DEVELOPING AN EARLY DESIGN STAGE EMBODIED CARBON PREDICTION MODEL: A CASE STUDY

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The focus of carbon management has shifted from operational carbon towards Embodied Carbon (EC) as a result of zero carbon agenda. Even though effort is made to quantify EC in detail design stage and choose the best solution for design there is no such approaches in managing EC during early stages of the design. The reason for this is lack of sufficient design information to quantify EC at early design stages. Hence, this research intends to fill that gap by using a unique approach of predicting EC by capturing the relationship between design and morphological parameters (such as plan shape, storey height, no. of storeys, finishes quality, services quality, etc.) and EC. Some building elements can be considered as 'carbon hotspots' (carbon intensive). Since carbon and cost are known to be the currencies of sustainable construction projects, the aim of the study is to develop a decision support system to optimise design in terms of carbon and cost during early stages of design. The aim is to be achieved by developing a database of elemental (NRM compliant) EC and cost (using Hutchins UK Building Blackbook and other data sources) of sample office buildings in the UK and identifying the correlations of EC and cost with design parameters. Consequently, regression models will be derived as the key component for the DSS development. This paper presents a detailed literature review of EC and EC estimating tools, a detailed discussion of the proposed research method and exemplar case study of an office building and EC and capital cost analysis of the building. The paper concludes with the identification of the carbon hotspots for the building (mainly, substructure, frame, upper floor and external walls) and compares it with published case studies while exploring the implications of the case study for the DSS to be developed.

Keywords: carbon hotspots, early stage design, embodied carbon, office building.

INTRODUCTION

Industrial revolution between 18th and19th centuries is one of the main reasons for significant rise in the global mean temperature. As a result, climate started to change radically due to excessive presence of heat trapping gases like carbon dioxide in the atmosphere. Consequently, economic, environmental and social conditions of the world regions started to be affected. Especially, poor nations are reported to be suffering more due to insufficient financial means to safeguard themselves against climate impacts (Intergovernmental Panel on Climate Change, 2012, 2013; Stern, 2007). Hence, developed regions came on board to combat climate change or to reduce greenhouse gas emissions by policy formulation and commitments to international climate change agreements like Kyoto Protocol (United Nations, 1998). More importantly, the UK government has set more stringent national targets to meet the 2050 emission reduction target of Kyoto Protocol through UK Climate Change

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Act 2008. Furthermore, action plans are also continually reviewed to suite the projected climate change and reported to the government periodically by Committee on Climate Change. Mainly, carbon control in the building sector is identified as one of the significant action plans to reach the target because building sector is one of the major exploiters of resources and energy (Committee on Climate Change, 2013). However, in the action plans more focus was given to reduce carbon emissions during the operation of the building (known as 'operational carbon') which contributed to nearly 70-80% of total emissions from buildings until the zero carbon agenda for buildings was introduced. Eventually, zero carbon agenda implicitly emphasise the need to control the other component of the building sector emissions, namely 'embodied carbon'. EC is driven by process and affected by the supply chain, thus, hard to manage. However, dual currency approach of clients and consultants highlight the importance of EC estimating and management. Therefore, it can be expected that the knowledge of cost and carbon relationship will become a valuable asset for the construction practices in the near future which makes the study outcomes significant.

LITERATURE REVIEW

Carbon in buildings

There are two types of carbon emissions in buildings namely: operational carbon and embodied carbon (also known as capital carbon). The contribution of the two in total emissions varies depending on the type of the building and design variables. The relationship between operational and embodied carbon was studied by Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, and Acquaye (2013) by drawing evidence from various studies from different countries. Accordingly, the findings of the above study suggested that there is no static relationship and it often varies. However, generally, operational carbon emissions are much higher than embodied emissions in most of the building types while there are exceptions like warehouses (See, RICS, 2014).

Operational carbon in buildings

RICS (2014) defines operational carbon in buildings as emissions related to energy consumption during the operation of the building. These emissions include both regulated loads (e.g. heating, cooling, ventilation and lighting) and unregulated/plug loads (e.g. ICT equipment, cooking and refrigeration appliances). Building Regulation Part L has provisions of controlling regulated operational carbon in buildings as the unregulated emissions are entirely depended on occupants' behaviour.

As per the Part L of the Building Regulations, the operational emissions or the Target CO_2 Emission Rate (TER) for the notional building design is calculated using either Standard Assessment Procedure (SAP), or Simplified Building Energy Model (SBEM) or other approved software tools where actual Building CO_2 Emission Rate (BER) should be less than the TER for the building design to be approved. The operational emissions are expressed in mass of CO_2 emitted per year per square meter of usable floor area of the building (kg/m^2/year). Although the benchmarks are set for the BER, there is a performance gap between predicted emission levels and actual emission levels (Pan and Garmston, 2012; UK-GBC, 2008, 2014) which is a serious issue to be addressed at the earliest possible in order to meet 2050 target.

Conceptually, in a zero carbon building operational carbon (regulated energy use) will be zero whereas the remaining component to be controlled becomes the embodied carbon in buildings. Further, Ibn-Mohammed *et al*. (2013) also stress that serious attention needs to be given on embodied carbon during design decision making.

Embodied carbon in buildings

Ibn-Mohammed *et al*. (2013) reviewed various interpretations of embodied energy and carbon from various studies. The review demonstrated variations in the definitions in terms of the terminologies used and the scope of the emissions considered. However, the definition proposed by Hammond and Jones (2008) can be regarded as acceptable as they are the producers of the very first inventory of embodied carbon and energy which drives most of the embodied carbon researches. Hammond and Jones (2011) revised the older definition (Hammond and Jones, 2008) and define embodied carbon as *"the sum of fuel related carbon emissions and process related carbon emissions"*. Authors did not confine the scope of emissions in the definition as embodied carbon can be calculated from cradle (earth)-to-gate (factory gate), cradle-to-site, cradle-to-end of construction, cradle-to-grave, or even cradle-to-cradle (includes recycle, reuse etc.) depending on the scope of data available. This is called as the system boundary of embodied carbon calculations. Few scholars noted that many embodied carbon datasets available are cradle-to-gate due to difficulties in capturing data (Hammond and Jones, 2011; Sansom and Pope, 2012). However, transport of materials to site adds significantly to total embodied carbon emission for some materials which has less embodied emissions in other phases (Hammond and Jones, 2008). Furthermore, lesser transport distance not necessarily means lesser carbon emissions as mode of transport and type of fuel also plays a significant role in addition to distance of travel (RICS, 2014; Sundarakani, de Souza, Goh, Wagner, and Manikandan, 2010).

Managing embodied carbon requires great deal of understanding and attention to detail. In a construction project, most (around 70 - 85%) of the cost is committed during design stage of the project (Asiedu and Gu, 1998) and so as with the carbon as both carbon and cost depends on the same factors like, material quantity, transport, construction method and so on. On the other hand, as more cost and carbon is committed into the project, the reduction potential decreases increasingly as possible design solutions are constrained by previous design decisions. Then, during construction phase the reduction potential can be regarded as nearly zero unless there is a design change (see Figure 5). Therefore, any measures to minimise the embodied carbon or cost in buildings has to be taken at very early stages of design due to the fact that reduction potential diminishes as design progresses (RICS, 2014). Further, the design becomes static as the project progresses and changing the design at a later stage will result in loss of time and money.

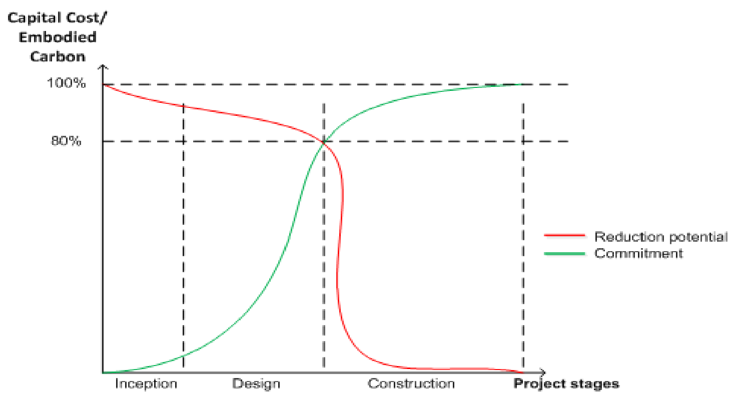

Figure 5: Behavioural pattern of Embodied Carbon and Capital Cost over project stages After, RICS (2014)

Furthermore, RICS (2014) states that investigating embodied carbon emissions in different types of buildings is a completely new research avenue. Evidently, there are limited regulatory standards or academic researches to aid decision making at early stages of projects. In addition to that intense calculations involved in embodied carbon measurement also makes it complex and undesirable (Ibn-Mohammed *et al*., 2013). Nevertheless, this research identified carbon hotspots in buildings as an ideal way of dealing with this issue; according to 80:20 Pareto rule, it can be assumed that 80% of emissions are to be coming from 20% of elements. However, that 20% of elements (carbon hotspots) are not yet firmly configured.

RICS (2014) defines 'Carbon hotspots' as the carbon significant aspect of the project. It not necessarily means the carbon intensive elements but also the elements where measurement data is easily available and reduction is possible. These carbon hotspots may vary from project to project depending on the type of the building. Generally, foundations, frame, roof, walls, and floors are considered as carbon hotspots. Furthermore, due to the complex nature of measurements of services in early design stages and lower reduction potential among others make building services less significant carbon hotspot even though it might contribute 10-25% of total embodied carbon (Hitchin, 2013; RICS, 2014). However, a study found that cladding finishes and services are to be the biggest component of recurring carbon emissions of an office building (Cole and Kernan, 1996). Hence, services and finishes cannot be disregarded when taking initial design decision as the contribution is significant. Therefore, it is important that the indication of likely embodied carbon of building services and finishes are revealed at the early stages of design to understand the carbon accountability of the project.

Subsequently, the study identified and analysed some of the embodied carbon case study findings of office buildings in the UK (Clark, 2013; Halcrow Yolles, 2010a; 2010b, WRAP; Sturgis Associates, 2010). It was noticed that the element classification differs from one study to the other (for example, NRM, SMM/BCIS - older version, British Council of Offices 2011, some studies did not follow any standards) makes it difficult to compare. Further, Clark (2013) also observed that findings of two different experienced consultants for the same building greatly differed. Dixit, Fernández-Solís, Lavy, and Culp (2010) identified a list of factors that affects the embodied carbon measurements. However, diversity of assumptions, source of embodied carbon factor and variation in methodology adopted (Clark, 2013) can be regarded as the most significant factors for the reported variations. Furthermore, element classification also highly alters the findings. Especially, analysis of embodied carbon in building services remains as a mystery due to lack of comprehensive published dataset. Furthermore, most studies lack elaboration on the methodology which questions the validity and applicability of the findings.

Eventually, this study attempts to eliminate the drawbacks identified in previous studies and develop a robust hierarchy of carbon hotspots in office buildings in the UK. The study follows NRM element classification, the standard which is in practice at the moment in the UK and makes it comparable with cost estimates. From that the study proposes a novel technique of predicting embodied carbon at early design stages based on well-established relationship of cost and design variables (Ashworth, 2010; Seeley, 1996) as both capital cost and EC depends on the same factors. Accordingly, the research tries to capture building morphological parameters and quality parameters (plan shape, storey height, total height, finishes quality, service quality and the like) related to the carbon hotspots and modelling them into a mathematical equation to capture carbon at early design stage.

Finally, the research idea can be presented in a conceptual regression model as follows:

$$Carbon\ Factor \left[\frac{\text{Carbon}}{\text{m2}}\right] \propto Morphology\ Parametrs\ (M_P)$$

$$Carbon\ Factor \left[\frac{\text{Carbon}}{\text{m2}}\right] = f(M_P, L_S, L_F)$$

$$Carbon\ Factor \left[\frac{\text{Carbon}}{\text{m2}}\right] \propto Level\ of\ Sevices\ (L_S)$$

$$Carbon\ Factor \left[\frac{\text{Carbon}}{\text{m2}}\right] \propto Level\ of\ Finishes\ (L_F)$$

$$Carbon\ Factor \left[\frac{\text{Carbon}}{\text{m2}}\right] = \text{a}\left(\frac{\text{Wall}}{\text{Floor}}\right) + \ \text{b(Storey Height)} + \ \text{c(Total Height)} + \cdots$$

$$\ldots\ldots + \text{Service Index} + \text{Finshes Index} + \ \text{k}$$

(a, b, c…k = regression)

Yet, it is useful to review the existing early stage carbon prediction models and underlying methodologies so that the strengths and weaknesses of the tools can be identified and issues can be addressed during the development of the decision support system.

Carbon Estimating Tools

Carbon estimating tools are in abundance and access is either free or licensed. Even though all tools tend to perform the same function there are differences in input information, system boundary, outputs, methodology and data sources. The study identified some freely accessible early stage carbon estimating tools include: Construction Carbon Calculator developed by Build Carbon Neutral; Embodied CO_2 Estimator developed by Phlorum (Phlorum, 2011), in collaboration with the University of Brighton; Green Footstep developed by Rocky Mountain Institute (Rocky Mountain Institute 2009); Building Carbon Calculator developed by University of Minnesota(University of Minnesota, 2014); and Steel Construction Embodied Carbon Tool developed by TATA steel (TATA Steel, 2014). First three are web based tools whereas Building Carbon Calculator is an excel based tool and Steel Construction Embodied Carbon Tool is a computer based tool. Each tool has its own limitations. Major limitation is to be the applicability of the tools which depends on the context and type of the building. This limitation becomes unavoidable for small scale projects with limited funds. Another common factor among these tools is the system boundary. Most of the tools cover cradle to construction (excluding transport) system boundary while this is not clearly stated in few identified tools which is a drawback.

In addition to those there are tools that estimate carbon in detailed design stages such as Carbon calculator for construction projects (an excel tool developed by Environment Agency), The Green Guide Calculator (A web based tool developed by BRE in compliance with 'The Green Guide to Specification'), Interoperable Carbon Information Modelling (iCIM - a tool developed in a BIM platform by *"OpenBIM"*), Sturgis Carbon Profile Model (model developed by Sturgis which combines both operational and embodied carbon into one unit and proposed a methodology to measure life cycle carbon of a building in $kgCO_2/m^2/year$) are to name few. In summary, it is clear that each tool is different and do have limitations. Further, among early stage carbon estimating tools cost is rarely incorporated.

Nevertheless, cost also changes along with embodied carbon when design variables change. Further, construction clients are becoming more conscious about dual currency, cost and carbon, in building development. Therefore, it is ideal to club both carbon and cost in one tool so that decision making is made easy with cost and carbon information that can be easily generated during early design stages. The shortfalls like differing element classification of previous studies and lack of cost consideration among the identified early stage carbon estimating tools justify the case for the study. Therefore, this study capitalises existing limitations in the literature and current tools and tries to develop a decision support system (DSS) that predicts embodied carbon and capital cost of early stage designs based on the correlations between design variables, and carbon and cost.

METHODOLOGY

Primary source of data for this research will be building data and published data. Building data (Bills of Quantities and architectural drawings) is obtained from consultancy organisations. Sample of 30 buildings' data are expected to be collected to build the principal database for the research.

Firstly, embodied carbon will be calculated for each building manually with excel aided functions and carbon intensive elements will be analysed. The major data sources to perform this task would be Inventory of Carbon and energy (ICE) version 2.0, UK Building Blackbook and where necessary manufacturer’s data. Then, hypothesis will be test to understand whether there is a significant relationship between different morphological (i.e. plan shape, building height etc.) and quality parameters (services quality and finishes quality) of the building with that of the respective carbon emissions and cost. Subsequently, correlation coefficient will be calculated as it is an appropriate measure of the strength and direction of the linear correlation between two numerical variables. Finally, algorithms will be developed with multiple variables to predict carbon and cost at early design stages with the aid of SPSS software and significance of each identified design parameters will be investigated subsequently during modelling and a best predictive model (algorithm) will be derived from the database of processed building data.

However, this paper presents a case study of an office building as an exemplar due to the ongoing nature of the research. The case study involves cost and carbon estimating of the building using detailed cost plan of the building and the data sources mentioned above. The cost and carbon estimating follows the conventional cost estimating process (Pre-tender estimate pricing) and both unit cost and unit carbon data are obtained from the same source to maintain consistency and comparability.

FINDINGS

Case study

Office A

- Gross Internal Floor Area : 33,663 m^2
- Net Internal Area : 22,634 m^2
- Number of Floors : Above Ground- 18, Below Ground - 2
- Brief Description : Raft foundation with concrete core walls, hybrid framed building comprising flat roof, curtain walling system and aluminium cladding, brick, block, dry lined partitions and glazed units, moderate finishes and highly sophisticated services including mechanical,

electrical and plumbing as well as specialised services like Building Management System (BMS).

- Capital cost : £23,131,452.04
- Embodied carbon : 23,769,592.57 $kgCO_2$

Figure 6 and Table 5 below presents the findings of the study in compliance with NRM element classification.

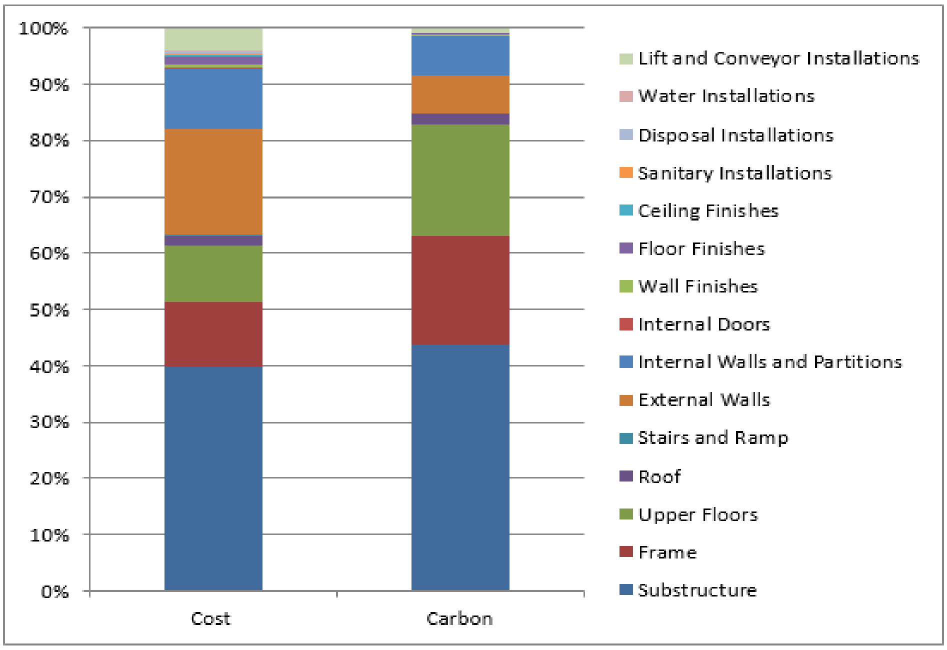

Figure 6: Elemental Embodied carbon and cost profile of case study office building

Table 5: Hierarchy of carbon and cost intensive elements- Findings of the case study

Element	Cost	Carbon
Superstructure	52.89%	54.66%
Substructure	39.70%	43.79%
Services[2]	4.91%	0.93%
Internal Finishes	2.20%	0.57%
Fittings & Furnishings	0.30%	0.05%

Findings suggest that there is a close relationship between cost and carbon. In terms of both carbon and cost the intensive element hierarchy remains the same. This knowledge can lead to effective decision making in early stages of design. However, this finding is based on one case study and more case studies to be conducted in the future. Further, external work is not included in the cost and carbon estimates as it depends on client's special needs, landscape and location of site, thus, tends to have a wider range irrespective of the scale of project.

Despite the benefits that the study yields there are also various problems encountered during this process. Major issue was carbon and cost calculations are performed from detailed cost plans of the office building, thus, some items are combined and measure in 'Item' or 'Lump sum' which makes it difficult to analyse the lowest level of specifications and details. Then, the UK Building Blackbook does not contain data for all the items, in which case a closer item specification is matched to obtain the carbon and cost factors. More importantly, building services embodied carbon data are

[2] Includes only Disposal, Sanitary, Water and Lift installations.

limited[3] due to the sophisticated nature of the element as mentioned by RICS (2014) and Hitchin (2013). Hence, calculations are not holistic and some of the items could not be included in the quantification due to lack of sufficient information or published data. However, care was taken to include most of the significant items. Moreover, author presumes that under representation of building services among other elements in terms of embodied carbon may be due to lack of published data. Further, the study points out the importance of embodied carbon data of building services and it is envisaged that the need for it will rise in the future.

Comparison with other studies

Table 6 presents and compares the findings of the study with other studies. Findings of other studies are altered to be aligned with the element classification of the study (NRM compliant classification). Accordingly, substructure and superstructure together are to contribute to more than 80%, in line with the findings of most of the studies. Services element demonstrates a huge variation among presented studies ranging from 0.93% - 25%. This is due to difference in the scope of analysis of services element and the methodology employed. The study had limitations in EC quantification of major services like electrical installations, gas installations, communication installations, fire and lighting protection installation and various other specialist installations due to lack of EC data. As a result, EC of building services of the study is comparatively very low. Furthermore, many studies do not clarify what constitutes the services element in the analysis which becomes a drawback for comparisons. Moreover, when EC of building services items are closed analysed it appears to be very small resulting in less contribution. If that is the case, then as RICS (2014) claims, services can be disregarded during early stage decision making.

Table 6: Comparison of the case study findings with other studies

	The Study	Halcrow & Yolles (Average of 3 case studies)	Sturgis Associates	WRAP	Davis Langdon from Clark (2013)
Substructure	43.79%	**89% (some elements are combined)**	25%	18.3%	**Structure - 45%-85%, Facade - 5%-25%**
Superstructure	54.66%		56%	58.24%	
Internal Finishes	0.57%	Not given	**Fit-out (shell & core) - 8%, Fit-out (Cat B) - 8%**	8.619%	**4%-25% (Internal walls included)**
Fittings & Furnishings	0.05%			Not given	
Services	0.93%	3%		11.96%	2-25%
Others		8% (External works)	4% (Waste)	2.9% (External works)	

However, the findings are based on single case study and the project is yet to progress with more case studies. Therefore, the study does not draw any conclusions regarding building services EC.

CONCLUSIONS

Increasing significance of embodied carbon in buildings and difficulty in prediction during early stages of design due to very little design information became the driver for the study. Eventually, analysis of relationship between embodied carbon and

[3] Except for that are available in Blackbook - plumbing, drainage, electrical and transport systems. Especially electrical data are for two storey housing installation which cannot be used in the context, which is why electrical installation is not presented in figure 6.

design variables provided the direction for the study as some of the building elements are to be carbon critical (hotspots). Therefore, modelling design variables related to carbon hotspots tends to make the predictive model simple and closer to the actual figure which is also supported by 80:20 Pareto rule. However, it was also noticed that there are many studies that analysed carbon hotspots and often reflected inconsistency in findings. Subsequently, a standard method of presenting building elements was adopted in the study which is NRM compliant element classification, making it easier for interpretations and re-use of results. Consequently, case study of an office building was presented and the findings were compared with other studies. Substructure and superstructure (especially, frame, upper floor and external walls) are identified to be the carbon hotspots being responsible for more than 80% of embodied carbon emissions. It was also noticed that there is a huge variation in embodied carbon figures of building services among studies due to the variation in the scope of analysis which is not transparent. Findings of the case study demonstrated a similar hierarchy of elements in embodied carbon and cost profile of the building which knowledge is mostly missing in other studies. This knowledge will become crucial for designers to economically achieve 2050 emission reductions target of the Kyoto Protocol.

FUTURE WORK

The project will conduct more building case studies (approximately 30) and analyse the relationship between carbon and cost. Further, early stage carbon and cost models will be derived based on design variables. The derived models will lay the foundation for the development of the decision support system to optimise design in terms of carbon and cost during early stages of design.

CONTRIBUTION TO THE KNOWLEDGE

The research contributes to the knowledge by: identifying carbon hotspots in office buildings; capturing the relationship between EC and design variables; showcasing capital cost and EC relationships; and developing a DSS to optimise design during early stages.

REFERENCES

Ashworth, A. (2010). *Cost studies of buildings* (5th ed. ed.). Harlow, England and New York: Pearson.

Asiedu, Y., and Gu, P. (1998). Product life cycle cost analysis: State of the art review. *International Journal of Production Research, **36***(4), 883-908.

Clark, D. H. (2013). *What Colour is your Building?: Measuring and reducing the energy and carbon footprint of buildings*. UK: RIBA Enterprises Limited.

Cole, R. J., and Kernan, P. C. (1996). Life-cycle energy use in office buildings. *Building and Enrironment, **31***(4), 307-317.

Committee on Climate Change. (2013). Fourth carbon budget review – part 2 the cost-effective path to the 2050 target. UK: Committee on Climate Change.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., and Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings, **42***(8), 1238-1247.

Halcrow Yolles. (2010a). *Embodied Carbon Sustainable Offices: a supplementary report*. UK: South West Regional Development Agency.

Halcrow Yolles. (2010b). *Sustainable offices – embodied carbon*. South West Regional Development Agency.

Hammond, G., and Jones, C. (2008). *Inventory of carbon energy* (ICE). UK: University of Bath.

Hammond, G., and Jones, C. (2011). *A BSRIA guide Embodied Carbon The Inventory of Carbon and Energy* (ICE). UK: BSRIA.

Hitchin, R. (2013). *CIBSE Research Report 9: Embodied Carbon and Building Services*. UK.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., and Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings*, **66**(0), 232-245.

Intergovernmental Panel on Climate Change. (2012). *Managing the risks of extreme events and disasters to advance climate change adaption: special report of the Intergovernmental Panel on Climate Change*. New York, Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2013). Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. In T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (Eds.). United Kingdom and New York, NY, USA,.

Pan, W., and Garmston, H. (2012). Building regulations in energy efficiency: Compliance in England and Wales. *Energy Policy, **45***(0), 594-605.

Phlorum. (2011). *Embodied CO_2 Estimator*. Retrieved 20th October 2014, from http://eco2.phlorum.com/calculator/save

RICS. (2014). *Methodology to calculate embodied carbon* . UK: RICS.

Rocky Mountain Institute (2009). *Welcome to green footstep - an assessment tool for reducing carbon emissions from building construction projects*. Retrieved 15 October 2014, from http://www.greenfootstep.org/

Sansom, M., and Pope, R. J. (2012). A comparative embodied carbon assessment of commercial buildings. *The Structural Engineer, October*, 38-49.

Seeley, I. H. (1996). *Building economics: appraisal and control of building design cost and efficiency* (4th ed. ed.). Basingstoke: Macmillan.

Stern, N. H. (2007). *The economics of climate change: the Stern review*. Cambridge: Cambridge University Press.

Sturgis Associates. (2010). *Carbon profile: ropermark place*. UK: Sturgis carbon profiling.

Sturgis, S., and Roberts, G. (2010). *Redefining zero: Carbon Profiling as a solution to whole life carbon emission measurement in buildings*. UK: RICS.

Sundarakani, B., de Souza, R., Goh, M., Wagner, S. M., and Manikandan, S. (2010). Modeling carbon footprints across the supply chain. *International Journal of Production Economics, **128***(1), 43-50.

TATA Steel. (2014). *Steel construction embodied carbon*. UK.

UK-GBC. (2008). *The definition of zero carbon*. UK: UK-GBC.

UK-GBC. (2014). *Building zero carbon – the case for action examining the case for action on zero carbon non domestic buildings*. UK: UK-GBC.

Kyoto Protocol to The United Nations Framework Convention on Climate Change (1998).

University of Minnesota. (2014). *Minnesota Site and Building Carbon Calculator*. Retrieved 15 October 2014, from http://www.csbr.umn.edu/research/carboncalc.html.