Estimating embodied carbon: a dual currency approach

M. F. Victoria, S. Perera, L. Zhou & A. Davies
Northumbria University, Newcastle upon Tyne, United Kingdom

ABSTRACT: Embodied carbon (EC) estimating is a growing area of research. EC estimating is evolving since the recent past, thus, undergoing several criticisms. On the other hand, there is a lack of interest among industry practitioners on EC estimating and reporting. However, EC estimating is crucial in a world of swiftly changing climate and visible adverse consequences. Therefore, this paper covers important aspects of EC estimating and explains various sources and methods of estimating, ranging from complex to simple methods of estimating. EC estimating is further explained by case studies of seven office buildings. Further, problems like lack of a standard method of measurement, lack of a robust database/benchmark for EC, lack of EC data for modern products and lack of EC data for sophisticated services are discussed. More importantly, the paper introduces dual currency appraisal of construction projects in which EC estimating plays a crucial role.

1 INTRODUCTION

1.1 *Carbon emissions of buildings*

Emissions from buildings are categorized into mainly two types: operational carbon/emission and embodied carbon/emissions. Operational carbon includes the emissions resulting from fossil fuel usage during the operation of the building (heating, ventilating, air-conditioning and lighting) while embodied carbon accounts for emissions resulting from fossil fuels usage and process which includes raw material extraction, manufacturing of building materials and products, transport, construction on site, repair and maintenance of the building, replacement of any components of the building, and finally demolition and disposal of the building at the end-of-life. Embodied Carbon (EC) covers a larger scope in building life cycle while Operational Carbon (OC) covers nearly three quarter of total emissions. Further, UK-GBC (2014) reported that buildings contribute for nearly half of the UK's emissions of CO_2.

1.2 *Significance of estimating*

Climate change due to the increased concentration of CO_2 in the atmosphere created the rapid need for reducing emissions from all sources. As a result Kyoto Protocol, an international treaty for emission reduction, requires 80% emission reduction from 1990 levels by 2050 and sub targets assigned to signatories (UNFCCC 2014). UK as one the signatories leading the way forward by ambitious targets through Climate Change Act 2008, setting own targets for the country. Accordingly, first milestone is zero-carbon homes from 2016. However, inclusion of existing stock for the target is remaining undecided. The next target is the 2019 target for zero carbon buildings. Improvements are made to the Part L of the Building Regulations to achieve the above mentioned targets. In that, OC of the building is measured and checked for compliance. Further, the low carbon route map for built environment in the UK sets 34% reduction by 2020 followed by 50% and 80% reductions in 2025 and 2050 respectively. Of which 21% reduction of EC by 2022 and a 39% reduction by 2050 is expected (The Green Construction Board 2013).

This clearly indicates that from 2019 buildings in the UK are expected to be zero carbon building which implies zero OC. Also when attempt is made to reduce OC, most likely EC increases (RICS 2014, Ramesh et al. 2010). Furthermore, there are no any regulatory measures for mandatory measuring and reporting of EC. This highlights the danger of aggravating EC unless it is measured and reported. In fact, to control EC it has to be estimated first. Therefore, estimating EC becomes prominent at this point of time. However, EC estimating is considered to be complex and there is a lack of interest towards it within the industry.

Therefore, this paper intends to break the complexity by explaining fundamentals of EC estimating under the sections of: cost vs. carbon estimating, sources of EC estimating, development of EC estimating, factors to be considered and problems encountered. In addition to that paper also presents case studies of office buildings as an exemplar of EC estimating and also introduces dual currency approach which attests the need of EC estimating for construction. Finally, paper also proposes some solutions for the identified problems in EC estimating.

2 COST VS. EMBODIED CARBON ESTIMATING

Cost estimating is one of the core duties of Quantity Surveyor (QS) in the construction industry. The process is well established and governed by industry standards like New Rules of Measurements (NRM2). The detailed estimate is known as 'Bill of Quantities (BoQ)' with almost complete details of the project. However, there are various other techniques to estimate cost during different stages of project as prescribed by NRM which is presented in Table 1.

The table above indicates the maturity of cost estimating techniques in the industry. On the other hand, carbon estimating is still a developing branch within the construction industry as it is relatively a new scope of service for QS firms and many regards this as a value added service. As a result, mostly very big firms deliver carbon estimating service to their clients.

Table 1. Types of cost estimates prepared during various stages of a project (partially adopted from NRM1).

RIBA 2013 stages	RIBA 2007	Cost Plan/ Estimate	Technique
Preparation and Brief	Appraisal	Order of cost estimate	Single rate estimating - unit, superficial area
Concept Design	Concept	Formal cost plan 1	Single rate estimating - unit, superficial area, cube
Developed Design	Design Development	Formal cost plan 2	Elemental estimate
Technical Design	Technical Design/Production Information	Formal cost plan 3/ Pre-tender estimate	Approximate quantities
	Tender Documentation	Bill of Quantities	
	Tender Action	Post-tender estimate	Adjusted Bill of Quantities

Carbon estimating is very similar to cost estimating though it evolved within the past decade. Initially started with Hammond and Jones' Inventory of Carbon and Energy (ICE) and now it is highly influenced by Franklin & Andrews (2011) UK Building Blackbook. Next section introduces the data sources of carbon estimating available in the UK.

3 SOURCES OF EMBODIED CARBON ESTIMATING

3.1 *Inventory of Carbon and Energy (ICE)*

ICE is an extensive database of carbon and energy data of building materials which was developed by Professor Geoff Hammond (University of Bath) and Dr Craig Jones (Circular Ecology). The first version was made available in 2006 for free download which then underwent several revisions and version 1.6 was published in 2008. Then, with significant improvement to the previous version the second version was published in 2011 (version 2.0). One of the most important revisions includes, the data had been converted from kgCO2/kg of material to kgCO2e/kg of material in the latest version allowing accountability of other GHG emissions (Hammond & Jones 2011).

The database provides embodied carbon and energy data of materials for cradle to gate system boundary. For instance, EC factor of 2.34 means usage of 1kg of the respective material is accounted for 2.34 kgCO2e of emissions. Data is derived basically from typical primary energy usage during manufacturing for most of the materials while feedstock energy is considered in special circumstances. In addition to that, carbon sequestration of materials, if any, is excluded. Also authors state that the data sources include both native and foreign sources which are said to be fairly recent data at the time of database development (Hammond & Jones 2008).

Moreover, the inventory also recognizes the uncertainty in the carbon data due to variant fuel types. Nevertheless, this is the most widely used energy and carbon database for calculations, especially within the UK context, and most EC estimating tools have ICE database as the underlying data source.

3.2 *Hutchins UK Building Blackbook - Small and Major Works*

UK Building Blackbook is developed and published by Franklin+Andrews based on the ICE database and data from various stakeholders of the construction industry. This is the first book to present both cost and embodied carbon data with respect to building trades in accordance with SMM7 (for major works) and SMM6 (for small works). Blackbook lists the item description, the resource requirement for unit quantity of the item, and the unit cost and unit carbon of the respective item similar to a price book. The carbon data presented in the book is of cradle-to-gate boundary (see section 5.1). This data source is mainly developed for the use of quantity surveyor who is an expert in construction cost estimating and carbon estimating is no any different to cost estimating.

3.3 *Embodied Carbon Database - WRAP*

The Embodied Carbon Database was launched online by WRAP in collaboration with the UK Green Building Council in April 2015. Aim of the database is to capture the embodied carbon data of the buildings within the UK and allow data sharing for effective learning. The database works in a way that industry stakeholders register themselves in the database and upload estimated project carbon data to the database which can be accessed only by the registered users. WRAP and UK-GBC created it as a closed database to prevent misuse of the project information uploaded into the database. There are more than 400 registered users and more than 200 projects stored at present in the database. However, the numbers suggest inactive industry participation.

The database serves as an EC library where projects can be retrieved by specific commands and exported to an excel file for further analysis. Data presented in the database follows the BS EN 15804 standard for system boundary classification (product stage (A1-3), construction process stage (A4-5), use stage (B1-7), end of life stage (C1-4), benefits and loads beyond system boundary (D)). There are very few projects presents data for cradle to grave system boundary at the moment. Further, data are presented in elemental format in which services element is excluded from analysis. However, this is a great asset for EC estimators and researchers to gain insights into EC data. The database can be accessed through http://ecdb.wrap.org.uk/ (see for more details, WRAP and UK-GBC (2014)).

3.4 *End of Life Dataset of framing materials*

PE INTERNATIONAL (an international market leader in sustainability related consultancy and software solutions) developed an end of life (during and after demolition and disposal - C and D modules in BS EN 15804) dataset for common framing materials of buildings like brick, block, concrete and steel. End of life EC is an area which is less researched and lacks sufficient data. This dataset facilitates holistic assessment of framing material selection for building development.

3.5 *Department for Environment Food & Rural Affairs (DEFRA) carbon conversion factors*

This is an online repository with up to date carbon conversion factors for fuels to calculated carbon footprint of business operations and products. However, this repository is suitable only for UK businesses, researchers and international organizations reporting on the UK operations. This repository allows three options in downloading the factors as an excel file as follows (Department for Environment Food & Rural Affairs 2015):

- Specific data demanded by the user: this option allows users to filter data depending on the scope, fuel or activity type and by the type of data that needs conversion. DEFRA also recommends this option as it eases the process of locating relevant data. However, this option is only available for dataset from 2012.

- DEFRA's frequently used data: this allows users to download pre-filtered factors used by DEFRA frequently for estimating purposes. This includes range of factors which are adequate for average footprint calculations of businesses.

- All available data: this option allows users to download all the factors for a respective year. This option is not recommended by DEFRA for usual carbon accounting while users may be interested in this option for advanced use.

This data becomes useful when estimating EC during construction, use stage and end-of life stage.

3.6 *ecoinvent*

ecoinvent database is developed by the Centre for Life Cycle Inventories. It is an international life cycle inventory database with updated inventory of data from several disciplines, including carbon inventory. The database form as the underlying source of data in many design tools with LCA calculations. The latest version of ecoinvent database is 3.1 with new updates to the inventory and changes to the underlying methodologies. However, database is not freely accessible like other databases discussed above; access is allowed only for registered users (ecoinvent Association 2015).

4 DEVELOPMENT OF EMBODIED CARBON ESTIMATING

Measurement of EC has evolved during the recent past. Initially, Hammond & Jones (2008, 2011) Inventory of Carbon and Energy (ICE) became the fundamental source of reference for EC estimating (cradle to gate) which is composed of dataset of mass CO_2 emissions per mass of set of materials. Hence, mass of materials constituting the building needs to be quantified to estimate the EC of the building based on a bottom up approach – deconstructing a building element up until the material, labour and plant component and applying ICE embodied carbon factors to arrive at the EC of the building. This is considered to be a tedious task as building constitutes numerous items which needed to be decomposed to follow this method. Furthermore, this process is not very easy to understand.

Therefore, realizing the struggle of the industry RICS published a guidance note for carbon estimating using bottom-up approach. The initial guide on embodied carbon estimating was published in 2012 titled 'Methodology to calculate embodied carbon of materials' covering the cradle to gate system boundary. Later, RICS revised the guidance note to cover cradle to grave system boundary and published the revised guideline in 2014. RICS (2014) classifies the project into four main stages according to CEN TC 350 standard namely: product, construction process, use and end-of life stages and also explains the method step by step making it easy to understand. The methodology to be followed in embodied carbon calculations on each stage as per the guidance note is listed in Table 2. Even though the methodology is made clear it remained in reports than in application due to the amount of labour involved in estimating.

Table 2. Embodied carbon counting guide in different stages of project

Stage	Methodology	Data source
Product	$EC_{product} = \sum$ Quantity of material constituents in each item/element x EC factor of the respective material	Inventory of Carbon and Energy (UK) (Hammond and Jones 2011), SimaPro, GaBi
Construction Process	$EC_{construction} = \sum$ Quantity of energy used for the activity x EC factor for respective energy source	DEFRA Greenhouse Gas Conversion Factor Repository, GHG Protocol calculation tools
Use Stage	$EC_{use} = \sum$ Quantity of materials to be replaced x No. of replacements x EC factor of the respective material	BCIS Life Expectancy of Building Components (BCIS 2006) + product stage sources
End-of Life	$EC_{end\text{-}of\ life} = \sum$ Quantity of energy used for the activity x EC factor for respective energy source	Construction stage sources

However, another substitute for this method is UK Building Blackbook produced by Franklin and Andrews (2011). Blackbook presents itemized EC dataset for standard building items in accordance with Standard Method of Measurement (SMM) which is a familiar method for QSs and a replica of pricing BoQ. This made EC estimating more approachable resulting in few reported case studies on EC estimating by using the book (Halcrow Yolles 2010b, Sturgis Associates 2010, Clark 2013), yet the usage seems to be low.

Additionally, there are various tools and softwares specifically designed for carbon estimating. Some of which are freely available on web (Environment Agency 2012, Build Carbon Neutral 2007, Phlorum 2011, Rocky Mountain Institute 2009, University of Minnesota 2014) while others are licensed (PRé Consultants 2014, PE International 2014). Online tools are useful to understand the accountability of carbon footprint of the building and sometimes of the project. However, the methodology underlying the tools is not transparent which a major drawback of such tools.

5 FACTORS TO BE CONSIDERED IN EMBODIED CARBON ESTIMATING

A major issue encountered in carbon estimating is the variations in measurements. Many scholars noticed variations in EC measurements due to several factors (Dixit et al. 2010, Clark 2013). Therefore, despite the tedious process involved in carbon estimating many other factors need to be considered when preparing an EC estimate. Major factors affecting EC measurements includes: system boundary, method of estimating, assumptions, data sources used and element classification.

5.1 *System boundary*

This is a distinct feature of EC estimating compared to cost estimating. EC has various system boundaries on which the measurement is based upon. EC 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 (RICS 2014). For instance, cradle-gate system boundary includes all the emissions associated with energy and processes from raw material extraction up to the final manufacturing of the product within the factory. Similarly, cradle- site covers all the emission included in cradle-to-gate plus emission associated with transporting to site. Therefore, an estimate with a cradle-to-grave boundary will have higher figures than an estimate with a cradle-to-gate boundary. Therefore, system boundary is one factor to be considered when comparing studies.

5.2 *Method of estimating*

As discussed under the development of carbon estimating following two main methods could be employed in carbon estimating,

- Manual estimating: this can be either a bottom-up approach of estimating using ICE data source and other relevant sources or itemised estimating approach using Blackbook data. Even though Blackbook is based on ICE data there could be other variations from energy calculation for plant and machinery and additional data outside ICE.
- Automated: automated systems will have a unique in-built program for extracting quantities and retrieving carbon data. Also most softwares use ecoinvent database which is updated time to time. These can lead to varying result from manual measurements.

5.3 *Assumptions*

Similar to any other estimating carbon estimating also involves assumptions when data is not present. If an item description in imprecise then assumptions have to be made to in order to estimate EC of the item. For instance, a staircase measure in 'Nr' has to be decomposed in to concrete, formwork, reinforcement, balustrades and finishes to get the carbon estimate of that element. In this case, assumptions play a major role in the carbon estimate.

5.4 *Data sources*

As explained under method of measurement, data sources other than ICE and Blackbook might vary from study to study due to difference in manufactures, suppliers, age of data source and the like. This will result in different EC figures.

5.5 *Element classification*

Element classification is a common variation among studies. Different studies (Halcrow Yolles 2010b, WRAP, Halcrow Yolles 2010a, Clark 2013, Sturgis Associates 2010) adopt different element classifications such as NRM, SMM/BCIS - older version, British Council of Offices 2011 and some studies did not follow any standard at all. This makes the comparison of findings difficult.
Therefore, it is important to clarify all of the above mentioned factors in EC estimating for the knowledge to be transferable

6 CASE STUDIES: ESTIMATING EMBODIED CARBON OF OFFICE BUILDING

6.1 *Method*

BoQ or detailed cost plans of the office buildings in the UK are obtained from consultancy practices and EC estimating was carried out in a similar manner of a detailed stage cost estimate. The UK Building BlackBook and manufacturer's data were used as the EC data source in the estimating process. This implies the system boundary of the study - cradle-to-gate. However, estimating was not an easy process. Sometimes, data sources do not contain some of the required data. In that case, a) similar data was used or pro-rata was done where exact match was not found; b) manufacturers' data was obtained when no similar data was found; c) item was excluded when manufacturers' data could not be obtained. After estimating the EC of each item, items were classified according to NRM element classification.

6.2 *Findings*

Based on the method explained above EC was estimated for the following case study offices which are presented in Figure 1.

Accordingly, substructure and superstructure together are to contribute more than 90% of total emissions for most of the cases while finishes contribute a significant proportion to total emission in case studies 5, 6 and 7. Services element is very low than it should actually be because case studies 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 precise item measurements as well as lack of EC data. However, when EC of building services items are closely analysed it appears to be very small resulting in less contribution. Also as RICS (2014) claims that reduction potential is very low for services. Hence, services could be excluded from estimate which is reflected in WRAP Embodied Carbon Database. However, authors do not draw any conclusions regarding building services EC as the findings are based on few studies and this is a potential area for further research.

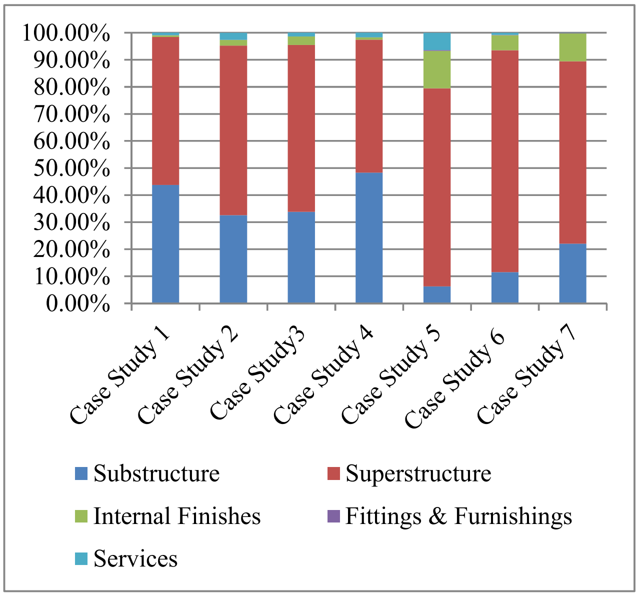

Figure 1. Elemental embodied carbon profile of case study buildings

7 PROBLEMS IN EMBODEID CARBON ESTIMATING

There are various issues pertaining to carbon estimating which are listed and discussed below:

- Lack of standard measurement: Dixit, Fernández-Solís et al. (2012) reported that existing ISO standards for Life Cycle Analysis (LCA) lacks precision and suffers due to truncation error and subjectivity. However, in case of carbon estimating the methodology is explained through RICS (2014) guideline. Any variation in EC measurement will be as a result of variation in factors discussed earlier (system boundary, methodology, assumptions, data sources, element classification). In fact, these factors are subjective and difficult to standardize except for element classification. For instance, system boundary cannot be standardized as data available are mostly cradle-to-gate and people who are interested in cradle-to-grave will employ other ways of capturing data and it should not be restricted.
- Lack of robust database/benchmark: this is a major issue faced by the industry at the moment. There are no any other publicly available databases except for WRAP Embodied Carbon Database to support various levels of carbon estimates. Lack of EC repository is a huge barrier for EC researches and development of EC estimating.
- Lack of EC data for new products: one of the major issues in EC estimating is lack of EC data for modern products. The EC sources discussed above include most of the conventional data as well as some modern product data. However, latest version of Blackbook is published in 2011 and it does not include products newer than 2011. Further, there is often less or no response from manufacturers regarding EC data queries.
- Lack of services EC data: case studies also witness this issue as Blackbook holds services data of disposal, sanitary, water and lift installations. Electrical installation is available for two-storey housing which is not suitable for office buildings.

8 OVERCOMING BOTTLENECKS IN EMBODEID CARBON ESTIMATING

Carbon estimating can be taken to next level only if it is treated in the same way as cost estimates. Carbon estimates should be produced in parallel to cost estimates during each successive design stage and estimates should be revisited and checked. This way carbon control can be exercised throughout the project in parallel to cost control. Further, HM Government (2010) highlight the growing concern on embodied carbon, by recommending the government and the industry to agree on a standard to measure embodied carbon to be used as a design tool. Inclusion of carbon appraisal in feasibility studies of a project magnifies the need of emission reduction to achieve a low carbon economy.

Environment Product Declaration (EPD) is a standardized way of reporting environmental impact of products. EN 15804 provides rules for the Europe-wide generation of EPD for construction products (Building Research Establishment 2015). However, not many organizations follow the standard. EPD should be made mandatory for all construction products so that the EC data is transparent and free from ambiguity. This will also stimulate EC estimating in a more positive manner.

Lack of services data can be overcome by developing dataset of elemental EC for various services. This will make the estimating process easier and help produce a holistic estimate.

Development of parametric carbon models to estimate EC during early stages of design will provide new avenue for quicker EC estimating with less design information.

9 DUAL CURRENCY APPROACH

As construction clients are becoming increasingly conscious about carbon emissions, it is important to included carbon appraisal in project appraisals. Especially, cost and carbon are now regarded as dual currency of construction projects. Clients expect not only to reduce emissions but also to achieve optimization in terms of both cost and carbon. This can be achieved if there is a positive relationship between cost and carbon. However, there is a gap in this regards and it is yet to be modelled.

From the case studies presented above cost is also captured in addition to EC which is depicted in the Figure 2. Figure illustrates a linear relationship between cost and carbon. However, it is based on few case studies, thus, it cannot be generalized. Nevertheless, with more case studies a conclusion can be derived.

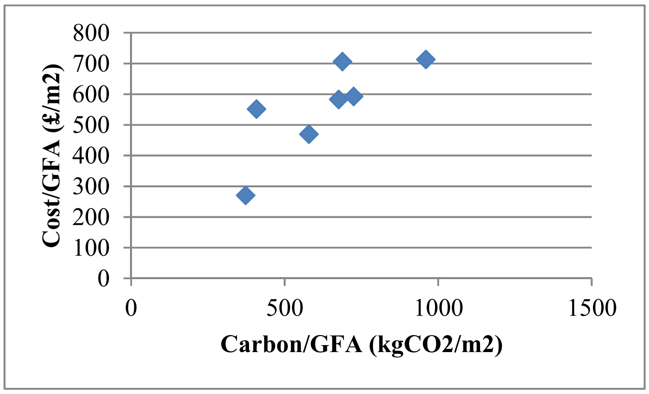

Figure 2. Cost-carbon relationship in case study buildings

This type of knowledge will definitely take EC estimating to next level in its development and for this to happen availability of rich EC data source is crucial.

Further, QS is the ideal person to deal with dual currency appraisal as he/she is already equipped with the right skills to do an EC estimate as suggested by RICS (2014). Therefore, it can be expected that EC estimating will become a core service in QSs' domain if EC estimating is effectively approached by the industry.

10 CONCLUSIONS

EC estimating, though considered to be a developing field it can actually be approached as similar to cost estimating. Use of EC data source dictates the method of estimating – ICE data source requires a bottom up approach, decomposing the items into material, labour, plant and building it up; UK Building Blackbook allows estimator to follow BoQ pricing approach. Both methods lead to cradle-to-gate EC estimating. However, estimates can also be prepared for other system boundary which is a tedious task as data sources are not readily available for other system boundaries. In addition to the system boundary few other factors need to be considered when estimating EC, including: method of measurement, assumptions, data sources and element classification. These factors are responsible for reported variations in EC estimating of published studies.

Case studies of office buildings suggest that substructure and superstructure to contribute to more than 90% of emissions while services' contribution is low mainly due to non-inclusion of all the services. Accordingly, EC estimating of case studies suffers from few issues such as: lack of EC data for services, lack of precise details of the items, lack of manufacturers' data on modern products, lack of robust databases/benchmarks for EC data. In addition to that lack of standard measurement is also identified as a problem for EC estimating though authors believe it is not a major issue due to the fact that it is subjective and cannot be standardized. Identified problems could be overcome by: developing robust database (like WRAP Embodied Carbon Database) or benchmark to which industry actively contributes; EPD can be made mandatory to allow all products to declare their environmental impact which is easily accessible by estimators; and developing parametric carbon models to encourage early stage carbon estimating.

Above all, carbon and cost are considered as 'dual currency' of construction projects and there is a strong possibility of treating EC estimating as similar to cost estimating. EC management and control can be achieved in parallel to cost management and control by the involvement of QS. In this manner, dual currency approach can be implemented within the construction industry effectively.

ACKNOWLEDGEMENT

Authors would like to acknowledge Northumbria University - UK, and consultancy practices in the UK such as EC Harris, AECOM, Gleeds and Adair Associates for supporting the research.

REFERENCES

Build Carbon Neutral. 2007. *Estimate the embodied CO2 of a whole construction project* [Online]. Available: http://buildcarbonneutral.org/ [Accessed 30th January 2014].

Building Research Establishment. 2015. *Construction products and CEN TC 350 standards* [Online]. Building Research Establishment. Available: http://www.bre.co.uk/page.jsp?id=2747 [Accessed 23 July 2015].

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

Department For Environment Food & Rural Affairs. 2015. *Greenhouse gas conversion factor repository* [Online]. Crown Available: http://www.ukconversionfactorscarbonsmart.co.uk/ [Accessed 23 July 2015].

Dixit, M. K., Fern Ndez-Sol S, J. L., Lavy, S. & Culp, C. H. 2010. Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings,* 42**,** 1238-1247.

Ecoinvent Association. 2015. *The ecoinvent Database* [Online]. Available: http://www.ecoinvent.org/database/ [Accessed 23 July 2015].

Environment Agency. 2012. *Carbon calculator for construction projects* [Online]. Available: https://www.gov.uk/government/publications/carbon-calculator-for-construction-projects [Accessed 20th October 2014].

Franklin & Andrews 2011. *UK Building Blackbook: The Cost and Carbon Guide : Hutchins' 2011: Small and Major Works,* Croydon, Franklin & Andrews.

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. & Jones, C. 2008. Inventory of carbon energy (ICE). UK: University of Bath.

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

HM Government 2010. Low carbon construction - innovation & growth team final report. UK: HM Government.

PE International. 2014. *GaBi software* [Online]. Available: http://www.gabi-software.com/uk-ireland/index/ [Accessed 29th October 2014.

Phlorum. 2011. *Embodied CO2 Estimator* [Online]. Available: http://eco2.phlorum.com/calculator/save [Accessed 20th October 2014.

PR Consultants. 2014. *Simapro LCA Software* [Online]. Available: http://www.pre-sustainability.com/lca-software-simapro?gclid=CLCqi76CprwCFdQPtAodTkoACw [Accessed 30th January 2014].

Ramesh, T., Prakash, R. & Shukla, K. K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings,* 42**,** 1592-1600.

RICS 2014. Methodology to calculate embodied carbon. 1 ed. UK: RICS.

Rocky Mountain Institute 2009. *Welcome to green footstep - an assessment tool for reducing carbon emissions from building construction projects* [Online]. Available: http://www.greenfootstep.org/ [Accessed 15 October 2014].

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

The Green Construction Board 2013. Low carbon routemap for the uk built environment. London: The Green Construction Board, WRAP, The Climate Centre and ARUP.

UK-GBC. 2014. *Key statistics: construction industry and carbon emissions* [Online]. Available: http://www.ukgbc.org/resources/additional/key-statistics-construction-industry-and-carbon-emissions [Accessed 23 July 2015].

UNFCCC. 2014. *Kyoto Protocol* [Online]. Available: http://unfccc.int/kyoto_protocol/items/2830.php [Accessed 29th July 2014.

University Of Minnesota. 2014. *Minnesota Site and Building Carbon Calculator* [Online]. Available: http://www.csbr.umn.edu/research/carboncalc.html [Accessed 15 October 2014].