CARBON HOTSPOTS OF OFFICE BUILDINGS IN THE UK

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ABSTRACT

Embodied carbon of buildings is receiving substantial attention due to the increasing statutory requirements on operational carbon of buildings. Even though the embodied carbon of buildings is not regulated at present there is a need to control embodied impacts of buildings because embodied carbon of buildings tends to increase as the operational carbon savings increase. Focusing on intensive emissions sources or the hotspots is an effective way of managing embodied carbon during the early stages of design though there is a gap with regards to the knowledge of carbon hotspots. Therefore, embodied carbon estimates of 28 office buildings in the UK were obtained and the carbon hotspots of buildings (in accordance with NRM element classification) were identified using the 80:20 Pareto Principle. Frame, Substructure, External walls, Services and Upper Floors were identified as carbon hotspots of the sample. However, findings do not support the 80:20 ratio in this case but propose a ratio of 80:36. In addition, the building elements were categorised into three types based on the probability of each element is being identified as a hotspot in the sample which is referred to as the 'carbon hotspot probability'. The elements that were categorised as 'Lead Positions' and 'Special Positions' are the elements with higher reduction potential compared to remainder positions and require more attention during the early stages of design to achieve maximum reduction in embodied carbon.

Keywords: *Carbon Hotspots; Embodied Carbon; Office Buildings; Pareto Principle.*

1. INTRODUCTION

A rise in the number of low and zero carbon buildings is evident in most developed countries as a result of stringent statutory requirements imposed on operational carbon of buildings. However, operational carbon reduction measures likely to make Embodied Carbon (EC) of buildings relatively more important which are unregulated at present. The reduction potential of EC is higher during the early stages of design compared to the latter and more detailed stages (RICS, 2014). The reduction potential decreases increasingly as more carbon is committed to the project due to the fact that the possible design solutions are constrained by previous design decisions. However, tools and techniques to manage EC during the early stages of design are still in their infancy. In fact, estimating EC during the early stages of design is challenging due to limited design information. However, it has been proposed that focusing on intensive emission sources would be one good approach for achieving high carbon reduction or to reap benefits during the early stages of design (Carbon Trust, 2010, RICS, 2014, Halcrow Yolles, 2010). These carbon intensive elements are referred to as 'carbon hotspots' in this paper. The paper introduces the concept of carbon hotspots and the importance of capturing carbon hotspots by presenting two case studies from the literature. The rationale for choosing 80:20 Pareto Principle for identifying the carbon hotspots is discussed in the research method. The carbon hotspots of the sample are presented in data analysis and discussion and the elements with high reduction potential were identified and reported.

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2. LITERATURE REVIEW

Carbon hotspots of buildings are the elements which are carbon significant, easily measurable and with high reduction potential (RICS, 2014). Hence, identifying hotspots is crucial to reduce embodied carbon impacts of building designs right from the early stages of design. These carbon hotspots may vary from one building to another depending on the type or the function of the building (Ashworth and Perera, 2015; Perera and Victoria, 2017) due to differing element intensities. However, the knowledge about carbon hotspots is not flagged yet and is still developing.

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 carbon hotspots of 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 the difference in embodied carbon was found to be attributed to the difference in foundations and external walls. The findings of the study (Monahan and Powell, 2011) identify the substructure and external walls as 'carbon hotspots' in the case study building and showcase 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 a few elements were studied including foundation, beams, slabs, columns and staircases, which can be related to the Substructure, Frame, Upper Floors and Stairs as per the New Rules of Measurement (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 structural elements have been considered in this study.

It is clear that embodied carbon studies in different types of buildings highlighted above (Monahan and Powell, 2011; Shafiq *et al*, 2015) have different focuses and hence, limit the analysis mainly to structural and facades. However, Cole and Kernan (1996) found that cladding finishes and services are to be the biggest component of recurring embodied carbon emissions of an office building and services can account for 10-25% of total embodied carbon emissions (Hitchin, 2013; RICS, 2014). This implies that finishes and services are also embodied carbon significant elements though these are based on a few case studies. Hence, a holistic analysis of typical buildings will paint a complete picture on the embodied carbon contributions of each element and will highlight the potential areas of embodied carbon reduction.

3. RESEARCH METHOD

Embodied carbon estimates of 28 office buildings that are in accordance with the NRM compliant element classification standard were obtained from a QS consultancy practice in the UK. The estimates were produced using Bills of Quantities (BOQ) of buildings and published sources of embodied carbon emission factors such as Inventory of Carbon and Energy (ICE) (Hammond and Jones, 2011) and the UK Building Blackbook (Franklin and Andrews, 2011). The obtained sample consisted of steel, concrete and hybrid framed buildings ranging from one (1) to thirty-six (36) storeys and the Gross Internal Floor Area (GIFA) of buildings ranges from 1,788 m^2 to 130,930 m^2. The profile of the sample suggests that there is a correlation between the number of storeys and the GIFA of buildings. However, a similar pattern was not displayed between the GIFA and the EC per GIFA of buildings (see Figure 1). This suggests that EC per GIFA of buildings are not influenced by GIFA itself, even though there is a relationship between the total embodied carbon and the building size due to increased element quantities. Therefore, this justifies the use of a sample containing a wide spectrum of GIFA.

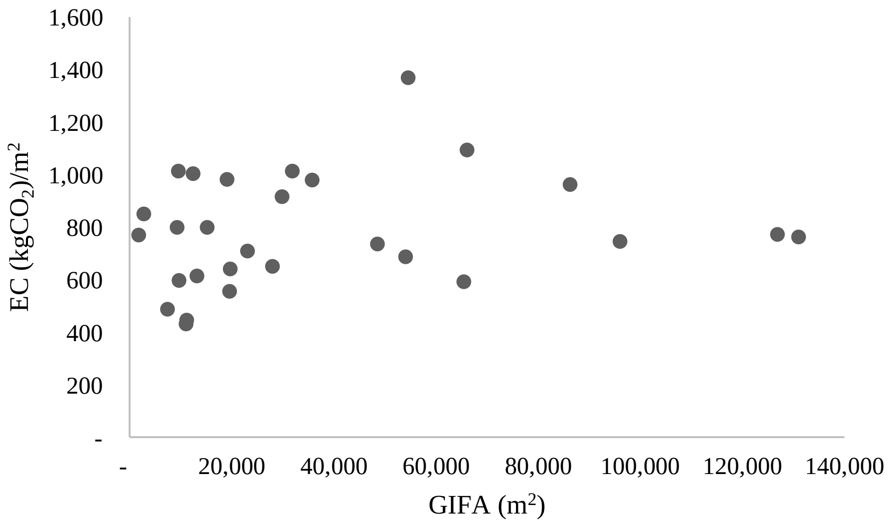

Figure 1: Plotting EC per GIFA against the GIFA of Buildings

The embodied carbon estimates have a system boundary of cradle-to-gate which includes the embodied carbon associated with the material manufacturing (raw material extraction up to the manufacturing factory gate). The carbon significant elements or the carbon hotspots were identified for the whole sample using the 80:20 Pareto Principle. Pareto Principle proposes that 80% of the results (or consequences) are attributable to 20% of the causes which implies an unequal relationship between the inputs and the outputs (Koch, 2011; Delers, 2015). Munns and Al-Haimus (2000) noted that the seminal texts in the cost management literature (Ashworth and Perera, 2015; Seeley, 1996; Ashworth and Skitmore, 1983) acknowledging the applicability of Pareto Principle to identify the cost significant items. Further, the works of Munns and Al-Haimus (2000) and Tas and Yaman (2005) are examples of embracing 80:20 Pareto Principle to identify the cost significant items of buildings and eventually, developing prediction models. Hence, Pareto Principle was adopted to identify carbon significant elements of buildings which are the elements contributing up to 80% of the total embodied carbon. Consequently, the 80:20 Pareto ratio was verified in the context of embodied carbon of building.

In addition, some building elements are more critical than the others and have higher reduction potential. Hence, carbon hotspots of each building were identified and the probability of each element is being identified as a carbon hotspot in the whole sample was calculated using the formula for probability calculation presented in Eq. 1.

$$P_i = \frac{n_i}{N} \qquad \textit{(Eq. 1)}$$

Where, P_i is the carbon hotspot probability of the respective element, n_i is the frequency of the respective element being identified as a hotspot in the whole sample and N is the sample size or the total number of buildings considered, which is 28.

Based on the carbon hotspot probability, the building elements were categorised into three types such as ‘Lead Position’, ‘Special Position’ and ‘Remainder Position’. The description of each category is as follows:

i. Lead positions: Carbon hotspot probability > 0.8)
ii. Special positions: Carbon hotspot probability 0 - 0.8)
iii. Remainder positions: Carbon hotspot probability = 0)

Accordingly, ‘Lead Positions’ were the elements that were frequently identified as carbon hotspots; ‘Special Positions’ were the elements identified as hotspots occasionally, and ‘Remainder Positions’ are the elements that were not identified as hotspots. In addition, the reduction potential of each element was conceived based on their carbon hotspot category. Lead positions were regarded as elements with high reduction potential due to their significant contribution to the total embodied emission while special positions were classed as elements with medium reduction potential due to their wavering nature in the hotspot category. Alternatively, the reduction potential of remainder positions was considered to be low due to their marginal contribution to the total embodied emissions.

4. DATA ANALYSIS AND DISCUSSION

The descriptive statistics of the whole sample is presented in Table. Accordingly, the EC per GIFA of office buildings ranges from 432 $kgCO_2/m^2$ to 1,368 $kgCO_2/m^2$ with an average of 785 $kgCO_2/m^2$. The confidence interval of the sample was found to be 80 which implies that it can be inferred with 95% confidence that the population mean (EC per GIFA) will lie between ±80 $kgCO_2/m^2$ from the sample mean (EC per GIFA) which is 785±80 $kgCO_2/m^2$. This statistic suggests that the sample mean can be used to predict EC per GIFA of a proposed building with 90% accuracy (±10% deviation in the prediction) which is acceptable for an early stage estimate (See, Ashworth and Skitmore, 1983).

Table 2: Descriptive Statistics of Elemental EC per GIFA of the Sample

Element	Average of the EC per GIFA ($kgCO_2/m^2$)	Minimum	Maximum	Standard Deviation
1A Substructures	137.20	33.21	320.72	65.31
2A Frame	236.72	98.00	486.41	101.13
2B Upper floors	75.99	1.72	191.08	38.68
2C Roof	25.05	2.88	103.25	19.69
2D Stairs	7.00	2.47	21.46	5.01
2E External walls	111.24	8.37	265.80	63.35
2F Windows and external doors	15.20	0.02	157.64	35.20
2G Internal walls and partitions	20.14	1.19	64.37	15.97
2H Internal doors	1.50	0.12	7.32	1.79
3A Wall finishes	3.65	0.22	18.47	4.23
3B Floor finishes	37.69	0.39	97.77	28.82
3C Ceiling finishes	8.55	0.65	24.62	6.05
4A Fittings and furnishings	0.86	0.02	3.39	1.15
5 Services	106.81	6.63	192.88	50.16
EC per GIFA	**785.31**	**431.61**	**1368.17**	**215.92**

Table 3 presents the carbon hotspot analysis of the sample with percentage contributions of each element and the cumulative percentage of the group. Frame, Substructures, External walls, Services and Upper Floors were identified as carbon hotspots (elements contributing up to 80% of EC) of office buildings in descending order of significance. In particular, Frame contributes up to 30% of EC of office buildings as concrete and steel which are main framing materials are high carbon intensive. Next, Substructure, External Walls and Services are contributing almost equally towards the total EC of buildings. The most common foundation type includes raft and pile which involves high usage of concrete, steel and machinery resulting in high EC contribution. Similarly, curtain walling being the most common External Wall type in offices in the UK makes External Walls a hotspot. Hence, the use of recycled concrete and steel, low energy intensive production methods, light pre-fabricated elements, recycled glass and low carbon façades such as bio-based materials and re-use of materials (Lupíšek *et al.*, 2015) will contribute towards EC savings. Furthermore, it can be noticed from Table that five out of fourteen elements are contributing up to 80% of the total EC, alluding a new ratio which is 80:36 in the context of EC of office buildings.

Table 3: Carbon Hotspot Analysis of the Sample

Element (NRM compliant)	Average EC per GIFA ($kgCO_2/m^2$)	Element contribution %	Cumulative %
2A Frame	236.72	30.1%	30.1%
1A Substructure	137.2	17.4%	47.5%
2E External Walls	111.24	14.1%	61.6%
5 Services	106.81	13.6%	75.2%

Element (NRM compliant)	Average EC per GIFA ($kgCO_2/m^2$)	Element contribution %	Cumulative %
2B Upper Floors	75.99	9.6%	84.8%
3B Floor finishes	37.69	4.8%	89.6%
2C Roof	25.05	3.2%	92.8%
2G Internal Walls and Partitions	20.14	2.6%	95.3%
2F Windows and External Doors	15.2	1.9%	97.3%
3C Ceiling Finishes	8.55	1.1%	98.3%
2D Stairs	7	0.9%	99.2%
3A Wall Finishes	3.65	0.5%	99.7%
2H Internal Doors	1.5	0.2%	99.9%
4A Fittings and Furnishings	0.86	0.1%	100.0%

Table 4 presents the carbon hotspot category of each element based on the probability of occurrences in the sample and their emission reduction potential. Accordingly, Frame has been identified as a hotspot in all the buildings. Substructure and Services were identified as hotspots in 90% of the buildings and External Walls were identified as a hotspot in 80% of buildings making Frame, Substructure, Services and External Walls 'Lead Positions'. These are the building elements with higher reduction potential. On the other hand, Stairs, Internal Walls and partitions, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings were not found as hotspots in any of the buildings making it 'Remainder Positions' and building elements with lower reduction potential. The rest (Upper Floors, Roof, Windows and External Doors and Floor Finishes) were identified as 'Special Positions' with medium reduction potential. This analysis showcases the building elements which are more critical than others in term of EC contribution and where most of the reduction can be achieved. Similarly, it also highlights the elements which are EC insignificant with lower reduction potential. It is clear from the findings above that building design determines the chances of an element being a hotspot in a particular building. Therefore, the design of 'Lead Positions' and 'Special Positions' can play an important role in influencing the embodied carbon accountability of buildings.

Table 4: Carbon Hotspot Category

Elements	n_i	P_i	Element Category	Reduction Potential
1A Substructures	25	0.9	Lead	High
2A Frame	28	1	Lead	High
2B Upper Floors	17	0.6	Special	Medium
2C Roof	4	0.1	Special	Medium
2D Stairs	0	0	Remainder	Low
2E External Walls	21	0.8	Lead	High
2F Windows and External Doors	3	0.1	Special	Medium
2G Internal Walls and Partitions	1	0	Remainder	Low
2H Internal Doors	0	0	Remainder	Low
3A Wall Finishes	0	0	Remainder	Low
3B Floor Finishes	5	0.2	Special	Medium
3C Ceiling Finishes	0	0	Remainder	Low
4A Fittings and Furnishings	0	0	Remainder	Low
5 Services	24	0.9	Lead	High

5. CONCLUSIONS

The aim of the paper was to capture the carbon critical elements or the carbon hotspots of office buildings and identify the building elements with emission reduction potential. 80:20 Pareto Principle was adopted to identify the carbon hotspots and the ratio was also verified in the case of embodied carbon of buildings. Accordingly, Frame, Substructures, External walls, Services and Upper Floors were identified as carbon hotspots of office buildings and the findings suggest that 36% of the elements are responsible for 80% of the embodied carbon impacts of buildings proposing an 80:36 ratio. Frame, Substructure, Services and External Walls were identified as the elements with high emission reduction potential while Upper Floors, Roof, Windows and External Walls and Floor Finishes were identified to have medium emission reduction potential. Elements including Stairs, Internal Walls and partitions, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings can be disregarded in the design decision-making during the early stages of design due to their minimal or almost negligible emission reduction potential. The findings display the significance of the design of building structure, façade, finishes and services in influencing the embodied carbon of buildings while suggesting that the highest reduction potential is achievable in the structure, façade and services of office buildings. Emission reductions can be achieved in the structure by using recycled concrete/steel and light pre-fabricated elements, re-use of materials and selecting low energy intensive production and operations; use of recycled glass and low carbon façade such as bio-based materials can bring savings in the façade embodied carbon. However, opportunities for reducing embodied carbon in services are limited which calls for in-depth research in this area.

6. REFERENCES

Ashworth, A. and Perera, S. 2015. *Cost studies of buildings.* Oxon: Routledge.

Ashworth, A. and Skitmore, R. M. 1983. Accuracy in Estimating. *CIOB Occasional Paper No. 27.* London: CIOB.

Carbon Trust, 2010. *Carbon: Reducing the footprint of the construction process*. UK: Carbon Trust.

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

Delers, A. 2015. *Pareto's Principle: Expand your business!*. Belgium: 50Minutes.com.

Franklin and Andrews 2011. *Hutchins UK building blackbook: the cost and carbon guide: hutchins' 2011: Small and Major Works*, Croydon, Franklin and Andrews.

Halcrow Yolles 2010. *Sustainable offices – embodied carbon*. UK: South West Regional Development Agency.

Hammond, G. and Jones, C. 2011. *A BSRIA guide to embodied carbon: the inventory of carbon and energy*. UK: BSRIA.

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

Koch, R. 2011. *The 80/20 Principle*. London: Nicholas Brealey Publishing.

Lupíšek, A., Vaculíková, M., Manľík, Š., Hodková, J. and Růžiľka, J. 2015. Design Strategies for Low Embodied Carbon and Low Embodied Energy Buildings: Principles and Examples. *Energy Procedia,* 83**,** 147-156.

Monahan, J. and Powell, J. C. 2011. An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings,* 43**,** 179-188.

Munns, A. K. and Al-Haimus, K. M. 2000. Estimating using cost significant global cost models. *Construction Management and Economics,* 18**,** 575-585.

Perera, S. and Victoria, M. 2017. The role of carbon in sustainable development. *In:* LOMBARDI, P., SHEN, G. Q. and BRANDON, P. S. (eds.) *Future challenges for sustainable development within the built environment.* UK: Wiley's Publication.

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

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

Shafiq, N., Nurrudin, M.F., Gardezi, S.S.S. and Kamaruzzaman, A.B., 2015. Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM). *International Journal of Sustainable Building Technology and Urban Development*, 6(3), 157-172.

Tas, E. and Yaman, H. 2005. A building cost estimation model based on cost significant work packages. *Engineering, Construction and Architectural Management,* 12**,** 251-263.