming increasingly significant as the currently regulated operational energy and carbon decreases (Sturgis and Roberts, 2010; Emmanuel and Baker, 2012; RICS, 2012; Moncaster and Symons, 2013). Whilst there is now greater standardisation in measurements of operational carbon, the research focuses on the relatively new and still unregulated embodied carbon assessment. Despite these previous studies on operational carbon measurements, there is no known quantitative comparative evaluation case study on the selected embodied carbon counting tools. Due to the increasing need for standardisation of embodied carbon measurement and tools to regulate life cycle carbon emissions in buildings and there is a gap in analysing the inconsistencies in the available tools using a typical building element, particularly using quantitative comparative study. Therefore, this study becomes imperative with a view to providing insights into the use and capabilities of the identified open source UK embodied carbon counting tools. It is also relevant to the on-going debate about carbon regulation.

The aim of this study is to review the concept of life cycle carbon emissions in buildings, the available carbon estimation tools and to further investigate some identified open source UK tools for embodied carbon counting. Mathematical equations were formulated for life cycle carbon emissions through content analysis of the review. These were used to explain and simplify the varied, complex and sometime confusing literature on life cycle carbon emissions in buildings. A comparative evaluation of some selected UK tools for embodied carbon counting was conducted using a typical building element and reported as case study. The building element used for the case study is a hypothetical example of 1m$^2$ of a typical upper floor of a multi storey building. The case study findings were used to verify and validate an earlier literature review and some important conclusions were drawn. Using a quantitative comparative case study enabled an in-depth analysis of an established phenomenon from the review. This approach is in line with the grounded theory strategy of enquiry (Bryman, 2016; Creswell and Creswell, 2018). Also, it is widely acceptable in construction sustainability and carbon studies (Moncaster and Symons, 2013; Zhang and Wang, 2017; Fernando, Victoria and Ekundayo, 2018).

## Literature review

### LIFE CYCLE CARBON EMISSIONS IN BUILDINGS: WHAT ARE WE COUNTING?

Different authors have diverse views of what total or life cycle carbon emissions represent (Ekundayo et al., 2012; Moncaster, 2015). Pandey, Agrawal and Pandey (2010) are of the opinion that the carbon footprint of a product throughout its lifecycle includes the carbon content of the product from manufacture through to distribution, consumption/use and disposal. The carbon footprint associated with the different stages of a product's entire life cycle, otherwise known as cradle-to-grave, can either be direct or embodied emissions. Roche and Campanella (2010) simply refers to the carbon content associated with a product from cradle-to-grave as carbon emissions. The UK Building Cost Black book classified carbon footprint as either embodied or direct carbon (Franklin and Andrews, 2010) whilst embodied and operational carbon were the terms used by Hammond and Jones (2008a).

The use of the terms may differ from one author to another but Sturgis and Roberts (2010) gave a more definitive explanation of the carbon footprint associated with a building. They stated categorically that building carbon emissions comprise operational and embodied carbon. Notably, several other researchers in this field agree with this classification(Shipworth, 2002; Yohanis and Norton, 2002; RIBA, 2007; Fieldson and Rai, 2009; Hamilton-MacLaren et al., 2009; Rule et al., 2009; BIS, 2010; Yan et al., 2010; Chen and Chen, 2011; You et al., 2011; RICS, 2012). The subsequent sections discuss the operational and embodied carbon emissions associated with a building's life cycle.

## OPERATIONAL CARBON

Operational carbon is the emissions generated from the operational energy usage and the activities of the building users (Sturgis and Roberts, 2010). These emissions are as a result of lighting, electricity, heating and cooling during building occupation (in-use)(Emmanuel and Baker, 2012). Operational carbon contributes a staggering 70% to the total carbon emissions from a building (BIS, 2010; Sturgis and Roberts, 2010). The UK government and industry have taken considerable measures to reduce these emissions by developing legislation such as Part L of the Building Regulations, and formalised methods of managing carbon due to operational energy usage in new buildings. Operational energy usage and carbon emissions of buildings can be quantified by various standard assessment methods such as Energy Performance Certificates (EPCs) and Display Energy Certificate (DECs) (BIS, 2010; Sturgis and Roberts, 2010). Informally, several carbon footprint calculators such as Act on $CO_2$, Carbon footprint calculators etc. are being developed in the industry for this purpose and to raise environmental awareness(Ekundayo et al., 2012).

A meter shows the actual total energy usage in a building and there are different tools for modelling and predicting energy use in a proposed development. Examples include Design Builder® and HEED™ (Home Energy Efficient Design) (Roche and Campanella, 2010). In different parts of the world, there are standard published sources available that provide the emission factors for each energy supply for converting the operational energy usage in a building into carbon emissions such as DEFRA in the UK. Carbon emissions resulting from operational energy usage can be calculated using the UK national electricity grid which is currently rated at 0.55 $kgCO_2/kWh$, as indicated in DEC methodology (BIS, 2010). Gas heating has an emission factor of 0.194 $kgCO_2/kWh$ and Biomass heating, a factor of 0.025 $kgCO_2/kWh$. Other local grids will have different carbon emission factors due to different types and sources of energy (BIS, 2010).

## EMBODIED CARBON

Embodied carbon of materials used for construction and subsequent building maintenance accounts for approximately 30 to 40% of life cycle carbon emissions in building (Hammond and Jones, 2008a). Similar studies agree with this but concluded that the figure could vary based on building types (RIBA, 2007; BIS, 2010; Nawarathna et al., 2018). Indeed, the relative contribution of embodied carbon to life cycle carbon emissions is on the rise, particularly for new build (see Figure 1). This is due to tighter Part L Building Regulations and local planning policies which require energy efficient design and measures to regulate operational carbon (RICS, 2012). In other words, embodied carbon is been spent upfront through the use of carbon-intensive solutions to achieve efficiency in operational energy and carbon benchmark (Sturgis and Roberts, 2010; Zhang and Wang, 2017). Yet, embodied carbon measurement has not received sufficient regulatory focus and currently has no standard assessment methodology (BIS, 2010; Sturgis and Roberts, 2010; RICS, 2012).

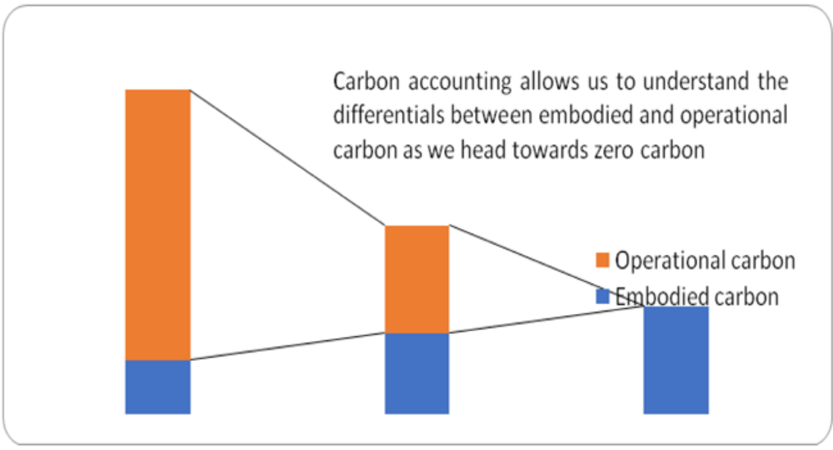


Figure 1 The ratio of embodied to operational carbon on a range of projects (Adapted from RICS (2012))

Unlike operational carbon which only relates to energy used to keep the building running when in-use, embodied carbon emissions are associated with different phases of the building's life cycle. These are called system boundaries (see Figure 2) - the different points in a building's life cycle that embodied carbon could be counted. Interestingly, there is common agreement in the industry as to the definition of these boundaries (Hammond and Jones, 2008a, 2008b; Anderson, Shiers and Steel, 2009; Fieldson et al., 2009; Franklin and Andrews, 2010; Kneifel, 2010; Pandey, Agrawal and Pandey, 2010; Pei and Williams, 2010; Mah et al., 2011; Moncaster and Symons, 2013; Luo, Yang and Liu, 2016).

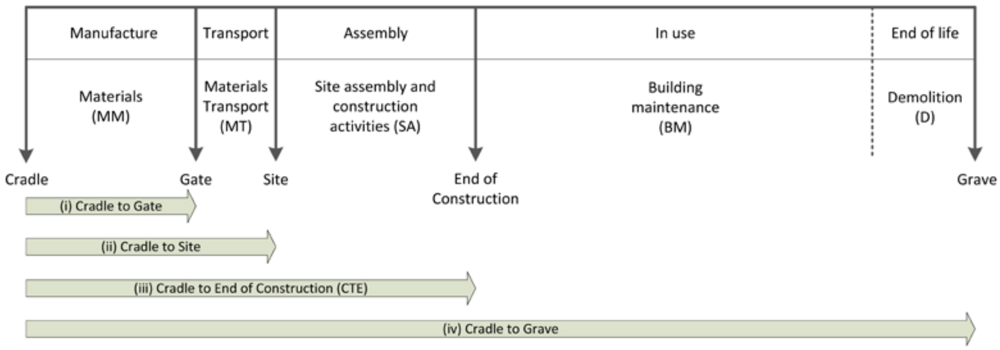


Figure 2 Embodied carbon life cycle phases of a building

The system boundaries are explained as follows:

i. Cradle-to-Gate: all carbon emitted until the building materials leave the factory gate (i.e. from extraction and manufacturing).
ii. Cradle-to-Site: carbon emissions until the building materials have reached the point of use (i.e. building site), which is cradle-to-gate plus transport to site.
iii. Cradle-to-End of construction: all carbon emitted in cradle-to-site plus carbon emissions as a result of assembly on site and construction activities.

iv. Cradle-to-Grave: all carbon emitted from the extraction of the building materials until the end of the building's lifetime or study period (i.e. materials extraction, manufacturing, transportation, assembly on site, building maintenance, disposal etc.).
v. Cradle-to-Cradle: applies only to recycled building materials as it also includes element of recycling., hence its limited use (Franklin and Andrews, 2010; RICS, 2012).

Figure 2 also indicates the time differentials between the life cycle phases of a building. When compared with the building's occupation (i.e. in use) phase; the materials manufacture, and site assembly and construction activities phases are considerably shorter though can each take up to two years for a typical building. The materials transportation to site, which of course depends on the site location, should be the shortest phase while the demolition of a building at the end of its useful life can take up to six months. However, the materials manufacture (MM), materials transportation to site (MT), and site assembly and construction activities (SA) phases are the most significant in terms of embodied carbon emissions. These phases i.e. MM, MT and SA, together represent the cradle-to-end of construction (CTE) system boundary as indicated in Figure 2.

The longest period of the life cycle phases of a building is the occupation or 'in use' phase, as illustrated in Figure 2. The building occupation phase can span up to 100 years or even more. Hence, why operational carbon emissions are a significant part of the life cycle carbon emissions. The embodied carbon emissions during building occupation come from building maintenance (BM) while embodied carbon is also emitted during demolition (D) at the end of the building life (see Figure 2).

## MATHEMATICAL MODELS FOR CARBON EMISSIONS

To promote standardisation of carbon measurement and tools, which is relevant to the ongoing debate about carbon regulation, mathematical equations were formulated for life cycle carbon emissions through content analysis of the review. These were used to explain and simplify the varied, complex and sometime confusing literature on carbon modelling. See for example; Yohanis and Norton (2002), RIBA (2007), Fieldson and Rai (2009), Hammond and Jones (2008a, 2008b), Sturgis and Roberts (2010), RICS (2012), Emmanuel and Baker (2012), Moncaster and Symons (2013), and Luo, Yang and Liu (2016). In common with most current practice and in line the method most commonly used in the UK, the mathematical equations have been formulated based on the above review to suggest a consistent approach to life cycle carbon emissions, especially embodied carbon measurement. The carbon emissions associated with a building's life cycle phases are a combination of embodied and operational carbon (see Eq. 1).

i.e.

$$\textit{Life cycle carbon emissions } (LCO_2) = \textit{Embodied } (ECO_2) + \textit{Operational } (OCO_2) \quad \text{– (Eq. 1)}$$

The carbon emissions generated through $ECO_2$ depend on three major stages. These include:

- Formation of the building, that is, cradle-to-end of construction (CTE)
- Building maintenance including refurbishment and replacement works (BM)
- Disposal at the end of the building's life, that is, demolition(D)Embodied carbon from cradle-to-grave can therefore be estimated using the following equation:

$$ECO_2 = \sum_{t=0}^{n} (CTE + BM + D) \qquad \textit{measured in } kgCO_2 \textit{ per unit} \quad \text{– (Eq. 2)}$$

| | |
|---|---|
| t | Time variable |
| 0 | Cradle |
| n | Grave |

The tools available for counting the carbon emissions due to building formation, building maintenance and disposal are reviewed and further investigated in later section of this study. The carbon emissions as a result of materials transportation to site are project specific and will vary from one project to the other (Franklin and Andrews, 2010). Similarly, building disposal is dependent on numerous factors and largely influenced by client types and building use (Flanagan et al., 2005). The carbon emissions as a result of building disposal may thus be difficult to assess as they may include some elements of re-use, recycling, and/or landfill, where not enough data is currently available (Hammond and Jones, 2008a, 2008b). The above mathematical model was used for the quantitative comparative evaluation case study using a typical building element.

Estimating the operational carbon emissions of a building is relatively straightforward and there are now standardised methods available in the industry for this purpose. Operational carbon emissions ($OCO_2$) are determined by the use of the building, that is, energy usage during building occupation. It is measured in $kgCO_2/kWh$. The next section examines the various tools available in the industry for operational and embodied carbon counting.

## GENERAL OVERVIEW OF CARBON COUNTING TOOLS

The terms 'carbon counting', 'carbon accounting', 'carbon estimating', 'carbon quantification' and 'carbon measurement' have all been used regarding the same concept with increasing familiarity in recent years, generally in response to concerns about climate change. In effect, these terms all refer to a common concept or protocol (Seo and Hwang, 2001; Urge-Vorsatz et al., 2007; Dias et al., 2009; Pandey, Agrawal and Pandey, 2010; Sturgis and Roberts, 2010; Mah et al., 2011). Carbon counting is quantifying in unit (i.e. $kgCO_2$) the carbon emissions of a product over its lifetime (Sturgis and Roberts, 2010). Fieldson et al. (2009) concluded that there are many carbon counting tools available for operational carbon measurement, but limited tools exist for calculating the embodied carbon emissions associated with construction activities and processes. Roche and Campanella (2010) suggested that carbon counting tools can be divided into different classifications based on the type of carbon information they provide. These carbon counting tools and the type of information they produce are discussed below under the two classifications commonly referred to by the various proponents in this area.

## CARBON FOOTPRINT CALCULATORS

These mostly free online tools can be used to determine personal carbon emissions within the home such as gas and electricity, water, food, waste and transportation (Roche and Campanella, 2010). There are countless example of these tools available worldwide and they include: American Forests, Best Foot Forward, BP calculator, California Carbon calculator, Chuck Wright, Clear Water, EPA Personal Emissions calculator, Safe climate etc. Some of these tools even offer the opportunity to buy carbon offsets, which involves investing in renewable technologies to balance energy usage (Pandey, Agrawal and Pandey, 2010).

Some further examples of these online carbon footprint calculators according to Pandey, Agrawal and Pandey (2010) include Act on $CO_2$ calculator (UK region), Nature conservancy carbon footprint calculator (USA region), Carbon footprint calculator (UK and cross boundary), Resurgence quick carbon calculator (UK region), An inconvenient truth carbon calculator (USA). Others include Live climate (USA based), Conservational international carbon calculator (USA and outside USA region), Climate change (USA based), Greenhouse gas calculator (Australia based), Live green carbon offset programme (USA), etc. The commonality amongst all these tools is that they are mainly for calculating domestic carbon footprints and operational carbon emissions as a result of energy usage during building occupation. They are individual and household carbon footprint calculators intended mostly for raising environmental awareness, and quantifying building operational energy and carbon (Pandey, Agrawal and Pandey, 2010).

## CARBON ESTIMATORS AND CALCULATORS

These tools can be used for estimating embodied carbon emissions in buildings such as carbon emissions associated with construction materials, activities and building maintenance (Hammond and Jones, 2008a; Anderson, Shiers and Steel, 2009; Jones, 2009). There are limited open source tools for counting embodied carbon in buildings (Hammond and Jones, 2008a; Pandey, Agrawal and Pandey, 2010; Mah et al., 2011). Furthermore, they are seldom freely available online (Mah et al., 2011). Many of the currently available carbon estimators and calculators are still mostly for domestic use (Roche and Campanella, 2010). Examples of publicly available carbon estimators and calculators include Build Carbon Neutral Construction Calculator, Athena Eco Calculator for Assemblies etc (Roche and Campanella, 2010). The former is a simple American calculator that provides rough embodied carbon results based on general information such as floor area, number of stories, basic structural material and the like while the latter gives better results but is only suitable for buildings in certain regions of North America. Examples of publicly available carbon estimators and calculators in the UK include CapIT™ and UK Building Black book (Franklin and Andrews, 2010), BRE Green Guide (Anderson, Shiers and Steel, 2009), Carbon Calculator for Construction Activities (Jones, 2009) and ICE Database (Hammond and Jones, 2008a, 2008b).

Estimating embodied carbon in buildings is still problematic due to the many uncertainties involved, the absence of formal standards and the lack of regulatory focus (BIS, 2010). Furthermore, the complexity and uncertainties associated with embodied carbon calculation are often given as reasons for the inconsistency of the available tools (Pandey, Agrawal and Pandey, 2010; Roche and Campanella, 2010; Mah et al., 2011). Hammond and Jones (2008a) regard these complexities and uncertainties to be the different boundary definitions, underlying assumptions, age of data, sources and rigour of original life-cycle assessments of embodied carbon tools. Also, factors such as the quantity of materials, maintenance and replacement frequency, sourcing of materials, transportation to site and waste in construction make it difficult to develop a standard benchmark for assessing embodied carbon in buildings (BIS, 2010; Sturgis and Roberts, 2010).

In the UK, there is currently no industry-agreed and formal assessment method for embodied carbon (BIS, 2010; Sturgis and Roberts, 2010; Ekundayo et al., 2012). The Royal Institution of Chartered Surveyors (RICS) in its recently published carbon information paper alluded to this lack of a common methodology for embodied carbon counting in building (RICS, 2012). In view of the above, the next section further investigates and compares some of the stated tools, currently publicly available in the UK, for embodied carbon counting. This will help to identify some of the ways embodied carbon is currently being measured, the deficiencies and variances in the available tools and the wider implications for the industry as a whole.

### COMPARISON OF UK EMBODIED CARBON COUNTING TOOLS

The stated tools currently and publicly available in the UK construction industry for embodied carbon counting are comparatively discussed in Table 1. The characteristics of each tool are examined based on their usage, capabilities, system boundaries, limitations, source and availability. These provided a common backdrop against which to compare the stated tools as shown in Table 1.

As presented in Table 1, the commonality of all these tools is that none of them addresses embodied carbon figures for building services. Moreover, there is still no known open source tool, or if available then not popular, for embodied carbon counting of building services (Hammond and Jones, 2008a, 2008b; BIS, 2010; Sturgis and Roberts, 2010).

## Research method

The aim of this study is to review the concept of life cycle carbon emissions in buildings, the available carbon estimation tools and to further investigate some identified open source UK tools for embodied carbon counting using secondary data source which involve information from the theoretical framework. The comparative evaluation case study considers the several literatures available by narrowing down the scope in order to seek understanding of a phenomenon, which is the aim of this study. The empirical design for this study involves the use of ethnography and case study, which are considered appropriate. According to Bryman (2016), ethnography as a research approach involves explaining and judging what is being studied primarily based on critical discourse and content analysis, and in some cases combined with personal observation and experience of the researcher. Using ethnography to conduct a thorough literature review of life cycle carbon emissions and carbon counting tools simply means accessing the field and carrying out content and discourse analysis to know the present state of development, judging from the theoretical framework (Ekundayo, 2009). The specified approach was used to explain and simplify the varied, complex and sometime confusing literature on life cycle carbon emissions in buildings. Same was done to formulate mathematical equations for life cycle carbon emissions and to further investigate some identified open source UK tools for embodied carbon counting but this will also be complemented with the analysis of a case study, which collectively will serve as benchmark for subsequent comparison. This approach was used in Ekundayo (2009), where ethnography and a single (best practice) case study were considered viable for a comparative study on project management competencies.

Table 1 Comparison of UK construction carbon counting tools (Adapted from Ekundayo *et al*. (2012)

| Tool | Description/ Comment | System boundary | Limitation | Source/ Availability |
|---|---|---|---|---|
| Inventory of Carbon and Energy (ICE) Version 2.0<br>ICE was developed at the University of Bath | **Calculates:** embodied $CO_2$ and/ or $CO_2e$ of approximately 200 different building materials.<br>**Measurement unit:** $kgCO_2e/kg$ and/or $kgCO_2/kg$ OR $kgCO_2/m^2$ and/or $kgCO_2e/m^2$.<br>**Generic conversion factor:** $CO_2e$ is 6% higher than the $CO_2$ value based on UK fuel mixes.<br>**Waste**: explicitly excludes waste in construction.<br>**Note:** ICE used to be the only open source, freely available **peer-reviewed tool** for its purpose until recently. It is currently the most comprehensive source of figures for carbon embodied in building materials. | Cradle-to-gate (i.e. factory gate) | **Lower level info:** embodied $CO_2$ or $CO_2e$ values for primary materials like gravel, cement, sand, etc. and secondary materials like concrete, windows, bricks, etc. Hence it is a tedious option to calculate embodied carbon for the entire building.<br>**Detailed information:** such as drawings, materials and project specification required for ease of use.<br>**Unit of measurement:** not consistent for all the materials in the database. | (Hammond and Jones, 2008a, 2008b; Emmanuel and Baker, 2012).<br>University of Bath ICE Database. It was initially made freely available via an online website as an Excel spreadsheet. |
| Construction Carbon Calculator Developed by the UK Environmental Agency (EA) and Jacobs Engineering | **Calculates:**$CO_2e$ (in tonnes) of construction activities (i.e. $CO_2e$ of construction materials and the $CO_2e$associated with their transportation, site energy use and waste).<br>**Unit of measurement:**$CO_2e$ per tonne.<br>**Note:** developed using $CO_2e$ values derived from ICE database. The tool (an Excel spreadsheet) allows inclusion of materials not covered if $CO_2e$ per tonnage of materials is known. | cradle-to-end of construction | **Lower level info:** CO2e values for basic materials and composite items only. Hence a tedious option for embodied carbon calculation of buildings.<br>**Detailed information:** required.<br>**Coastal and fluvial projects**: tool only covers some materials mostly common to this kind of work.<br>**Limited CO2e data:** for building projects. | (Hammond & Jones, 2008a; Jones, 2009).<br>Environmental Agency Carbon Calculator. Freely available online as an Excel spreadsheet for public usage. |

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Table 1 continued

| Tool | Description/ Comment | System boundary | Limitation | Source/ Availability |
|---|---|---|---|---|
| The Green Guide From BRE (Building Research Establishment) | **Calculates:** $CO_2e$ of more than 1500 specifications of building materials and components in terms of various building element sections and subcategories across a range of 6 different generic building types. **Unit of measurement:** $kgCO_2e/m^2$ (on an elemental uniform basis). **Note:** the Green Guide Calculator is an online bespoke tool that generates $CO_2e$ values not listed in the Green Guide (available in hardcopy print and also as an online tool). | Cradle-to-grave (over a 60-year building life) | **Carbon information source:** has been largely developed based on estimation. **Extent of information:** not all building elements and building element material specifications are covered. **System boundaries:** a single $CO_2e$ value for cradle- to- grave does not allow embodied capital carbon analysis. **Service life:** 60years assumed for the specifications and components though most buildings can last longer or less. | (Anderson, Shiers and Steel, 2009) The Building Research Establishment Green Guide to Specification. It is publicly and freely available online by registering on the BRE website and using the specified details to log in. |
| CapIT™/ Black book (Capital Cost and Embodied $CO_2$ Guide) Developed by Economic and Research Unit of Franklin and Andrews (part of the Mott MacDonald group) | **Calculates:** embodied $CO_2$ values of construction work activities including direct emissions from plants usage on site and tools. **Unit of measurement:**$kgCO_2$/ SMM work item unit **Note:** developed using published database and other reliable sources. Elements of waste have been included in the CapIT carbon figures. The database for the tool was developed in accordance with SMM with an embodied carbon value for each work item. The Black book is the hardcopy version of CapIT (which is regularly updated). | Cradle-to-End of Construction (excluding transport) | **Carbon information:** the tool appears to have embodied $CO_2$ values not $CO_2e$. However, $CO_2e$ can be assumed since ICE was used in its development. **Extent of information:** used to provide embodied capital carbon analysis. The $CO_2$values of construction work activities of CapIT however exclude plant and materials transport to site. **Info required:** need to identify all related construction work items (using bill of quantities) in order to estimate embodied $CO_2$ values. | (Franklin and Andrews, 2010) Mott MacDonald CapIT is available for public use on a paid subscription basis. |

This study was carried out in a systematic approach involving two distinct data gathering phases: (i) literature review and (ii) case study for further investigation. The data collection and analysis method used for this study are described. Firstly, a review was carried out to investigate life cycle carbon emissions in buildings and the different carbon counting tools currently available globally and specifically in the UK. The review seeks to eliminate confusion over scoping and terminologies related to building life cycle carbon emissions. It also raises concerns over the issues contributing to the currently unregulated embodied carbon measurement and the increasing need for standardisation. A qualitative comparison of identified open source UK embodied carbon counting tools was carried out and presented in tabular form. Mathematical models for building life cycle carbon emissions were formulated through content analysis of the review. These were used to demystify, simplify and harmonise the variegated literature on building life cycle carbon emissions.

The UK embodied carbon counting tools identified from the literature were used for the quantitative comparative evaluation case study. A number of open-source tools available in the UK, which have relevant carbon information needed for embodied carbon estimation, were selected for the case study. The tools were used to calculate the embodied carbon emissions of a typical building element (upper floor) and presented as case study. Using a typical building element enabled an in-depth analysis of an established phenomenon from the review. This approach is in line with the grounded theory strategy of enquiry as suggested by Creswell and Creswell (2018). This is based on the assertion that a single or limited sample with further probing and detailed understanding of the subject matter is more appropriate to large sample with little comprehension (Yin, 2014; Fellows and Liu, 2015). This is a form of research strategy according to Silverman (2017) and it involves the use of two or more research techniques, which in this study are review and case study, to investigate the same thing. Having thoroughly and broadly reviewed building carbon emissions and the tools available, the case study approach was used to study an example of embodied carbon assessment of a typical building element. This approach is widely acceptable in construction sustainability and carbon studies (Moncaster and Symons, 2013; Zhang and Wang, 2017; Fernando, Victoria and Ekundayo, 2018).

## COMPARATIVE EVALUATION CASE STUDY

There is no known research that seeks to quantify the embodied carbon emissions from actual building construction or element using the available tools, for comparison purposes and to identify deficiencies (Mah et al., 2011). This comparative evaluation case study addresses this gap in knowledge and compares the identified open-source UK tools by computing the embodied carbon of a typical building element. This will also provide a better understanding of the use and capabilities of the identified embodied carbon counting tools.

## CASE STUDY TOOLS

ICE, CapIT and Green Guide have been selected from Table 1 for the comparative evaluation case study. These tools have significant capacity to compute the embodied carbon of a typical building element. EA Construction Carbon Calculator has been excluded on the premise that it was primarily developed for tidal projects and not buildings. Indeed, there are other carbon counting tools available but many of them are not suitable for embodied carbon counting of buildings or not open source tools (Hammond and Jones, 2008a; Mah et al., 2011).

## CASE STUDY

A typical building element such as the upper floor of a multi storey building has been selected for the case study. The upper floor has been selected because it is one of the major, carbon intensive building elements (RIBA, 2007). According to RICS (2012) concrete work elements including upper floors area carbon hotspot, that is, a carbon significant element of a building that should be targeted for embodied carbon counting. The case study tools are used to calculate *the embodied carbon emission of 1m2 of a typical upper floor* (see Figure 3).

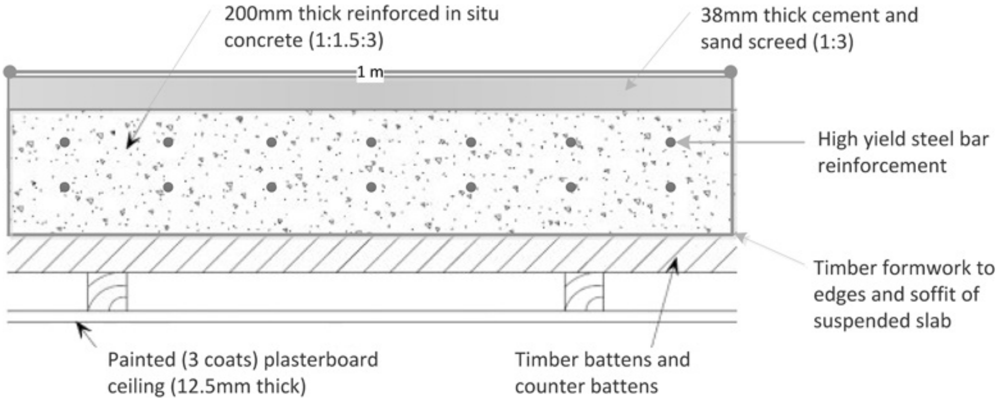


Figure 3 Cross section of 1m$^2$ of a typical upper floor

The limitations of the case study include, in particular: (i) the limited number of tools used for the calculation and (ii) the single element considered, although these have been justified in the study. Also, due to the information provided by these tools, embodied carbon emission of the typical element cannot be calculated on a similar system boundary. However, using the selected tools in its designed form for a typical building element made the results more original and enabled an in-depth analysis, from which some important conclusions were drawn. Note: the terms "embodied carbon figure", "embodied carbon amount" and "embodied carbon quantity" have been used interchangeably in this study to denote embodied carbon emission. Details of the calculations using the identified tools are presented as follows:

## THE GREEN GUIDE

A particular type of upper floor that meets the specification in Figure 3has been selected from the Green Guide and this will be used for the other tools, for consistency. The construction and materials specification of the selected element will be taken into consideration when determining its embodied carbon figure using the other tools. An upper floor element 807280054 (Green Guide page 58) has been selected for the case study and it is briefly described below:

*1m2 of power floated in situ reinforced concrete floor slab. It consists of concrete mix, reinforcement, formwork, cement screed top, ceiling plasterboard and paint finish.*

*The embodied carbon amount/quantity= 90 kgCO2e per m2 (Green Guide)*

The basis of this figure is 1m$^2$ of upper floor construction to satisfy Building Regulations - capable of supporting a live floor load of 1.5 kN/m$^2$ based on a 4m column grid and surface ready for the addition of a sheet carpet and underlay with a painted plasterboard ceiling. It includes any repair, refurbishment or replacement over a 60-year study period. There is no need for any calculation using this tool as it has embodied carbon figures (cradle-to-grave) for different building elements with different specifications (see Table 1). Therefore, it is just a matter of identifying the relevant element in the Green Guide or using the best comparator, if any.

## CAPIT™/BLACKBOOK

The Blackbook is arranged in Common Arrangement of Work Sections (CAWS) format (see Table 2), which is the authoritative UK classification of work sections for building work (Franklin and Andrews, 2010). CAWS has been used for the arrangement of National Building Specification, the National Engineering Specification and the seventh edition of the Standard Method of Measurement of Building Works (SMM7) which is used for preparing bills of quantities(Allott, 1998; Seeley and Winfield, 1999). The use of Blackbook for calculating the embodied carbon of $1m^2$ of the typical upper floor element requires two basic steps. Firstly, the relevant work items that make up the element as well as their embodied carbon figures need to be identified and extracted from the Blackbook. Secondly, the extracted figures are converted to a common unit of measurement and summed up. The first step is illustrated in Table 2 while the second step is illustrated in Table 3 as follows:

Table 2 Typical upper floor extracts from Blackbook

| Section | Work items | Unit | kg $CO_2e$ |
|---|---|---|---|
| **E10** | **IN SITU CONCRETE** | | |
| E1014 | Reinforced mix C35P | | |
| E101417B | 150-450mm thick: Slabs | $m^3$ | 309.144 |
| **E20** | **FORMWORK** | | |
| E2001 | To general finish | | |
| E200103A | n.e. 250mm high: to suspended slab edges | m | 1.770 |
| E200112E | n.e. 200mm thick: soffits: 1.5 – 3.0m above floor level | $m^2$ | 5.733 |
| **E30** | **REBAR** | | |
| E3011 | Y, BS 449 in cut and bent | | |
| E301105E | 16mm diameter | Tonne | 1735.525 |
| **M10** | **CEMENT: SAND, CONCRETE SCREEDS AND TOPPINGS** | | |
| M1013 | Cement and sand (1:3); floated finish | | |
| M101309C | To floors and landings; 38mm thick | $m^2$ | 14.761 |
| **K10** | **PLASTERBOARD DRY LINING, PARTITION AND CEILINGS** | | |
| K1065 | Gyproc linings; 12.5mm tapered edge wallboard to woodwork backgrounds; fixing with screws; joints flush filled, taped and finished for direct decoration | | |
| K106541A | Linings to ceilings; over 300mm wide | $m^2$ | 6.544 |
| **M60** | **PAINTING AND CLEAR FINISHING** | | |
| M6010 | Emulsion paint | | |
| M601002F | Prepare, apply one mist coat and two full coats; plasterboard backgrounds; ceilings | $m^2$ | 1.068 |

Table 3 Blackbook embodied carbon of typical upper floor / $m^2$

| Section | Work items | Conversion to per $m^2$ | kg $CO_2e$ |
|---|---|---|---|
| **E10** | **IN SITU CONCRETE** | | |
| E1014 | Reinforced mix C35P | | |
| E101417B | 150-450mm thick: Slabs (Note: 200 mm thick slab) | 309.144/$m^3$ x 0.2m | 61.829 |
| **E20** | **FORMWORK** | | |
| E2001 | To general finish | | |
| E200103A | n.e. 250mm high: to suspended slab edges | 1.770/m x 1/0.2m | 8.850 |
| E200112E | n.e. 200mm thick: soffits: 1.5 – 3.0m above floor level | n/a | 5.733 |
| **E30** | **REBAR** | | |
| E3011 | Y, BS 449 in cut and bent | | |
| E301105E | 16mm diameter Note: typical average weight of reinforcement in concrete upper floor (solid slab) = 150 kg/$m^3$ = 0.15 tonnes/$m^3$ (1000kg = 1tonne) | 1735.525/tonne x 0.15tonne/$m^3$ x 0.2m | 52.066 |
| **M10** | **CEMENT: SAND, CONCRETE SCREEDS AND TOPPINGS** | | |
| M1013 | Cement and sand (1:3); floated finish | | |
| M101309C | To floors and landings; 38mm thick | n/a | 14.761 |
| **K10** | **PLASTERBOARD DRY LINING, PARTITION AND CEILINGS** | | |
| K1065 | Gyproc linings; 12.5mm tapered edge wallboard to woodwork backgrounds; fixing with screws; joints flush filled, taped and finished for direct decoration | | |
| K106541A | Linings to ceilings; over 300mm wide | n/a | 6.544 |
| **M60** | **PAINTING AND CLEAR FINISHING** | | |
| M6010 | Emulsion paint | | |
| M601002F | Prepare, apply one mist coat and two full coats; plasterboard backgrounds; ceilings | n/a | 1.068 |
| | | | **150.851** |

Note: n/a – not applicable

*The embodied carbon amount/quantity = 151 kgCO2e per m2(CapIT™/Blackbook)*

## ICE VERSION 2.0

ICE only provides embodied carbon values for primary and composite building materials that make up a building element, unlike the Green Guide that provides a carbon value for the building element or Blackbook for building work items that make up an element. Table

4 shows the primary and composite building materials that make up the typical upper floor element and the relevant carbon information and supporting data from ICE.

Table 4 ICE building materials: embodied carbon figures and supporting data

| Materials | $kgCO_2e/kg$ | $kgCO_2e/m^2$ | Supporting data |
|---|---|---|---|
| **Reinforced concrete (1:1.5:3)** | 0.155 | | Density of concrete: 2300 $kg/m^3$ |
| **Timber** | 0.31 | | Density of timber formwork: 600 $kg/m^3$<br>Note: Timber sourced from a sustainably managed forest |
| **Steel bar** | 1.40 | | Excludes final cutting of steel bar to length |
| **Cement screed (1:3)** | 0.221 | | Density of cement screed: 2100 $kg/m^3$ |
| **Plasterboard** | 0.39 | | Density of plasterboard: 950 $kg/m^3$ |
| **Paint (3 coats)** | | 1.31 | |

ICE is a lower level tool due to the basic information that it provides. Deriving an embodied carbon value for $1m^2$ of the typical upper floor element requires relatively detailed information and the making of further assumptions. Further assumptions made in order to do the calculation are stated as follows:

Assumptions:

- 10% extra concrete and screed as waste
- 5% extra plasterboard and paint as waste
- Proportion of concrete mix in reinforced concrete: 94%
- Excludes plasterboard fixing screws and other sundry items
- Negligible embodied impacts of water (consumed in concrete and cement screed)

Table 5 shows the calculations - converting the identified building element materials into the unit of measurements provided by ICE using the supporting data and stated assumptions. The calculation is carried out in respect of the quantity of each material in $1m^2$ of the typical upper floor.

Table 5 Calculations and conversion to ICE units of measurement

| Material | Calculation | Quantity (mass) |
|---|---|---|
| **Concrete** | $1\ m^2 \times 0.20\ m \times 2300\ kg/m^3 \times 0.94$ | 432.40 kg |
| **Timber formwork (edges of slab)** | $4 \times 1\ m \times 0.20\ m \times 0.018\ m \times 600 kg/m^3$ | 8.64 kg |
| **Timber formwork (soffits of slab)** | $1\ m^2 \times 0.018\ m \times 600\ kg/m^3$ | 10.80 kg |

Table 5 continued

| Material | Calculation | Quantity (mass) |
|---|---|---|
| **Timber battens** | 2 x 3 nr x 1 m x 0.025 m x 0.038 m x 600 kg/m$^3$ | 3.42kg |
| **Steel bar** | 1 m$^2$ x 0.20 m x 150 kg/m$^3$ | 30.00 kg |
| **Cement screed** | 1 m$^2$ x 0.038 m x 2100 kg/m$^3$ | 79.80 kg |
| **Plasterboard** | 1 m$^2$ x 0.0125 m x 950 kg/m$^3$ | 11.875 kg |

Table 6 brings together data in Table 4 and Table 5 to derive the embodied carbon amount for the typical upper floor element. This is carried out by multiplying each material quantity within each m$^2$ of upper floor (see Table 5) by the corresponding ICE carbon data (see Table 4), adjusting for waste (where applicable) and then summing up.

Table 6 ICE embodied carbon of typical upper floor per m$^2$

| Material (Primary/ Composite) | Quantity | Unit | ICE Data (EC/unit) | Waste | Total EC (kgCO2e) |
|---|---|---|---|---|---|
| **Concrete (1:1.5:3)** | 432.40 | kg | 0.155 | +10% | 73.72 |
| **Timber** | 22.86 | kg | 0.31 | | 7.09 |
| **Steel bar** | 30.00 | kg | 1.40 | | 42.00 |
| **Cement screed (1:3)** | 79.80 | kg | 0.221 | +10% | 19.40 |
| **Plasterboard** | 11.875 | kg | 0.39 | +5% | 4.86 |
| **Paint (3 coats)** | 1 | m$^2$ | 1.31 | +5% | 1.38 |
| **Total** | | | | | **148.45** |

The embodied carbon amount/quantity = 148 kgCO2e per m2(ICE Version 2.0)

## Discussion

Table 7 shows the embodied carbon values per m$^2$ of a typical upper floor element using the identified open source UK construction carbon counting tools.

The three tools used for embodied carbon counting produced different results as shown in Table 7. There are different factors responsible for this variation as seen in the calculation. The different system boundary of each tool is a significant contributory factor. This is a limitation of all the tools compared and of this study as a whole, as it affects the way the tools and their carbon outputs are compared in this case. These tools do not allow embodied carbon counting for each and/or all of the possible system boundaries in a building life cycle (see Figure 2). Instead, the Green Guide is cradle-to-grave, CapIT is cradle-to-end of construction (excluding transport emission which is project specific) whilst ICE is cradle-to-gate.

Table 7 Embodied carbon emission per $m^2$ of a typical upper floor using stated tools

| | Quantity(kg$CO_2$e/$m^2$) | System boundary | Source |
|---|---|---|---|
| **ICE Version 2.0** | 148 | Cradle-to-Gate | Table 1, Table 4, Table 5 and Table 6 |
| **CapIT™/ UK Building Blackbook** | 151 | Cradle-to-End of Construction (excluding transport) | Table 1, Table 2 and Table 3 |
| **BRE Green Guide** | 90 | Cradle-to-Grave | Table 1 and Section 0 |

In the case study, the Green Guide figure, which is for the cradle-to-grave system boundary, should be the highest. This is however not the case, and the explanation according to earlier review is that the Green Guide only provides a rough estimation of embodied carbon values of building elements(Anderson, Shiers and Steel, 2009). Furthermore, it is rational that the embodied carbon figure for CapIT™ is greater than that of ICE due to a higher system boundary. However, as CapIT's cradle-to-end of construction figure includes ICE's cradle-to-gate figure plus construction and site activities, the difference is indeed not adequate. Assumptions made in the ICE calculation such as mortar mixes, waste percentage uplift and material densities etc. are factors that have influenced the derived embodied carbon figures. These were some of the assumptions which Hammond and Jones (2008a) argue can lead to disparity between the results produced by different construction carbon counting tools, notwithstanding the different system boundary. Because the stated tools provide different types of information and at different levels as shown in the case study, they require different calculation methods and assumptions capable of producing diverse results.

The case study findings validate an earlier review and showed that there is no logic and consistency in the carbon figures produced by embodied carbon counting tools. Further, the different tool proposes different approach based on their capability and the data available, for estimating building carbon emissions. The findings suggest that an industry-agreed data structure and common methodology is needed for embodied carbon counting. Using a quantitative comparative case study enabled an in-depth analysis of an established phenomenon from the review. This approach is in line with the grounded theory strategy of enquiry (Bryman, 2016; Creswell and Creswell, 2018) and it is widely acceptable in construction sustainability and carbon studies (Moncaster and Symons, 2013; Zhang and Wang, 2017; Fernando, Victoria and Ekundayo, 2018).

## Conclusion

In order to address climate change, carbon has become a key measure of building environmental performance. The life cycle carbon emissions in a building can be divided into embodied and operational carbon. Indeed, enormous progress has been made in the industry and by the government to quantify, regulate and reduce operational carbon. This is no surprise as a significant part of carbon emissions in a building's lifecycle currently comes from operational carbon. The relative importance of embodied carbon counting is however growing with the decrease in operational carbon output. Embodied carbon's contribution to life cycle carbon emissions is becoming ever more significant, especially in new builds with energy efficiency measures. Yet, there is still no formal assessment method and industry agreed standard for embodied carbon counting in buildings.

Some identified open-source UK embodied carbon counting tools were further investigated to understand developments in this area and to identify some of the methods by which embodied carbon is currently being measured. A comparative evaluation of these tools reported as a case study in effect complements the findings from an earlier review. The study revealed that the currently available embodied carbon counting tools provide disparate levels of information and their carbon generated results are inconsistent. The wide disparities in the results produced by the tools were due to different boundary definitions, varying underlying assumptions and methodological differences in calculations. The uncertainties and relative complexities associated with embodied carbon calculation cannot be discounted. Further variances in embodied carbon tools causing disparity in their outputs include different units of measurement, the level of information required and provided, age, sources and the rigour of the underlying data.

According to the findings, ICE is more suitable for embodied carbon counting (i.e. cradle-to-gate) of stated primary and composite construction materials. It has not been designed to calculate the embodied carbon of construction assembly and site activities. Nevertheless, a comprehensive and peer-reviewed tool such as ICE has the potential to be widely explored and/or exploited in the industry as a basis for the development of more useable and higher-level tools. Perhaps CapIT is a step in the right direction for these reasons as it also uses acceptable industry standard such as CAWS. However, CapIT is only suitable for embodied carbon counting of construction (i.e. cradle-to-end of construction).The Green Guide is a much higher-level tool. But it can only provide a preliminary carbon (cradle-to-grave) guide for certain building elements. This may be useful where and when insufficient information is available at the project preliminary stage for in-depth calculation.

In general, this study provides insights into the use and capabilities of the publicly available UK embodied carbon counting tools which are relevant to the on-going debate about carbon reduction and the need for standardised embodied carbon accounting, particularly in energy efficient new builds. Emmanuel and Baker (2012) and RICS (2012) alluded to the lack of a common methodology for embodied carbon counting in buildings and argue for a common methodology. These and the findings from this study suggest the need for a standardisation of embodied carbon measurement and tools to regulate life cycle carbon emissions in buildings. There is a need to agree on a common methodology to be used for embodied carbon counting in buildings which considers the issues raised in this paper. The methodology should align the carbon data structure with industry recognised standards like CAWS and the RICS New Rules of Measurement (NRM) which provide guidance on the quantification and description of capital building construction and maintenance works. This should lead to an industry accepted methodology and tools which facilitate a more consistent approach and application of embodied carbon counting.

This study is not without limitations. More research is needed as the study does not fully encompass all the likely open source embodied carbon counting tools available in the UK. Although using ethnography and a case study are considered appropriate and viable for the study (Yin, 2014; Bryman, 2016; Moncaster and Symons, 2013; Zhang and Wang, 2017; Fernando, Victoria and Ekundayo, 2018), providing more case studies may enrich the findings. Despite these limitations, the study does demonstrate that embodied carbon is rising relative to operational carbon, that there is variance between the measurement of embodied carbon using different tools, that there is a need for a well-accepted standard in the measurement of embodied carbon, and that a common tool could well be developed for embodied carbon measurement. Agreement on a consistent approach, at a universal level, should enable embodied carbon measurement to become more widespread. Government intervention in terms of policy, incentives and taxation is equally essential in the standardisation of embodied carbon measurement/tools as well as measured international guidelines. Whilst this study can be seen as UK centric as reflected in the scope; climate change is a global issue and a collective approach is required to end the unregulated embodied carbon assessment. This research will influence the use and/or development of carbon assessment tools in other countries, especially in advanced economies such as the USA, Australia and parts of Europe, where carbon is increasingly seen as a metric of building environmental performance and energy efficiency.

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