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An Elemental Approach for Predicting Embodied Carbon of Office Buildings

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ABSTRACT

Embodied Carbon (EC) in buildings is increasingly becoming an important factor in carbon management. There are numerous tools and methods to estimate EC right from the beginning of a construction project. However, each tool has its own pros and cons. One such approach is to estimate EC using Element Unit Rates (EC-EUR) and Element Unit Quantity (EUQ). This is made possible by identifying carbon hotspots in buildings in the first instance and developing EC-EURs for different specifications of the carbon hotspots. Development of elemental EC-EUR benchmarks and its application in the proposed elemental approach for predicting EC is presented in the paper. Carbon hotspots of office buildings were identified using a sample of 28 office buildings in the UK where Substructure, Frame, Upper Floors, External Walls and Services were identified as the carbon hotspots. EC-EUR benchmarks were developed for different specifications of the hotspots by statistically modelling the sample for Frame. However, EC-EURs of the rest of the hotspots were not developed due to lack of specification information. The key outcomes of the research include the carbon hotspots of office buildings leading to the development of an early design stage EC prediction model and the concept of developing EC-EUR benchmarks which are not established at the moment and hence, fill the knowledge gap in the literature.

Keywords: *carbon hotspots, Embodied Carbon Element Unit Rate (EC-EUR), Element Unit Quantity (EUQ), office buildings*

1. INTRODUCTION

A hotspot may mean different things to different people from different discipline. RICS (2014) defines 'carbon hotspot' as the carbon significant aspect of a project which can be building elements or other aspects in supply chain. However, carbon hotspots in this research refers to the carbon critical or significant building elements. RICS (2014) further extends that carbon hotspots are not only carbon intensive but also easily measurable and carbon reduction is possible. Pareto Principle defines that 80% of the results (or consequences) are attributable to 20% of the causes which implies unequal relationship between the inputs and the outputs (Koch, 2011, Delers, 2015). According to 80:20 Pareto rule, it can be assumed that 80% of embodied emissions are caused by 20% of building elements (yet to be proved). These carbon hotspots may vary from one building to the other depending on the type or function of the building (Ashworth and Perera, 2015).

Monahan and Powell (2011) highlighted the importance of identifying hotspots in buildings by modelling a two storied residential building (in the UK) in three different scenarios – timber frame and larch cladding, timber frame and brick cladding, conventional masonry cavity wall. The substructure (including foundation and ground floor) accounted for 50% of embodied carbon in timber frame and larch cladding building and substructure, external walls and roof were identified as the carbon hotspots in the building (elements responsible for 81% of embodied carbon, however, not all the building elements were included in the accounting). Further, the same building (timber frame with larch cladding) substituted with timber frame and brick cladding and conventional masonry resulted in additional embodied carbon of 32% and 51% respectively. The majority of difference in embodied carbon was found to be attributed to the difference in foundations and external walls. The findings of the study (Monahan & Powell, 2011) reveal substructure and external walls as 'carbon hotspots' in the particular residential building and highlight the potential for embodied carbon reduction.

Shafiq et al. (2015) studied a two storied office building in Malaysia by modelling six different scenarios for structural composition using Building Information Model (BIM). However, Shafiq et al. (2015) used UK databases to estimate embodied carbon due to lack of embodied carbon databases in Malaysia. Different grades or classes of concrete and steel were combined to generated different composition which resulted in different material quantities producing varying embodied carbon impacts. Only few elements were studied including foundation, beams, slabs, columns and staircases which can be related to substructure, frame, upper floors and stairs as per NRM element classification. Shafiq et al. (2015) found that it was possible to reduce up to 31% of embodied carbon by designing these elements with different classes of concrete and steel to meet the given design criteria. However, it should be noted that only the elements that consititute concrete and steel are considered because concrete and steel are considered as the main structural building materials and emit high embodied carbon during production. Particulalry, upper floors were identifed as the key carbon hotspot followed by substructure, frame and stairs.

It is clear that embodied carbon studies in different types of buildings highlighted above (Monahan & Powell, 2011; Shafiq et al, 2015) has different focus and hence, limit the analysis to few elements. However, analysis of the whole building will provide a holistic picture of the embodied carbon contribution of each element and will highlight the potential areas for carbon reduction. Generally, floors (ground and upper floors), frame, external wall and roof are identified as carbon hotspots in building case studies (Clark, 2013, Davies et al., 2014, Halcrow Yolles, 2010). However, the knowledge of carbon hotspots is still obscure and there is a need for research in this area especially to facilitate early design stage EC estimating as proposed by Victoria et al. (2016).

2. THE METHOD

Historical data were obtained from a QS consultancy practice which include embodied carbon estimates of twenty-eight (28) office buildings prepared in an NRM compliant element standard. Carbon hotspots were analysed using the Pareto principle which suggest that 80% of the results (or consequences) are attributable to 20% of the causes which implies unequal relationship between the inputs and the outputs (Koch, 2011, Delers, 2015). The same 80:20 theory was used to identify the carbon hotspots in the buildings due to its popularity and applicability in especially, economics, business and management related areas. Consequently, it was deduced that 80% of the EC is coming from 20% of the building elements. These 20% of the building elements are named as the 'carbon hotspots' in the context of the research. Even though 80:20 is accepted as the universal ratio, Pareto Principle neither dictates that the 80:20 ratio is applied to all the situation nor should the two figures add up to 100 (say, it could be 90:10 or 80:30) (Business Balls, 2016). Therefore, this ratio is also tested in the case of the relationship between embodied carbon (and cost) and building elements.

The elements contributing up to 80% of the EC were identified as shown in **Error! Reference source not found.**. irstly, embodied carbon of individual elements was estimated and the percentage contribution was calculated. Then, the elements were arranged in descending order based on the EC intensity. Then, cumulative percentage was calculated to draw a cut-off point at 80% as shown in **Error! Reference source not found.**.

Building Elements (NRM compliant)	Embodied Carbon % (in descending order)	Cumulative Embodied Carbon%
2A Frame	38.54	38.5
2E External walls	20.30	58.8
5 Services	13.82	72.7
1A Substructures	9.90	82.6
2B Upper floors	6.71	89.3
2C Roof	3.94	93.2
2D Stairs	2.44	95.7
2G Internal walls and partitions	1.66	97.3
3B Floor finishes	1.50	98.8
4A Fittings and furnishings	0.43	99.2
3A Wall finishes	0.34	99.6
2H Internal doors	0.32	99.9
3C Ceiling finishes	0.09	100.0
2F Windows and external doors	0.01	100.0

Table 1: Identifying carbon hotspots of a building – an example

According to the example presented in **Error! Reference source not found.**, Frame, External Walls, Services and ubstructure are the identified as the carbon hotspots of the particular building and 28% of the building elements (4 of the 14 elements) are being responsible for the 80% of the embodied carbon emissions form the example building. The carbon hotspots of the sample (28 buildings) were calculated in this manner by using the average EC values of the elements. In addition to that, descriptive statistics (mean, minimum, maximum and standard deviation) were also presented to convey the dispersion of the sample analysed.

The identification of the carbon hotspots lead to the development of the early design stage EC prediction model for office buildings based on the idea proposed by Victoria et al. (2016). The proposed concept of Victoria et al. (2016) suggest that the sum of the product of EUQ and EC-EURs of the carbon hotspots and the residuals will yield the EC of the building. Consequently, EUQs of the carbon hotspots were defined using BCIS and EC-EURs were also calculated using 'mean' while minimum, maximum and standard deviation were also presented to enable the readers to understand the data dispersion.

3. FINDINGS

3.1 Carbon hotpots

Carbon hotspots of the sample were analysed using 80:20 Pareto Rule as described in the method. Accordingly the carbon hotspots (building elements contributing up to 80% of the EC emissions in descending order) were identified and plotted in a table as shown in **Error! Reference source not found.**. Accordingly, each row epresents a building and the elements that were identified as carbon hotspot in the respective building were marked with a 'x'. Last row of the table presents the probability of each element being identified as a hotspot in the sample. Accordingly, Frame found to be a hotspot in all the buildings; Substructure and Services found to be a hotspot in 90% of the buildings; and External Walls found to be a hotspot in 80% of the buildings in the sample. On the other hand, elements like Stairs, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings were not found as hotspots in any of the buildings in the sample. Rest of the elements were found to be hotspots in some of the buildings.

Building ID	**1A Substructures**	**2A Frame**	**2B Upper floors**	**2C Roof**	**2D Stairs**	**2E External walls**	**2F Windows and external doors**	**2G Internal walls and partitions**	**2H Internal doors**	**3A Wall finishes**	**3B Floor finishes**	**3C Ceiling finishes**	**4A Fittings and furnishings**	**5 Services**
#D1001	x	x				x								x
#D1002	x	x				x								x
#D1003	x	x	x			x								
#D1004	x	x				x								x
#D1005	x	x				x								x
. . . .														
#D1028	x	x	x			x								x
Probability of occurrence	0.9	1	0.6	0.1	0	0.8	0.11	0	0	0	0.2	0	0	0.9

Table 2: Example of identifying carbon hotspots of the sample buildings

Descriptive statistics of EC per GIFA of the sample for each element are presented in **Error! Reference source ot found.**. Elements are presented in a descending order according to their EC intensities. Further, cumulative EC percentage was also calculated to identify the elements responsible for 80% of the EC emissions. Frame, Substructure, External Walls, Services and Upper Floors (highlighted in greyscale) were identified as carbon hotspots in the sample. Findings suggest that 36% of the elements are responsible for 80% of the EC emissions. Also, it can be noticed that the standard deviation is comparatively high for the hotspots which implies EC-EUR range is wide for these elements.

Element	Average EC per GIFA (kgCO_2 per m^2)	Minimum	Maximum	Standard Deviation	Cumulative EC %
2A Frame	236.72	98.00	486.41	101.13	30.1
1A Substructures	137.20	33.21	320.72	65.31	47.5
2E External Walls	111.24	8.37	265.80	63.35	61.6
5 Services	106.81	6.63	192.88	50.16	75.2
2B Upper Floors	75.99	1.72	191.08	38.68	84.8
3B Floor Finishes	37.69	0.39	97.77	28.82	89.6
2C Roof	25.05	2.88	103.25	19.69	92.8
2G Internal Walls and Partitions	20.14	1.19	64.37	15.97	95.3
2F Windows and External Doors	15.20	0.02	157.64	35.20	97.3
3C Ceiling Finishes	8.55	0.65	24.62	6.05	98.3
2D Stairs	7.00	2.47	21.46	5.01	99.2
3A Wall Finishes	3.65	0.22	18.47	4.23	99.7
2H Internal Doors	1.50	0.12	7.32	1.79	99.9
4A Fittings and Furnishings	0.86	0.02	3.39	1.15	100.0
EC of the building	**785.31**	**431.61**	**1,368.17**	**215.92**	

Table 3: Descriptive statistics of the sample

3.2 The proposed EC model

Based on the carbon hotspot analysis of the sample, the proposed idea by Victoria et al. (2016) for an early stage EC model can be presented as follows for office buildings:

$$EC = EUQ_{Fr}.EUR_{Fr} + EUQ_{Sub}.EUR_{Sub} + EUQ_{EW}.EUR_{EW} + EUQ_{Ser}.EUR_{Ser} + EUQ_{UF}.EUR_{UF} + k$$

EC - EC of the Building
EUQ_F - Element Unit Quantity of Frame
EUR_F - Element Unit Rate of Frame
EUQ_{Sub} - Element Unit Quantity of Substructure
EUR_{Sub} - Element Unit Rate of Substructure
EUQ_{EW} - Element Unit Quantity of External Walls
EUR_{EW} - Element Unit Rate of External Walls
EUQ_{Ser} - Element Unit Quantity of Services
EUR_{Ser} - Element Unit Rate of Services
EUQ_{UF} - Element Unit Quantity of Upper Floor
EUR_{UF} - Element Unit Rate of Upper Floor
k - Minor EC components of the rest of the elements (20% of EC emissions)

Equation 1

According to the proposed EC model for office buildings, EUQs have to be defined in a standard way and EC-EURs need to be developed for the identified elements in the model. NRM compliant Building Cost Information Services (BCIS) defines the measurement rules for EUQs of the elements which is adopted as the standard definition of the EUQs of the identified hotspots. However, in the case of Services, each type of service is measured in different unit of measurements. For instance, Sanitary Installations are measured in Nr while Water Installations are measured as floor area serviced by water installations (m2). However, details such as number of appliances and service equipment are less likely available during early design stage. Hence, GIFA was selected as the appropriate EUQ for Services. **Error! Reference source not found.** presents the definitions adopted for EUQs of he selected carbon hotspots.

Elements	EUQ
Frame	GIFA - area of a building measured to the internal face of the perimeter walls at each floor level (m²).
Substructure	Area of lowest floor measured to the internal face of the external wall (as for GIFA) (m²).
External Walls	Area of external walls measured on the inner face (excluding openings) (m²).
Services	GIFA – same as for Frame (m²).
Upper Floors	Area of upper floor measured to the internal face of the external wall (as for GIFA) (m²).

Table 4: Definitions of EUQs for the identified carbon hotspots from NRM compliant BCIS

3.3 Developing EC-EURs

The next step in using the model is to develop EC-EURs for possible alternative design options of the identified carbon hotspots. Based on a survey of 41 buildings from BCIS online database, the design options which were found to be predominant in the office buildings are presented in **Error! Reference source not found.**.

Elements	Design options
Frame	Concrete, steel and hybrid
Substructure	Pile, raft, pad and strip
External Walls	Cavity and curtain walls
Services	Non-air-conditioned, air-conditioned – with and without BMS or lift installations
Upper Floors	In-situ concrete floors, pre-cast concrete floors, metal decking and timber floors

Table 5: Typical design options for the identified carbon hotspots

Consequently, EC-EURs were developed for the identified design options using the available EC data. Frame EC-EURs of the sample (28 buildings) are presented in **Error! Reference source not found.** where the sample size f each design option is indicated in parentheses. It can be noted that the EC-EUR of the concrete frame is derived from one (1) building which cannot be considered as a representative of the population. Similarly, hybrid frame EC-EUR is also calculated from three (3) buildings which is also unsatisfactory. In comparison to concrete and hybrid frames, steel frame EC-EUR has been derived from a larger sample with fourteen (14) buildings though the sample size is not statistically significant. Hence, a larger sample is required to benchmark EC-EURs.

Frame	Average EC per GIFA	Minimum EC per GIFA	Maximum EC per GIFA	Standard Deviation
	kgCO_2/ m²			
Concrete (1)	108.51	-	-	-
Steel (14)	242.86	98.00	486.41	104.87
Hybrid (3)	230.36	191.49	291.38	53.50

Table 6: EC-EURs for the possible design options of frame

Further, EC-EURs of the other elements could not be developed due to the unavailability of specification information of the rest of the elements of the sample buildings.

4. CONCLUSIONS

Application of a proposed EC estimating method is presented in this paper using the concept of carbon hotpots. Carbon hotspots in this research context is defined as the carbon critical building elements. Frame, Substructure, External Walls, Services and Upper Floors were identified as the carbon hotspots of the selected sample whose EC-EUR range is wider than the other elements. Also, 80:20 Pareto Rule was not supported in the research context instead the findings propose an 80:36 ratio for EC of office buildings which implies that the 80% of EC emissions in office buildings are attributable to 36% of the building elements. However, the findings are based on a sample of 28 buildings and hence, are not generalised which is a limitation of the study. However, the study can be repeated with a larger sample to attain statistically significant results. Further, there is also a need for a larger sample to benchmark EC-EURs for alternative design options of the identified carbon hotspots. Developing such EC-EURs will facilitate EC estimating during early stages of design which has the potential for huge emission reductions.

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