A PRAGMATIC APPROACH FOR EMBODIED CARBON ESTIMATING IN BUILDINGS

Michele VICTORIA[1], Srinath PERERA[2], Alan DAVIES[3]

[1] Northumbria University, Newcastle upon Tyne, United Kingdom, michele.f.victoria@northumbria.ac.uk

[2] Northumbria University, Newcastle upon Tyne, United Kingdom, srinath.perera@northumbria.ac.uk

[3] Northumbria University, Newcastle upon Tyne, United Kingdom, alan.davies@northumbria.ac.uk

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Abstract

Embodied Carbon (EC) estimating is driven by the development of Inventory of Carbon and Energy (ICE) in 2008 along with the initial information paper of Royal Institution of Chartered Surveyors (RICS) on the methodology to calculate EC in 2012. RICS's latest guidance note (RICS, 2014) suggests good practices to estimate EC during various stages of a construction project. However, EC estimating was daunting and laborious which is then simplified to some extent by the introduction of the UK Building Blackbook. Despite the efforts of institutions and researchers to encourage EC estimating, construction industry is slow to embed EC estimating in day-to-day business. Nevertheless, EC research is breaking its boundaries and embarking into new avenues. This paper adds new knowledge to the existing body of literature by presenting analyses of EC in different types of buildings including offices, residential buildings and educational buildings. Data were obtained from WRAP EC Database and presented in accordance with the element classification system of New Rules of Measurement (NRM). Descriptive statistics were used to analyse the data and inferences were made based on the findings. 'Carbon hotspots' or the carbon intensive elements in the selected three types of buildings were identified and an approach to estimate EC based on carbon hotspots is proposed in light of encouraging practices of EC estimating from an early stage of design process.

1 Introduction

EC emission consists of fuel related and process related carbon emissions (Hammond & Jones, 2011) which can be measured from raw material extraction (Cradle) till factory gate (Gate) or construction site (Site) or end of construction (Construction) or end of life (Grave) or even reuse/recover/recycling (Cradle). These are commonly termed as System Boundaries indicating from and to which point carbon emissions area measured. EC can also be categorised into three types: initial EC, recurring EC and end-of-life EC (Brandt, 2012; Shafiee & Topal, 2009). Initial EC is the emissions associated with the production of the building including raw material extraction, manufacturing, transport and construction; recurring EC includes emissions during the use of the building such as repair, maintenance and replacement; and end-of-life EC includes emissions associated with demolition of the building where benefits beyond system boundary is excluded from the three types as cradle to cradle analyses are very rare.

Latest climate conference COP21 in Paris highlighted the increasing significance of emissions reduction strategies where 187 countries including developing nations committed to reduce greenhouse gas emissions. Particularly, plans for sectoral (buildings, transport, industry, etc.) energy efficiency measures are also devised (COP21, 2015). Therefore, managing EC in construction projects is becoming significant at a national level. Improvements made to the Part L of the Building Regulations and zero carbon agenda aims at eliminating operational carbon from buildings. However, the Low Carbon Routemap for Built Environment of the UK sets 34% of carbon emissions reduction by 2020 followed by 50% and 80% reductions in 2025 and 2050 respectively to achieve targets of the UK Climate Change Act 2008. Of which, 21% reduction of EC emissions are expected by 2022 and a 39% reduction by 2050 (The Green Construction Board, 2013). This emphasise the need of reducing EC from buildings which forms an integral part in urban development.

Nearly 70-80% of the capital cost and EC are committed during early design stages of construction projects (Asiedu & Gu, 1998; Kelly, Graham, & Male, 2015). On the other hand, as more cost and carbon is committed into the project, the reduction potential diminishes as possible design solutions are constrained by previous design decisions (RICS, 2014). This behaviour demands effective management of EC during early stages of design which in turn calls for EC estimating in the first place. The key source of EC estimating is ICE developed by (Hammond & Jones, 2008, 2011) which presents primary EC data for a series of base materials in kg of carbon dioxide emitted for each kg of material produced. This requires the building components to be decomposed into material, labour and plant; and then EC factor is applied to materials and fuel consumed by plant. Only difference in EC estimating compared to cost estimating being the exclusion of labour emissions (Langston & Langston, 2008). However, intense calculations involved in this method of EC estimating makes it complex and unapproachable (Ibn-Mohammed et al., 2013; Moncaster & Song, 2012). Also this method can only be applied to detailed stages of design where detailed specification is available and there is only limited academic research to aid decision-making at early stages of projects. For instance, Hitchin (2013) suggested that EC per GIFA for a new office building ranges from $600kgCO_2/m^2$ to $1200kgCO_2/m^2$ based on the case studies of 30 office buildings in the UK; Clark (2013) suggests that it ranges from $570kgCO_2/m^2$ to 1350 $kgCO_2/m^2$. However, existing benchmarks are merely a guide and are not subject to rigorous scrutiny. Consequently, a method to encourage EC estimating during early design stages of construction projects is proposed in this paper.

2 Literature Review

2.1.1 EC Estimating

Cost estimating is one of the core duties of Quantity Surveyor (QS) in the construction industry in the UK and Construction Economists or Cost Engineers in other parts of the world. The process of cost estimating is well established and governed by industry standards like New Rules of Measurements (NRM). The most detailed estimate is known as Bill of Quantities (BoQ) with almost complete itemisation of all work related to a 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 demonstrates the maturity of cost estimating techniques in the industry. On the other hand, carbon estimating is still evolving within the construction industry as it is a value added service provided by cost consultancy firms. Hence, the service is offered mostly by large construction firms. Carbon estimating is very similar to cost estimating though it evolved within the past decade. Similar techniques used in cost estimating can be applied in carbon estimating, however, there is an issue of robust EC data. Initially started with Hammond and Jones' Inventory of Carbon and Energy (ICE) and then it was simplified by Franklin & Andrews (2011) UK Building Blackbook as it presents EC data in a similar fashion to a BoQ. Therefore, the Blackbook allows parallel estimating of project cost and EC. This is known as dual currency estimating where cost as per the financial currency of the country and EC measured in Kg as the second currency.

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

There are many EC estimating tools for early stage estimating and detailed stage estimating where 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 (Build Carbon Neutral, 2007; Phlorum, 2011; Rocky Mountain Institute 2009; TATA Steel, 2014; University of Minnesota, 2014). Each tool has its own limitations. Major limitation is 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 variation 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 (Also see, Moncaster & Song, 2012). Many of these tools can be considered as a 'black box' as the underlying methodology is not transparent. Further, lack of standard methodology to estimate EC also causes variation in the outcome of the tools.

Nevertheless, the guidance note on EC estimating for construction projects published by RICS (2014) encourages estimating EC without relying on the available 'black box' tools. The initial guide on EC calculations was published in 2012 covering the cradle to gate system boundary. Later, RICS developed the guidance note to cover cradle to grave system boundary for EC estimating which remains as the latest guidance note providing step-by-step guide for EC estimating. The key sources needed for estimating EC include ICE, DEFRA Greenhouse Gas Conversion Factor Repository and BCIS Life Expectancy of Building

Components. RICS (2014) classifies the project into four main stages namely: Product, Construction Process, Use and End-of Life stages which comply with TC350 EN 15978:2011 Standard for Life Cycle Assessment. This guidance note enables estimators to calculate EC of projects that can be executed in parallel to cost estimating of projects. Hence, the guidance note channels the competencies of a QS /estimator into EC estimating without investing on expensive EC estimating tools (Also see, Ashworth & Perera, (2015) for detailed account of measuring EC). In addition to that there are other carbon estimating tools ranges from early stages to detailed stages of design (see, Ekundayo, Perera, Udeaja, & Zhou, 2012; Ashworth & Perera, 2015; Anderson, 2015). However, there is a lack of EC benchmarks to facilitate early design stage EC estimating unlike cost estimating (Ashworth & Perera, 2015; Victoria, Perera & Davies, 2015). Therefore, the concept of 'Carbon hotspots' become significant to assist early design stage EC estimating.

2.1.2 Carbon Hotspots

RICS (2014) defines 'Carbon hotspots' as the carbon significant aspect of a project which may not necessarily represent the most carbon intensive elements but also the elements where measurement data is easily available and greater levels of reduction is possible. Carbon hotspot can also be defined by 80:20 Pareto rule which claims that 80% of the effects are due to 20% of the causes. Similarly, carbon hotspots can be defined as 20% (or even more or less) of the building elements that are responsible for 80% of the EC emissions attributable to the building. Carbon hotspots may vary from one project to the other and from one building to the other due to heterogeneity of construction projects. Generally, Foundations, Frame, Roof, Walls and Floors are considered as carbon hotspots due to heavy use of steel and concrete in these elements. In addition to that even though it is reported that the building services contribute up to 25% of EC emissions (Hitchin, 2013), it is not widely regarded as a 'hotspot' as measuring building services during early design stages is a challenging and hence its reduction potential may be limited compared to other building elements (RICS, 2014). However, Cole and Kernan (1996) found that cladding finishes and building services are to be the biggest component of recurring carbon emissions of an office building. Hence, building services and finishes cannot be disregarded during design decision-making if it is a carbon significant element. Therefore, an indication of likely EC of building services should be included in early design stage estimates.

However, carbon hotspots of various types of buildings are not known yet. Further, it is also assumed that the hierarchy of carbon hotspots might change for different types of buildings (Ashworth & Perera, 2015). Different studies on EC of office buildings in the UK identified substructure and superstructure to be the most carbon significant elements (Clark, 2013; Halcrow Yolles, 2010a; 2010b, WRAP; Sturgis Associates, 2010, Victoria, Perera & Davies, 2015). Particularly, Frame, Upper Floors and External Wall in Superstructure are the commonly identified 'hotspots'. Knowledge of carbon hotspots in different types of buildings simplifies the process of estimating and management of EC during early design stages. Further, design variables related to each identified carbon hotspot can be measured and elemental rates can be applied to derive the total EC of the building. Elemental rates can be either EC per Gross Internal Floor Area (GIFA) or EC per Element Unit quantity (EUQ). Table 2 lists the design variables influencing building element/s whereby EUQ is affected by related design variable. Nevertheless, benchmarks needed to be developed to facilitate this kind of elemental EC estimating.

Table 2 Building elements influenced by building parameters (After Dell'Isola and Kirk (1981) and Collier (1984))

Building Elements	Building Parameters
Substructure	Footprint area
Frame	No. of storeys/total height of the building, Gross floor area
Floors	Gross floor area
Roof	Area of roof
Stairs and Ramp	No. of storeys/total height of the building
External doors and windows	Area of exterior doors/windows
External walls	Area of exterior wall
Internal Walls and Partitions	Gross floor area, Planning efficiency/circulation space
Internal Doors	Planning efficiency/circulation space
Finishes	Total area finished (including partitions)
Services – mechanical	Gross floor area, Total enclosed volume
Services - electrical	Gross floor area, Transformer rating
External works	Gross site area

3 Method

EC of offices, residences and educational buildings were analysed and presented in the paper. EC data were obtained from WRAP EC Database which is developed and maintained by WRAP and UK Green Building Council (2014). Database contained EC data of 48 office buildings, 53 residential buildings and 10 educational buildings. However, all the data could not be utilised due to the lack of elemental breakdown of the EC data. Therefore, resulting sample after screening includes 28 office buildings, 43 residential buildings and 4 educational buildings. Also the database contains data with different system boundaries in accordance with TC350 Standards: Cradle to Gate (A1-A3), Cradle to Site (A1-A4), Cradle to Construction (A1-A5), Cradle to Grave (A-C) and Cradle to Cradle (A-D). EC data of residential buildings and educational buildings are measured using a Cradle to Grave system boundary while office buildings are measured using a Cradle to Gate system boundary.

The data presented here uses a NRM element classification. The elements of the buildings are presented in six categories including Substructure, Superstructure structural, Superstructure non- structural, Envelope, Internal finishes and External works. EC with respect to External works were excluded from the study analysis as its EC component demonstrated a high variation in the dataset and it does not have an intricate relationship to the building concerned due to the fact that it varies depending on clients' requirements and site conditions. Therefore, the results presented contains 5 types of elements - Substructure, Superstructure structural, Superstructure non- structural, Envelope and Internal finishes. Superstructure structural includes Frame, Upper Floors and Roof Structure; Superstructure non-structural includes Roof non-structural, Internal Walls and Partitions, Internal Doors; Envelope includes External Walls and Windows and External Doors; Internal Finishes included Wall Finishes, Floor Finishes and Ceiling Finishes.

As literature suggests carbon hotspots can be an ideal way of dealing with EC estimating during early stages of design (conceptual stage/detailed design stage according to RIBA plan of work 2013). Eventually, a conceptual model is proposed to estimate EC based on carbon significant elements of different types of buildings as follows:

$$EC = \sum_{i=1}^{n} EUQ_i \, . EUR_i + \; GIFA . UR_{Res} \tag{1}$$

Where,

EC - EC of the Building

EUQ_i - Element Unit Quantity of Element for the ith element

EUR_i - Element Unit Rate of Element for the ith element

1 to n - Carbon hotspots (or carbon intensive elements/elements responsible for 80% of emissions)

GIFA - Gross Internal Floor Area of the building

UR_{Res} - Unit Rate of Residual elements (elements responsible for 20% emissions)

EC of each carbon significant element and the residual of the carbon insignificant elements are summed to arrive at the total EC of the building. EUQ is captured from conceptual drawings while EUR to be obtained from industry developed benchmarks which are however, lacking at present. The list of carbon hotspots will vary for different types of buildings. Hence, effort is made to identify the carbon hotspots of office, residential and educational buildings from the EC data obtained from WRAP database and the results are reported using descriptive statistics – mean, variance, minimum and maximum. Further, cumulative graphs are presented to identify the building elements that contribute up to 80% of the EC emissions (carbon hotspots) in each type of the building. Further comparisons were made between the selected three types of buildings to understand variation in EC component in different types of buildings.

4 Results and Discussion

Mean elemental EC analysis of offices, residential and educational buildings are presented in Figure 1. The sample of offices (28) and residential buildings (43) consisted of adequate sample size for inferences to be drawn. However, educational buildings sample consisted only four buildings which therefore, gives only an indication of the likely elemental EC values. Figure indicates that office buildings elemental EC values are higher than residential and educational buildings except in Internal Finishes. Especially, Superstructure - Structural EC is extremely high which includes Frame, Upper Floors and Roof Structure. Of the 28 office buildings, 18 buildings were above 5 stories while only 2 of the 43 residential buildings are above 5 stories. On the other hand, out of 4 educational buildings, 3 building are single storied and one is 2 storied. Therefore, influence of storey height in the sample of the three types of the buildings explains the drastic difference in elemental EC of office buildings from other two types. On the other hand, Internal Finishes were expected to be higher in office buildings due to the focus given on aesthetics and quality of finishes while the results suggest that office buildings elemental EC is the lowest among the three which is surprising.

Table 3 presents the findings from descriptive statistics of the elemental EC values of offices, residential and educational buildings. Accordingly, offices EC ranges from 458.91kgCO$_2$/m^2 Gross Internal Floor Area (GIFA) to 2,650.57kgCO$_2$/m^2 GIFA with a mean value of 1,445.36 kgCO$_2$/m^2 GIFA. The mean value of residential EC is 491.40kgCO$_2$/m^2 GIFA ranging from 313.59kgCO$_2$/m^2 to 886.44kgCO$_2$/m^2 GIFA. On the other hand, educational buildings have higher EC than residential but lower than offices. The mean EC in educational building is 590.74 kgCO$_2$/m^2 GIFA ranging from 497.30kgCO$_2$/m^2 GIFA to 690.26kgCO$_2$/m^2 GIFA. Office building sample has the highest variance while educational has the lowest. This demonstrates that the EC values of the educational buildings are closer to the mean. However, it should be noted that educational building sample consists of only 4 buildings and thus, no inferences can be made from the dataset. On the other hand, office buildings having higher variance than residential buildings showcases that the EC of office buildings has a wide range due to multiple design options.

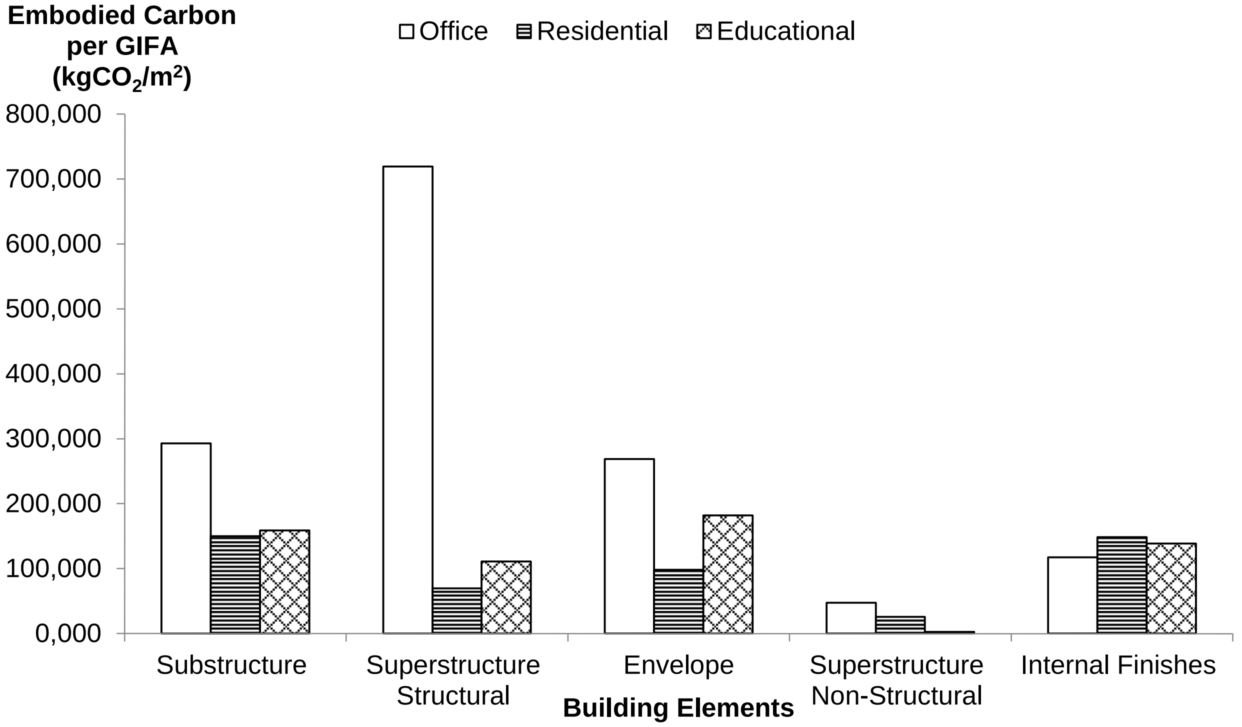

Figure 1 Elemental EC analysis of sample buildings

Table 3 Descriptive statistics of elemental EC of sample buildings

Building Type	**Building Elements**	**Mean (kgCO$_2$/m^2 GIFA)**	**Variance**	**Minimum**	**Maximum**	**Count**
Offices	Substructure	292.83	27,931.61	75.58	729.87	28
	Superstructure structural	719.54	80,183.14	168.99	1,439.73	28
	Envelope	268.64	24,405.63	72.09	625.96	28
	Superstructure non-structural	47.18	1,711.06	2.93	143.26	28
	Internal finishes	117.17	6,252.14	9.02	294.49	28
	Total EC/m2 GIFA	1,445.36	265,360.84	458.91	2,650.57	28
Residential	Substructure	149.87	3,311.68	40.04	251.46	43
	Superstructure structural	69.36	4,211.13	8.77	239.51	43
	Envelope	98.24	4,154.47	29.13	243.69	43
	Superstructure non-structural	25.59	657.10	-	90.52	37

Building Type	Building Elements	Mean ($kgCO_2/m^2$ GIFA)	Variance	Minimum	Maximum	Count
	Internal finishes	148.34	2,317.53	93.20	321.39	43
	Total EC/m2 GIFA	491.40	18,450.99	313.59	886.44	43
Educational	Substructure	159.01	387.32	134.52	182.60	4
	Superstructure structural	111.00	1,006.24	65.36	138.87	4
	Envelope	181.76	857.42	152.82	222.43	4
	Superstructure non-structural	2.36	-	-	-	1
	Internal finishes	138.38	3,432.01	88.55	216.84	4
	Total EC/m2 GIFA	590.74	7,136.92	497.30	690.26	4

Further, analysis of individual elements in the selected 3 types of buildings shows that in different types of buildings different building elements are carbon significant. For instance, the most carbon significant element in office buildings is Superstructure-Structural group element (Frame, Upper floors and Roof Structure); Substructure and Internal Finishes in residential buildings; and Envelop in educational buildings. Therefore, the 3 samples were individually analysed to identify the ‘carbon hotspots’ or the building elements that are responsible for 80% of EC emissions in each type of building. This lead to the identification of the carbon significant elements of different types of buildings under consideration which in turn lead to early stage EC estimating of buildings based on elemental EC benchmarks. Accordingly, in office buildings Frame, Upper Floor, Roof (Superstructure-Structural), Substructure and Envelop (part of it) are contributing up to 80% of EC emissions. On the other hand, Substructure, Internal Finishes and envelop are identified as the building elements contributing up to 80% of EC emissions in residential and educational buildings in different significance levels where substructure is the most carbon intensive element in residences while Envelope in educational buildings. This notably identifies that for different types of buildings level of carbon intensity of building elements varies. Therefore, gaining thorough knowledge of carbon intensive elements in different types of buildings is fundamental for successful early stage EC estimating and management.

Consequently, the proposed approach can be applied if the carbon intensive elements of various types of buildings are known and the respective elemental EC benchmarks are developed in a robust manner.

For instance, following equation can be applied for an office building:

$$EC = EUQ_F.EUR_F + EUQ_{UF}.EUR_{UF} + EUQ_R.EUR_R + EUQ_{Sub}.EUR_{Sub} + EUQ_E.EUR_E + GIFA.UR_{Res}$$

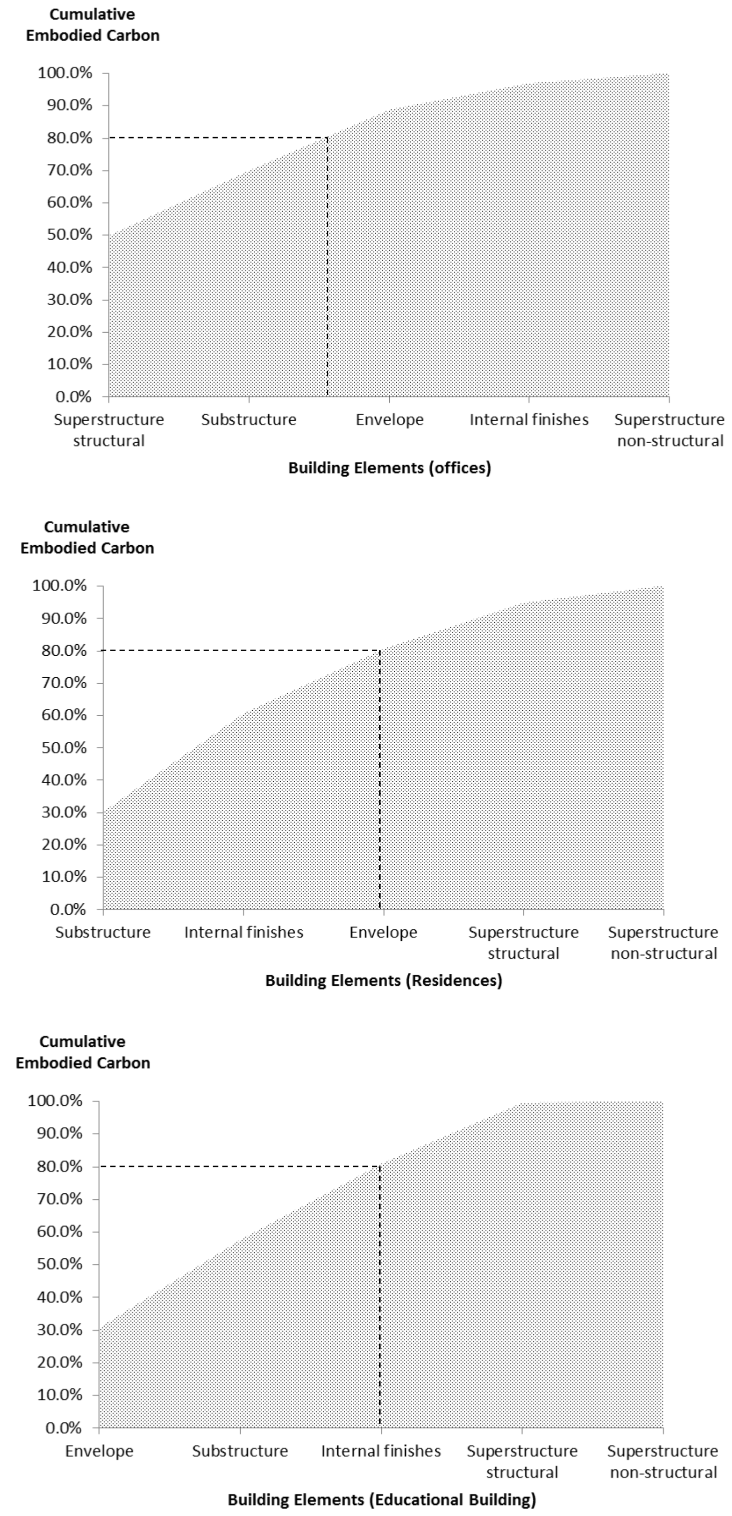

Figure 2 Carbon hotspot analysis of offices, residence and educational buildings

EC - EC of the Building
EUQ_F - Element Unit Quantity of Frame
EUR_F - Element Unit Rate of Frame
EUQ_{UF} - Element Unit Quantity of Upper Floor
EUR_{UF} - Element Unit Rate of Upper Floor
EUQ_R - Element Unit Quantity of Roof
EUR_R - Element Unit Rate of Roof
EUQ_{Sub} -Element Unit Quantity of Substructure
EUR_{Sub} - Element Unit Rate of Substructure
EUQ_E - Element Unit Quantity of Envelope
EUR_E - Element Unit Rate of Envelope
GIFA - Gross Internal Floor Area of the building
UR_{Res} - Unit Rate of Residual elements (Internal Finishes and Superstructure non-structural)

EUQ of Frame will be GIFA of the building; Upper Floor will be upper floor area; Roof will be roof area; substructure will be footprint area; envelope will be façade area. In this case, UR_{Res} for office buildings (EC of Internal Finishes and Superstructure non-structural) varies from 11.95 to 437.75 kgCO$_2$/m^2 GIFA, with a mean of 164.35 kgCO$_2$/m^2 GIFA. If, EURs are developed for different types of frame, foundations, roof, upper floors, envelope and the like, EC of different types of buildings can be computed at early stages of design. Hence, EC estimating can be carried out in parallel to cost estimating facilitating dual currency appraisals of construction projects. However, robust EC benchmarks are scarce at the moment in order to facilitate this type of estimating. Development of EC benchmarks for early design stage estimating is recognised as a fundamental need to manage carbon. Therefore, more research needed to be focused in these aspects despite the challenges in obtaining EC data.

5 Conclusions

There is an increasing level of significance attached to embodied carbon estimating as countries align themselves to achieving post COP21 carbon reduction targets. Although universally accepted EC estimating methodologies and rules are yet to be agreed, various data sources, guidance notes and tools have been developed to facilitate embodied carbon estimating at various stages of construction projects. However, early design stage embodied carbon estimating is challenging due to limited design information and lack of embodied carbon benchmarks. Therefore, a pragmatic approach to estimating embodied carbon with limited design data is proposed and the need for the development of robust embodied carbon benchmarks is highlighted. It is ideal to analyse all types of buildings and infrastructures, however, due to limitation in embodied carbon data only 3 types of buildings were explored – offices, residences and educational buildings. As expected, findings reveal that the hierarchy of carbon hotspots (elements responsible for 80% of embodied carbon emissions) vary for different types of buildings. The descending order of carbon hotspots of office buildings is Superstructure-structural and Substructure; residential buildings is Substructure, Internal Finishes and Envelope; residential buildings is Envelop, Substructure and Internal Finishes. Further, educational buildings EC per GIFA was higher than residential but lower than offices. Variance of EC per GIFA of office buildings was the highest while Variance of EC per GIFA of educational buildings was the lowest. However, educational building sample consists of only 4 buildings and thus, no inferences were made from the dataset. Higher variance of EC per GIFA in office buildings showcases that the EC of office buildings has a wide range due to multiple design options ranging from low rise to high rise whereas residences and educational buildings in the sample are mostly low rise. As a result, impact of building elements on different types of buildings varies. Hence, identifying carbon hotspots in different type of buildings pave the way for the proposed method of embodied carbon estimating during early design stages. EUQ of each carbon hotspot is measured and EUR of the respective element for different specification is applied. Summation of EC of the identified carbon hotspots and residual of carbon insignificant elements will give the embodied carbon content of the building. Measurements of EUQ can follow established building measurement practices like NRM. However, there is a lack of robust EC benchmarks which is a barrier for the application of the proposed method. Nevertheless, EC benchmarks are crucial to implement dual currency approach in construction projects. Elemental embodied carbon benchmarks are necessary for conceptual and detailed design stage carbon estimating to complement cost estimating for infirmed decision-making. Especially, buildings form an integral part of the society and thus, embodied carbon management plays an important role in urban sustainability and achieving carbon reduction targets agreed at COP21 in France in 2015.

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