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# MANAGING EMBODIED CARBON IN BUILDINGS: A PARETO APPROACH

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# MANAGING EMBODIED CARBON IN BUILDINGS: A PARETO APPROACH

## ABSTRACT

**Purpose:** The aim of this paper is to identify the carbon intensive building elements or 'carbon hotspots' of office buildings in order to maximize the carbon reduction potential during design stages.

**Design/methodology/approach:** Embodied carbon estimates of 28 office buildings in the UK were obtained and carbon hotspots of the sample (in accordance with NRM element classification) were identified using the 80:20 Pareto Principle.

**Findings:** Frame, Substructure, External walls, Services and Upper Floors were identified as carbon hotspots of the selected sample. However, findings do not support the 80:20 ratio in this case but propose a ratio of 80:36. Stairs, Internal Walls and partitions, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings were identified as carbon insignificant elements that have a lower EC reduction potential compared to the rest.

**Originality/value:** Findings unveil carbon intensive and carbon insignificant building elements of typical office buildings in the UK. This informs designers of the elements that could yield the highest potential embodied carbon savings via effective design choices. In addition, a logical design timeline is proposed for building elements based on their element hotspot category and design sequence to assist design decision making.

**Keywords:** Carbon Hotspots, Carbon Hotspot Probability, Embodied Carbon, Office Buildings, Pareto Principle.

**Article type:** Research paper

## 1. INTRODUCTION

Recent climate conventions and the number of academic papers published on climate change and carbon management evidence the increased attention to Embodied Carbon (EC) management of buildings. EC management, however, is only achievable through effective EC measurement. Material quantities and their respective EC data are the fundamental building blocks of EC measurement while system boundary, scope of analysis, methodology, estimator's assumptions and the source of data are the top five factors amongst others that cause variations in EC estimating (De Wolf *et al*., 2017; Dixit *et al.* 2010; Perera and Victoria, 2017). In fact, the figures can vary from 200 $kgCO_2e/m^2$ to 1650 $kgCO_2e/m^2$ in office buildings (De Wolf *et al*., 2017) and 370 $kgCO_2e/m^2$ to 620 $kgCO_2e/m^2$ in dwellings (Hammond and Jones, 2009) due to these factors. Hence, standardisation and regulation of EC measurements are at the heart of the EC debate. Nevertheless, EC estimating and management of buildings is inevitable to minimise emissions from the built environment.

The EC reduction potential decreases as the design progress due to the diminishing marginal gain (RICS, 2014; Victoria, *et al.*, 2015). However, estimating EC at early design stages is challenging due to limited design information (Perera and Victoria, 2017). Hence, early stage tools mostly rely on stochastic modelling that predicts EC by capturing patterns from past data resulting in a lower precision compared to the detailed stage EC models. Nevertheless, Marsh *et al.* (2018) show that 5 to 10% of precision can be achieved in early stage EC tools by carefully selecting building data to construct the model database. Of the many early stage EC tools, the tool conceptualised by Victoria *et al.* (2016) is unique and introduces the significance of carbon intensive elements in estimating EC. Furthermore, focusing on intensive emission sources is recognised as an effective approach for reducing a significant amount of EC during the early stages of design (Carbon Trust, 2010; RICS, 2014; Halcrow Yolles, 2010; Perera and Victoria, 2017). Literature evidence shows that substituting conventional materials in carbon intensive elements with low carbon alternatives can lead to a reduction of EC up to 51%. However, the knowledge of carbon intensive elements are still evolving and these elements are mainly dependent on the function of buildings (Perera and Victoria, 2017). These carbon intensive elements are referred to as 'carbon hotspots' in this paper. Carbon hotspots of a sample of office buildings in the UK were identified, compared against the literature and conclusions regarding carbon hotpots of office buildings were drawn in light of the stated limitations. The findings of the research help designers to focus on the carbon hotspots of office buildings early in the design process to maximize the carbon reduction ability of the project. The proposed method also allows researchers to replicate the study with different types of building to generate new knowledge or to alter the existing knowledge base.

## 2. CARBON HOTSPOTS OF BUILDINGS

Carbon hotspots of buildings are the elements which are carbon significant, easily measurable and with high reduction potential (RICS, 2014). Identification of hotspots is crucial to reduce embodied carbon impacts of building designs right from the early stages of the design process. However, the knowledge about carbon hotspots is still developing (see, Victoria and Perera, 2018; Victoria, *et al.*, 2017). Carbon hotspots may vary from one building to another depending on the function of the building (Ashworth and Perera, 2015; Perera and Victoria, 2017) due to differing element intensities. Monahan and Powell (2011) identified substructure and external walls as 'carbon hotspots' of a two-storied residential building and demonstrated that 51% of embodied carbon can be reduced by substituting conventional masonry construction with timber construction. Similarly, Shafiq et al. (2015) proved that it is possible to reduce up to 31% of embodied carbon of a two-storied office building by designing the structural elements (including substructure, frame, upper floors and stairs) using different classes of concrete and steel. Again, Perera and Victoria (2017) identified substructure, frame, upper floors and external walls as 'carbon hotspots' of four office buildings. Additionally, a building case study by Wen, Siong and Noor (2015) highlighted that painting can contribute up to 20% of the total embodied energy and 8% of embodied emissions. On the other hand, Cole and Kernan (1996) found that cladding finishes and services were the biggest components of recurring embodied emissions of an office building while services can account for 10-25% of total embodied carbon emissions (Hitchin, 2013; RICS, 2014).

Case studies on embodied energy reported by Reddy and Jagadish (2003), Wen, Siong and Noor (2015) also add insights into embodied carbon debate with the caution of conditional interchangeability of embodied carbon with embodied energy due to process related emissions (Lélé, 1991; Ayaz and Yang, 2009). Reddy and Jagadish (2003) compared buildings with conventional materials and methods against energy efficient materials and methods in India and found that substituting conventional materials and methods with energy efficient materials saves 50% of the energy consumed. Conventional materials included Reinforced Concrete (RC) frames, RC slabs, burnt clay brick masonry, concrete block masonry and tile roofs while stabilised mud blocks, prefabricated roofing systems, masonry vaults, filler slab roofs, lime-pozzolana cement were considered as energy efficient materials in the study (Reddy and Jagadish, 2003). Authors of this study also found that replacing 20% of cement by pozzolana or by diluting the cement with more soil results in 25% reduction of embodied energy. Similarly, pre-fabricated buildings consume less embodied energy than cast in situ buildings due to controlled production of components and reduce wastage on site. For instance, Wen, Siong and Noor (2015) noted cast in situ buildings consumed 32% more energy compared to pre-fabricated buildings.

All case studies reported above suggest that a significant reduction of EC (or embodied energy) is possible through wise design choices. Therefore, it is critical to identify the elements that have high reduction potential so that the highest possible EC reduction can be achieved efficiently. In fact, elemental analysis takes precedence over material analysis as it helps prioritising the design of hotspot elements when there is a budget constraint. For instance, instead of replacing all conventional materials with low carbon materials (e.g. cement with pulverised fly ash), it is wise to substitute only the carbon significant elements that could yield a substantial reduction in EC at an efficient cost.

Furthermore, an analysis of the whole building is inevitable to identify the hotspots as it provides a holistic picture of the EC contribution of all elements of the buildings (Victoria and Perera, 2018) which is lacking in most of the reported studies.

Victoria and Perera (2018) presented carbon and cost hotspots of office buildings based on a holistic analysis of a sample of 41 buildings. Substructure, Services, Frame, Upper Floors, External Walls and Roof (capitalised elements comply with the element definition of New Rules of Measurement (NRM)) were identified as carbon hotspots (elements responsible for 80% of the total EC of buildings) in descending order of intensity. The same six elements were found to be responsible for 72% of the capital cost on average. In addition, the authors also classified building elements into three categories based on the hotspot probability in the sample namely: 'Lead positions' – elements that were mostly identified as hotspots; 'Special positons' – elements that were occasionally identified as hotspots; 'Remainder positions' – elements that were never identified as hotspots. Accordingly, Victoria and Perera (2018) reported that Stairs, Internal Doors, Fittings, Furnishings and Equipment are carbon insignificant elements that can be overlooked in early design decisions. However, these findings are based on a sample of 41 buildings. Hence, it is useful to test the generalisability and applicability of the findings of Victoria and Perera (2018) by employing another sample.

## 3. RESEARCH METHOD

Most of the embodied carbon studies reported in the literature concerning the carbon intensive elements or materials follows a qualitative approach to analysis as they are based on one or a few (less than ten) building case studies. A quantitative approach to embodied carbon studies is lacking in the literature due to the difficulties in obtaining data. However, quantitative analyses provide a different angle to the problem investigated. It leads to objective findings, hence increases the credibility and generalisability of the work. Therefore, the research adopted a quantitative approach similar to Victoria and Perera (2018) in analysing carbon hotspots of buildings to gain a holistic view and compare findings to infer conclusions about the population. Figure 1 illustrates the research process – a sample of office buildings was obtained, carbon hotspots were identified using 80:20 Pareto principle, building elements were then classified into three types as proposed by Victoria and Perera (2018).

**Figure 1: Research method diagram**

Obtaining data from the whole population is impractical due to the lack of public repositories for construction projects in the UK. In particular, restrictions on data availability limits the sampling options. Therefore, non-probability sampling techniques were explored. According to Saunders *et al.* (2016), snowball sampling was identified as the most suitable technique for this research due to the data accessibility issues. Snowball sampling resulted in only one QS practice volunteering to supply the required data, which became the study sample. The study sample consisted of 28 office buildings (see, Table 1) with their elemental embodied carbon estimates. Building elements reported in this paper comply with the element definition of NRM, which is the latest measurement standard of the UK construction industry. The EC estimates were prepared using Bills of Quantities (BOQ) 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). This implies that the embodied carbon estimates have a system boundary of cradle-to-gate, which accounts for the embodied carbon associated with the material production only (raw material extraction up to the manufacturing factory gate).

**Table 1: Sample profile**

The obtained sample of buildings consisted of steel, concrete, hybrid framed buildings ranging from one (1) to thirty-six (36) storeys, and the Gross Internal Floor Area (GIFA) of buildings ranged from 1,788 $m^2$ to 130,930 $m^2$. Figure 2 suggests that there is a correlation between the number of storeys

**Figure 2: Profile of the sample buildings**

and the GIFA of buildings, which is self-explanatory. Conversely, data points in Figure 3 are randomly distributed suggesting a lack of correlation. This implies that EC per GIFA is not significantly affected by GIFA of buildings.

**Figure 3: Plotting EC per GIFA against the GIFA of buildings**

The next step in the analysis is to establish an objective definition or a cut-off point to determine hotspots in buildings. The 80:20 Pareto Principle was adopted after the work of Victoria and Perera (2018) who demonstrated the suitability of the technique by citing seminal text from the cost management literature (see, Munns and Al-Haimus (2000) and Tas and Yaman (2005)). This implies that the elements contributing up to 80% of the total EC emissions are identified as carbon intensive elements. In addition, the probability of each element being a carbon hotspot in the whole sample was calculated using the formula presented in Equation 1.

**Equation 1: Formula for probability calculation**

$$P_i = \frac{n_i}{N}$$

Where $P_i$ is the carbon hotspot probability of the respective element, $n_i$ is the frequency of the respective element being 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' (Victoria and Perera, 2018). The description of each category is as follows:

1. Lead positions: Carbon hotspot probability > 0.8)
2. Special positions: Carbon hotspot probability 0 - 0.8)
3. Remainder positions: Carbon hotspot probability = 0)

Accordingly, 'Lead Positions' are the elements that are always or mostly a carbon hotspot (identified as a hotspot in more than 80% of the buildings - 23 or more buildings of 28). 'Special Positions' are the elements that can potentially be a hotspot in some buildings (identified as a hotspot between 0-80% of buildings - 1 to 22 buildings of 28). 'Remainder Positions' are the elements that are not a hotspot (Never identified as a hotspot in the sample). Findings were then compared against the findings of Victoria and Perera (2018) and inferences were made.

## 4. DATA ANALYSIS AND DISCUSSION

The descriptive statistics of the EC analysis of the whole sample is presented in Table 2. 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 is 80 which implies that it can be inferred with 95% confidence that the population mean (EC per GIFA) will vary by ±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 an acceptable precision for an early stage estimate (Ashworth and Skitmore, 1983; Marsh *et al.* 2018).

**Table 2: Descriptive statistics of elemental EC per GIFA of the sample**

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. Accordingly, the study findings agree with Monahan and Powell (2011), Shaffiq *et al.* (2015), RICS (2014) and Hitchin (2013) except for Stairs, which contributed to less than 1% on average in the selected sample, given that the sample consisted of low to high-rise buildings. Henceforth, it can be argued that any low carbon alternatives for Stairs will reduce the total EC by less than 1%. The study findings also agree with the findings of Wen, Song and Noor (2015) on painting, as the average percentage contribution of Internal Finishes (Wall, Floor and Ceiling) is around 6%, which again is insignificant. However, Finishes can be a significant component at the outset of a life cycle assessment due to recurring emissions as Cole and Kernan (1996) alluded.

Five out of fourteen elements contributed up to 80% of the total EC, proposing a new ratio of 80:36 in the context of EC of office buildings. Similarly, Victoria and Perera (2018) also identified all these five elements and Roofs as carbon hotspots in a sample of 41 office buildings. This accentuates the ambiguity concerning the hotspot position of Roofs, which could have been attributable to design complexities and specifications. Element quantities and material choices are the two key variables that make these elements a hotspot. In terms of material choices, concrete and steel are the most common materials opted for Substructure, Frame and Upper Floors. Concrete and steel are carbon intensive materials and consume a significant amount of embodied energy in their production process. The embodied energy of steel is higher than concrete and it can be as high as 39MJ per kg of steel and emits roughly 2.82kg$CO_2$ per kg of steel (Hammond and Jones, 2011). On the other hand, curtain walling is the most common form of façade of office buildings in the UK. Curtain walls are responsible for 23.5 MJ of embodied energy consumption and emit 1.27 kg$CO_2$ per kg of glass. Services are identified as a hotspot due to the intensity of the element and the amount of work involved in the installation of electrical, mechanical and specialist installations such as building management systems. In fact, quantities of elements may also play a major role in making an element a hotspot. However, the influence of element quantities could not be explored due to the limited data availability.

**Table 3: Carbon hotspot analysis of the sample**

Table 4 presents the carbon hotspot category of each element based on the probability of occurrence as a hotspot in the sample and their priority rating. Frames were identified as a hotspot in all buildings. Substructure and Services were identified as hotspots in 90% of the sample and External Walls were identified as a hotspot in 80% of the sample. Accordingly, Frame, Substructure, Services and External Walls can be classed as 'Lead Positions' which again overlaps with the findings of Victoria and Perera (2018) who also identified these four elements in addition to Upper Floors as Lead positions. Stairs, Internal Walls and Partitions, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings were not identified as hotspots in any of the buildings, hence were classed as 'Remainder Positions'. Conversely, Victoria and Perera (2018) found Internal Walls and partitions, Wall Finishes and Ceiling Finishes to be Special Positions. Rest of the building elements (Upper Floors, Roof, Windows and External Doors and Floor Finishes) were identified as 'Special Positions'. The comparison of findings displays the variability in hotspot positions of elements even within the same type of buildings (i.e. offices) which could be due to the noted variability in the building characteristics of the sample data. This is a limitation of the study.

Lead Positions should be given the highest design priority due to their high carbon intensity. However, the reduction potential may be low in elements like Services due to limited low carbon alternatives. Remainder Positions can be given the least design priority as these elements contribute less than 20% of EC. The design of Special Positions is also as important as Lead Positions because notable EC reductions are possible in Special Positions if designed effectively. Therefore, it would be impractical to propose a linear design timeline for these elements starting from Lead Positions through to Special and Remainder Positions as elements such as structure and envelop need to be defined at the start and services are usually designed later in the design phase. Taking these into consideration a design matrix is proposed in Table 5 for different elemental categories based on RIBA Plan of Work 2013 (see, Table 5).

Accordingly, all Lead Positions should be designed during the Concept stage with the exception of Services, which can be designed at any stage between concept and technical design due to the complexity of the element and comparatively lower reduction potential. Upper Floors and Roofs can also be designed at the Concept stage irrespective of these elements being classed as special positions as they form part of the building structure. The remaining Special Positions can be designed at the detailed design stage. Similarly, Internal Walls and Partitions Wall Finishes and Ceiling Finishes can also be designed at detailed design stage regardless of these elements being classed as Reminder positions in the study as Victoria and Perera (2018) identified these as Special positions. This implies the design of Stairs, Internal Doors and Fittings and Furnishings can wait until the technical design stage. In this way, design efficiency can be maximised by enabling designers to channel their time and effort on elements that have higher reduction potential than others.

**Table 4: Carbon hotspot category**

**Table 5: Proposed design timeline for the elements**

## 5. CONCLUSIONS

The Pareto analysis highlighted Frame, Substructures, External walls, Services and Upper Floors as carbon hotspots of the sample suggesting 36% of the elements are responsible for 80% of the embodied carbon impacts from office buildings. This falsifies the 80:20 ratio and proposes an 80:36 ratio in the context of EC of office buildings. This reaffirms the findings of Victoria and Perera (2018) while the status of Roofs as a hotspot remains unverified. Frame, Substructure, Services and External Walls were classed as elements that should be given the highest design priority while Upper Floors, Roof, Windows and External Walls and Floor Finishes are classed as elements with medium design priority. The design of Stairs, Internal Walls and partitions, Internal Doors, Wall Finishes, Ceiling Finishes and Fittings and Furnishings can be disregarded during the early stages of design due to their minimal or almost negligible EC contribution. However, the design of elements follows a sequence (i.e. designing the structure, envelope, interior and services). Hence, a design timeline was proposed in the form of a matrix taking both design sequence and the carbon intensity of elements into consideration.

Findings also demonstrate 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 and façade of office buildings. Emission reductions in structures are possible by using recycled concrete or steel, light pre-fabricated elements, pre-used materials and selecting low energy intensive materials and operations; use of recycled glass and low carbon façades such as bio-based materials, which can reduce embodied carbon of façades. However, while Services are identified as a 'Lead Position', opportunities for reducing embodied carbon of services are limited. This calls for in-depth research on low carbon alternatives for building services.

Despite the smaller sample size and the wide range of data, the study findings agree with most of the literature findings apart from the hotspot positions of roofs and stairs. It was also demonstrated that the range of the data did not hugely influence the findings. Further, bias in the sampling due to sourcing data from only one QS practise is minimised if not eliminated due to the quantitative nature of the analysis and the chosen methods are proven valid and reliable in the literature. Although sample data came from only one QS practice the building designs represented many different sources. As such, data can be generalised to a great extent. In addition, lack of totality of data is identified as a limitation of the research. The absence of element specifications and quantities did not permit in-depth investigation of some findings such as the variation in EC contribution attributable to element specifications and the influence of element quantities on hotspots. However, future research should consider element quantity and specification in interpreting quantitative results to provide deeper insights into the findings. It is also recommended that a homogeneous sample (similar frame types –

steel/concrete/timber/hybrid, and storey heights – low/medium/ high-rise) is employed without compromising the quality of data to improve the generalisability of findings. Despite the reported limitations, the method presented in the paper is transparent, robust and can be adapted by researchers and practitioners to identify carbon hotspots of different types of buildings in different contexts.

## REFERENCES

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

Ayaz, E. and Yang, F. 2009. *Zero carbon isn't really zero: Why embodied carbon in materials can't be ignored* [Online]. Available: http://www.di.net/articles/zero_carbon/ [Accessed 27 February 2017].

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(4)**,** 307-317.

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings, 42*(8), 1238-1247, doi: 10.1016/j.enbuild.2010.02.016

De Wolf, C., Pomponi, F. and Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice, Energy and Buildings, 140, 68-80.

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

Hammond, G. and Jones, C. (2009). Embodied carbon: the concealed impact of residential construction. *In Green Energy and Technology* UK: Springer.

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

Lélé, S. M. 1991. Sustainable development: A critical review. *World Development*, 19(6), 607-621.

Marsh, R., Rasmuseen, F. N. and Birgisdottir, H. (2018). Embodied carbon tools fro architects and clients early in the design process. *In: Embodied Carbon in Buildings*. Pomponi, F., De Wolf, C. and Moncaster, A. (Eds), UK: Springer.

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(1)**,** 179-188.

Munns, A. K. and Al-Haimus, K. M. (2000). Estimating using cost significant global cost models. *Construction Management and Economics,* 18(5)**,** 575-585.

Perera, S. and Victoria, M. (2017). The role of carbon in sustainable development. *In:* Lombardi, P., Shen, G. Q. & 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.

Saunders, M., Lewis, P. & Thornhill, A. (2016). *Research methods for business students,* Essex, Pearson Education Limited.

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***,** 1-16.

Tas, E. and Yaman, H. (2005). A building cost estimation model based on cost significant work packages. *Engineering, Construction and Architectural Management,* 12(3)**,** 251-263.

Venkatarama Reddy, B.V. and Jagadish, K.S. (2003). Embodied energy of common and alternative building materials and technologies, *Energy and Buildings*, 35(2), 129-137.

Victoria, M, Perera, S and Davies, A. (2015). Developing an early design stage EC prediction model: A case study In Raidén, A. B. and Aboagye-Nimo, E. (Eds) *Proceedings of 31st Annual ARCOM*

*Conference*, 7-9 September 2015, Lincoln, UK, Association of Researchers in Construction Management, 267-276.

Victoria, M., Perera, S., and Davies, A. (2016) A pragmatic approach for embodied carbon estimating in buildings. *In SBE16 Torino*, 18-19 February 2016, Torino, Italy.

Victoria, M. and Perera, S. (2018). Carbon and cost hotspots: an embodied carbon management approach during early stages of design. *In: Embodied Carbon in Buildings*. Pomponi, F., De Wolf, C. and Moncaster, A. (Eds), UK: Springer.

Victoria, M. F., Perera, S., Davies, A., and Fernando, N. (2017). Carbon and cost critical elements: a comparative analysis of two office buildings, *Built Environment Project and Asset Management*, 7(5), 460-470, doi.org/10.1108/BEPAM-12-2016-0086

Wen, T.J., Siong, H.C. and Noor, Z.Z. (2015). Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: Case studies of residential buildings in Iskandar Malaysia, *Energy and Buildings*, 93, 295-302.

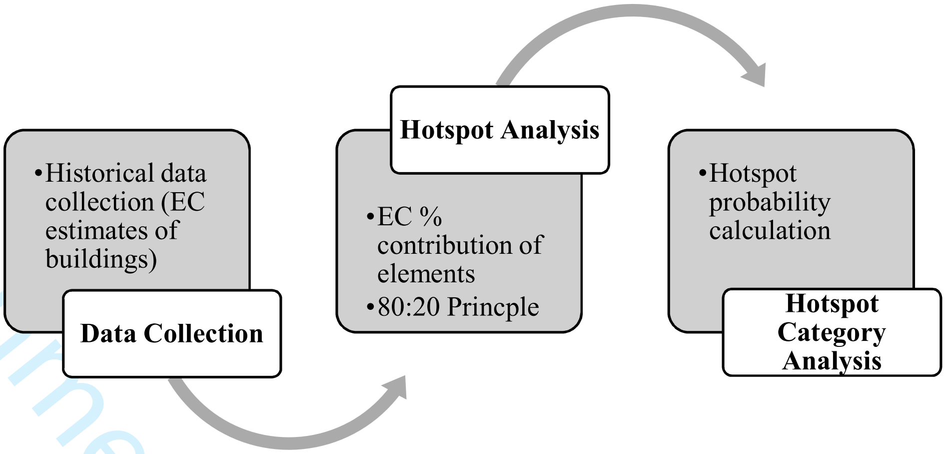

**Figure 1: Research method diagram**

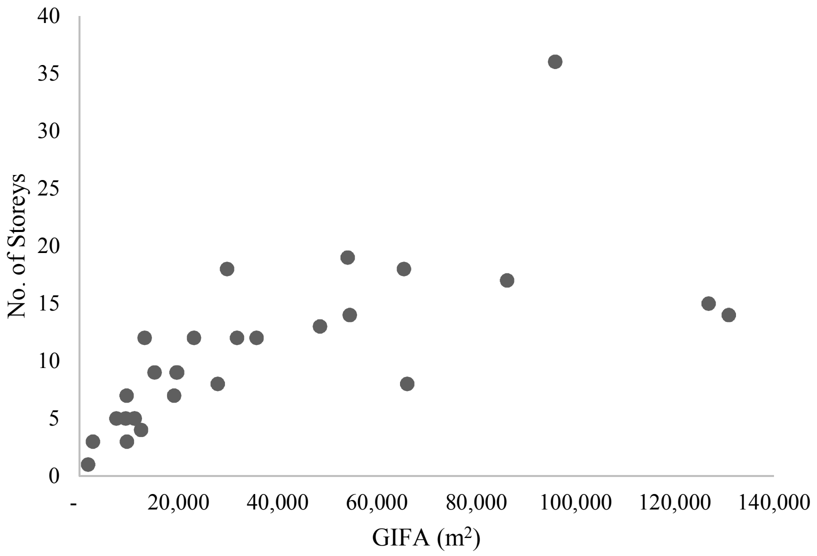

**Figure 2: Profile of the sample buildings**

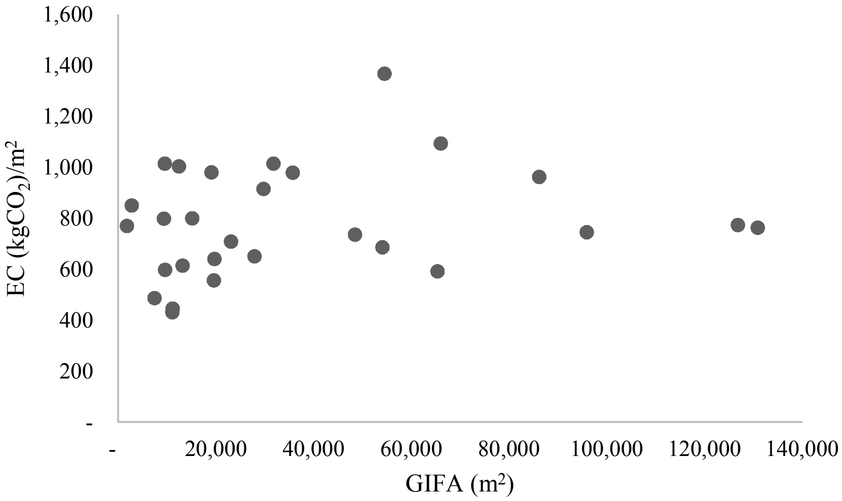

**Figure 3: Plotting EC per GIFA against the GIFA of buildings**

**Table 1: Sample profile**

| Building # | Frame | GIFA | Storeys |
|---|---|---|---|
| 1 | Steel | 95,945 | 36 |
| 2 | Steel | 54,101 | 19 |
| 3 | Steel | 65,414 | 18 |
| 4 | Steel | 29,806 | 18 |
| 5 | Steel | 86,211 | 17 |
| 6 | Steel | 126,872 | 15 |
| 7 | Steel | 130,930 | 14 |
| 8 | Steel | 54,550 | 14 |
| 9 | Steel | 48,509 | 13 |
| 10 | Steel | 31,833 | 12 |
| 11 | Steel | 35,760 | 12 |
| 12 | Steel | 13,209 | 12 |
| 13 | Steel | 23,156 | 12 |
| 14 | Steel | 19,764 | 9 |
| 15 | Steel | 19,600 | 9 |
| 16 | Steel | 27,940 | 8 |
| 17 | Steel | 66,093 | 8 |
| 18 | Steel | 9,587 | 7 |
| 19 | Steel | 19,125 | 7 |
| 20 | Steel | 11,170 | 5 |
| 21 | Steel | 7,472 | 5 |
| 22 | Steel | 11,117 | 5 |
| 23 | Steel | 9,645 | 3 |
| 24 | Steel | 1,788 | 1 |
| 25 | Hybrid | 9,372 | 5 |
| 26 | Hybrid | 12,470 | 4 |
| 27 | Hybrid | 2,776 | 3 |
| 28 | Concrete | 15,192 | 9 |

**Table 2: Descriptive statistics of elemental EC per GIFA of the sample**

| **Element** | **Average of the EC per GIFA (kgCO$_2$ per 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: Carbon hotspot analysis of the sample**

| Element (NRM compliant) | Average EC per GIFA (kgCO$_2$ per 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% |
| 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: Carbon hotspot category**

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

**Table 5: Proposed design timeline for the elements**

| **RIBA 2013 Design Stages**<br>**Element Category** | **2- Concept Design** | **3- Detailed Design** | **4- Technical Design** |
|---|---|---|---|
| **Lead position** | Substructure<br>Frame<br>External walls | | |
| | ⟵ | Services | ⟶ |
| **Special position** | Roof<br>Upper Floors | Windows and External Doors<br>Floor Finishes | |
| **Remainder position** | | Internal Walls and Partitions<br>Wall Finishes<br>Ceiling Finishes | Stairs<br>Internal Doors<br>Fittings and Furnishings |