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CARBON AND COST CRITICAL ELEMENTS OF OFFICE BUILDINGS: A CASE STUDY

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ABSTRACT

Buildings emit two types of carbon (and greenhouse gases) namely Operational Carbon (OC) and Embodied Carbon (EC). Operational carbon is regulated in the UK as it contributed up to 70-80% of total emissions. On the other hand, EC started gaining attention with the rise of zero carbon buildings and due to the fact that the EC is unregulated at present. However, estimating EC is not completely standardised and there is room for improvement. EC can be controlled only by vigilant building designs. Studying building closely will provide better understanding of the carbon significant elements and enable designers to make informed decisions. Accordingly, a case study of an office building located in London in the UK is selected for the study. Capital cost (CC) and EC estimates were prepared using detailed cost plan of the building. Then, the building elements were classified as per NRM1 (New Rules of Measurement 1) element classification and the most carbon and cost significant elements were identified in the case study building. Not all of the identified carbon significant elements are identified as cost significant but Substructure, Frame and Services are identified as both carbon and cost critical elements while Stairs and Ramps, Internal Doors and Fittings, Furnishings and Equipment were identified to be the least carbon and cost significant elements. Findings of the case study building inform designers about the elements that has a vast reduction potential and worth investing their time on experimenting. However, the findings are based on single case study and, hence, cannot be generalised but to be seen as an exemplar for further research.

Keywords: Carbon Hotspots; Capital Cost; Cost Hotspots; Embodied Carbon; Office Building.

1. INTRODUCTION

Climate change is the most serious threat to human society. It is a threat that human society has created itself. Global atmospheric concentrations of greenhouse gases (GHGs) have increased since 1750. Notably the carbon dioxide (CO₂) is the most pre-dominant greenhouse gas by volume. Emissions of CO₂ from fossil fuel combustion in conjunction with that emitted from manufacturing are responsible for more than 75% of the increase in atmospheric CO₂ since the pre-industrial 18th century (Solomon *et al.*, 2007). The construction and occupation of buildings is a substantial contributor of global CO₂ emissions, with almost a quarter of total global CO₂ emissions attributable to energy use in buildings (Metz *et al.*, 2007).

The UK's commitment to reduce carbon and other greenhouse gas emissions is now a matter of legal obligation. Under the Climate Change Act 2008, emissions are targeted to fall by 26% by 2020 (by comparison with a 1990 baseline) and by no less than 80% to 2050 (Committee on Climate Change, 2013). The UK to reach its legal obligations of greenhouse gas emission reduction, a low carbon transition plan has been put into place. The plan covers the next 40 years and "the transition to low carbon can almost be read as a business plan for construction, bringing opportunities for growth" (HM Government, 2010, p.4). Still, the focus of the UK Building Regulations has been on operational energy use to date with embodied energy absent from legislative attention (Densley and Davinson, 2011).

However, in the action plans more focus was given to reduce carbon emissions during the operation of the building (known as 'operational carbon') which contributed to nearly 70-80% of total emissions from buildings until the zero carbon agenda for buildings was introduced. Eventually, zero carbon agenda implicitly emphasises the need to control the other component of the building sector emissions, namely Embodied Carbon (EC). EC is driven by process and affected by the supply chain, thus, it is difficult to

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manage. However, dual currency approach of clients and consultants highlights the importance of EC estimating and management. Therefore, it can be expected that the knowledge of cost and carbon relationship will become a valuable asset for the construction practices in the near future. Hence, the paper intends to identify the carbon and cost significant building elements in office buildings in the UK.

2. LITERATURE REVIEW

Carbon and other Green House Gases (GHG) are emitted directly and indirectly during the development and construction of buildings and the construction industry is accounted for emitting half of the UK's carbon dioxide (UK-GBC, 2016). Such emissions are primarily classified into two types such as operational carbon and EC (also known as capital carbon). Operation carbon is the carbon (and GHGs) emitted during the operation of the building (or infrastructure) as a result of fuel consumption while EC is the carbon (and GHGs) emitted during the production (includes raw material extraction, material manufacturing, transport, construction of the project), repair, replacement and demolition of the buildings (or infrastructure). The contribution of the two in total emissions varies depending on the type and the features of the building. Generally, operational carbon emissions are higher than the embodied emissions in most of the building types while there are exceptions like warehouses (RICS, 2014). Understanding the relationships between 'embodied' carbon and 'operational' carbon can assist in determining the overall optimum carbon reductions.

2.1. OPERATIONAL CARBON IN BUILDINGS

Operation carbon can be divided into two parts such as regulated and unregulated. Regulated emissions covers heating, ventilating, air-conditioning, lighting and the like and unregulated emissions includes emissions from ICT equipment, cooking and refrigeration appliances and the like. Part L of the Building Regulations of the UK has provisions to control the regulated operational carbon in buildings as the unregulated emissions are influenced by the behavior of the building users. The operational carbon emissions are expressed in mass of CO₂ emitted per year per square meter of usable floor area of the building (kg/m²/year). As per the Part L of the Building Regulations, the operational carbon or the Target CO₂ Emission Rate (TER) for a notional building design is benchmarked and the Building CO₂ Emission Rate (BER) of the proposed building should be less than the TER for the building design to be approved. Therefore, any building should pass the regulatory requirement to be developed on a site.

The low carbon agenda in the UK demands the new building developments to be low and zero carbon by employing renewable energy sources. Low and zero carbon refer to the low and zero operational carbon (regulated) which leaves unregulated operational carbon and especially EC unattended. In fact, the UK government requires all newly built domestic buildings to be zero carbon from 2016 and non-domestic buildings from 2019 which is considered to be ambitious targets and still under debate. Yet, the UK is becoming more stringent towards operational carbon. This has increased the concern on EC because emissions from a zero carbon building will be equal to total EC emissions. As shown in Figure, operational carbon will contribute up to 70-80% of total emissions in a typical building. Then, in a low carbon building operational carbon will immensely reduce which increase the EC contribution. Further, all of the emissions result from EC in a zero carbon building (yet, it should be noted that a portion of carbon can also be emitted from unregulated operational carbon if the energy is not supplied from renewable sources). Therefore, EC emissions require special attention in a low and zero carbon building.

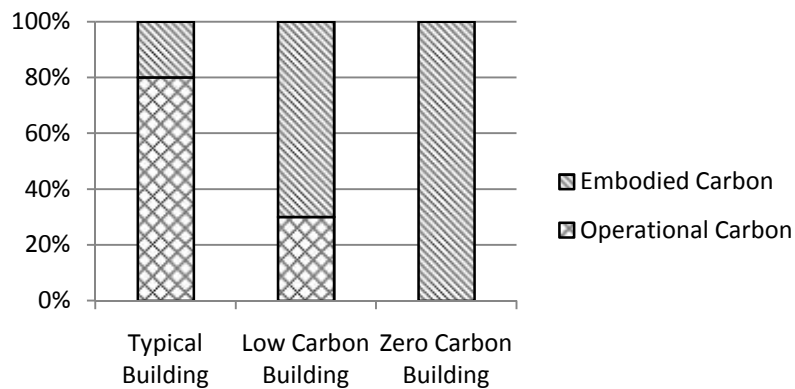


Figure 1: Significance of EC
Source: RICS (2012)

2.2. EC IN BUILDINGS

The EC is the carbon dioxide equivalent (CO_{2e}) or greenhouse gas (GHG) emissions associated with the non-operational phase of the project. This includes emissions cause by extraction, manufacture, transportation, assembly, maintenance, replacement, deconstruction, disposal and end of life aspects of the materials and systems that make up a building. Few scholars (Chen *et al.*, 2001; Ramesh *et al.*, 2010) categorise EC into three types such as Initial EC (raw material extraction, manufacturing, transport and construction), recurring EC (in-use EC such as repair, maintenance and replacement) and Demolition EC (EC during demolition). Further, EC can be saved due to recycling efforts of scrap materials or products after demolition which can be accounted in the carbon footprint calculation of the project; however, not all projects have this phase.

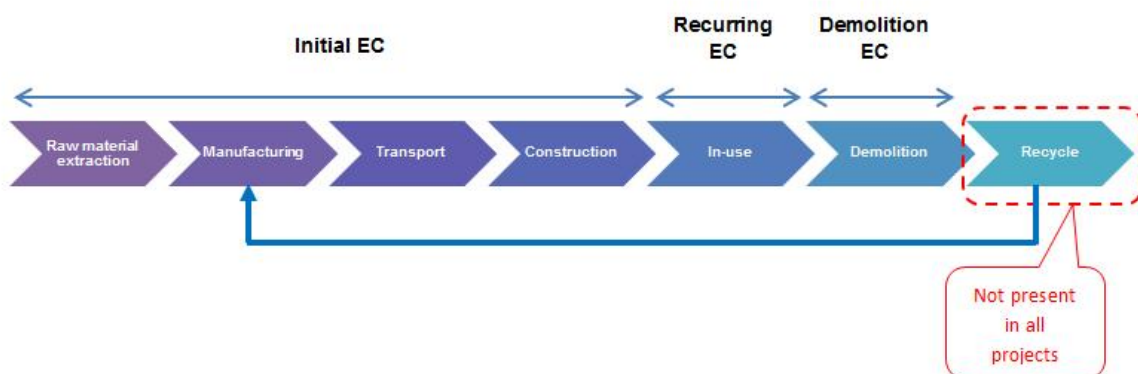


Figure 2: Classification of EC

EC can be calculated from cradle (earth)-to-gate (manufacturing factory gate), cradle-to-site (construction site), cradle-to-end of construction, cradle-to-grave (demolition), or even cradle-to-cradle (recycle, reuse and recovery). Hammond and Jones (2011) and Sansom and Pope (2012) noted that many EC datasets available are cradle-to-gate and fail to include emissions from latter stages of life cycle (such as construction, operation and maintenance and demolition and disposal) as they are project specific emissions. However, transport of materials to site can be significant for materials with lower EC emissions in other phases (Hammond and Jones, 2008). Furthermore, lesser transport distance not necessarily means lesser carbon emissions; mode of transport and type of fuel also plays a significant role other than the distance of travel (RICS, 2014; Sundarakani *et al.*, 2010)

Measures to minimise EC of the building has to be taken during the early stages of the design to yield greater savings as the carbon reduction potential is very high during the early stages of design (RICS, 2014). The reduction potential decreases more carbon is committed into the project as the possible design

solutions are constrained by previous design decisions. Then, during construction phase the reduction potential can be regarded as nearly zero unless there is a design change. Further, the design becomes static as the project progresses and changing the design at a later stage will result in loss of time and money. Therefore, it is crucial to identify possible EC saving options before the design develops to a greater detail. In fact, RICS (2014) states that investigating EC in different types of buildings is a completely new research avenue and there are limitations in regulatory standards or academic researches to aid the decision making at the initial stages of projects. Nevertheless, carbon hotspots are identified as an ideal way of dealing with this issue.

2.3. HOTSPOTS

'Hotspots' can be defined as the most critical or significant elements in a building which has enormous impact on project cost or EC. It can also be interpreted in this study as the building elements that are responsible for 80% of Capital Cost (CC) or EC which is derived from Pareto 80:20 rule. RICS (2014) further extends the definition by saying that the hotspots are not merely the significant elements but also the elements for which measurement data are readily available and reduction measures are possible. Hotspots vary for buildings with different functions and this knowledge can lead to greater carbon and cost savings or optimisation. Generally, foundations, frame, roof, walls, and floors are considered as carbon hotspots. Though, it is reported that the building services contribute approximately 15% of total EC, it is not widely regarded as a hotspot as measuring services at early design stages is a complex process and reduction potential may be limited (RICS, 2014). However, a study found that cladding finishes and services are to be the biggest component of recurring carbon emissions of an office building (Cole and Kernan, 1996). Hence, services and finishes cannot be disregarded when taking initial design decision as the contribution is significant. Therefore, it is important that the indication of likely EC of building services and finishes are revealed at the early stages of design to understand the carbon accountability of the project.

Table presents comparison of different studies on EC profile of office building in the UK. Accordingly, previous studies suggest that Substructure and Superstructure contributing up to 90% of the total EC. The major culprits of EC are the concrete and steel and apparently, concrete and steel are manifested in the Substructure and Superstructure of the buildings, identifying both as carbon hotspots. However, it is not possible to assert that all the superstructure elements are carbon significant as sub elemental breakdown is not given and the findings of Victoria *et al.* (2015) substantiate this claim. Frame, Upper Floor and External Walls were identified as the carbon hotspots in an office building in the study conducted by Victoria *et al.* (2015). Further, incomparability of literature findings due to the difference in element classification system adopted in presenting the results (for example, NRM, SMM/BCIS - older version, British Council of Offices 2011, own classifications) calls for a uniform classification system.

Table 1: Carbon Profile of Building Elements of Office Buildings from Published Studies

	Victoria <i>et al.</i> , (2015)	Halcrow and Yolles (Average of 3 case studies)	Sturgis Associates	WRAP	Davis Langdon from Clark (2013)
Substructure	43.79%	89% (some elements are combined)	25%	18.3%	Structure - 45%-85%, Facade - 5%-25%
Superstructure	54.66%		56%	58.24%	
Internal Finishes	0.57%	Not given	Fit-out (shell and core) - 8%, Fit-out (Cat B) - 8%	8.619%	4%-25% (Internal walls included)
Fittings and Furnishings	0.05%			Not given	
Services	0.93%	3%		11.96%	2-25%
Others		8% (External works)	4% (Waste)	2.9% (External works)	

Source: Victoria *et al.* (2015)

Increasing significance of dual currency appraisal - cost and carbon - in construction projects drives the development of knowledge with regard to cost and carbon comparisons. For instance, if cost and carbon hotspots are the same then both can be attended at the same time and an optimum solution can be achieved based on the project objectives (if client is concerned about the carbon footprint of the building then choose low carbon option which might compromise on cost).

3. RESEARCH METHOD

A building case study is presented in this paper to understand the distribution of EC and CC among building elements and to draw insights in to the results. EC and CC of the building was estimated using the Inventory of Carbon and energy (ICE) version 2.0 (Hammond and Jones, 2011) which is an inventory of EC and energy data of common construction materials, UK Building Blackbook (Franklin and Andrews, 2011) which is a book containing itemized cost and EC data as per Standard Method of Measurements and manufacturer's data where necessary. Estimates were prepared using the detailed cost plan of the building applying relevant cost and carbon values per unit quantity of each item obtained from UK Building Blackbook. However, Blackbook data were based on the 2010 2Q (218) prices and a location index of 100. Subsequently, the cost was updated to 2016 1Q (276) and location index kept unchanged. Even though adjustment for price was made adjustment for EC data was not made as EC is affected by the process of manufacturing of the building materials. Unless and until the process is changed adjustment is not required to the EC data. Therefore, a crucial assumption is made in terms of the EC data that the manufacturing process considered when developing the database has not changed radically.

Then, each item was mapped as per the NRM 1 element classification, which is the latest measurement standard prevailing in the UK, as shown in Table. Afterwards items were grouped into elements such as Substructure, Frame, Upper Floors and the like. However, there were some shortcomings with the data. Cost plan of the building lacked detailed measurement of most of the services and Black book did not contain data for all services. However, benchmarks were obtained from Spon's price book (Davis Langdon Consultancy, 2014) (cost benchmarks) and an in-house carbon data from a UK consultancy practice for other services to make the estimate complete and present a holistic analysis of the building. The CC and EC values used for the other types of services are roughly £386 per m² GIFA and 163 kgCO₂ per m² GIFA respectively.

Table 2: Mapping Items for Finishes as Per NRM Element Classification

Item Description	Quantity	Unit	NRM Main Element Group	NRM Sub Element Group
Masonry paint; to blockwork walls	500	m ²	3	3.1
Dry lining and paint	55	m ²	3	3.1
Entrance matting	17	m ²	3	3.2
Carpet tiles	100	m ²	3	3.2
Painted soffit	74	m ²	3	3.3
Suspended plasterboard ceiling 1 x 12.5mm	37	m ²	3	3.3

Carbon and cost hotspots were analysed by sorting the CC and EC of the building elements separately from the highest to the lowest and a hierarchy of elements was produced. Then, the cumulative percentage was calculated and the elements that contribute up to 80% towards the CC and EC were identified as cost hotspots and carbon hotspots respectively.

4. DATA ANALYSIS AND DISCUSSION

Case study building is an office building located in central London and the profile of the building is presented in Table. The building is a hybrid framed building with raft foundation comprising concrete flat roof. Façade is made of pre-engineered stone concrete and glass. Combination of brick, block, dry lined partitions and glazed units forms the internal partitions of the building. Building is finished with moderate

type of finishes and installed with highly sophisticated services including Building Management System (BMS). The estimated total CC of the building was £14,157,600 and the EC was 8,806,100kgCO₂.

Table 3: Case Study Building Profile

Gross Internal Floor Area (GIFA)	11,320 m²
No of floors	8
No. of basements	1
External girth	148 m
Average storey height	3.6 m
Building height	29.7 m
Wall area	4,410 m ²

The CC and EC breakdown of the main elements are presented in Figure. Accordingly, it can be noticed that the superstructure of the building contributes equally towards CC (44%) and EC (49%) and superstructure is the predominant carbon and cost hotspot among the others. In terms of substructure, it contributes more than twice as CC (10%) towards EC (23%) and substructure is the second most significant carbon hotspot.

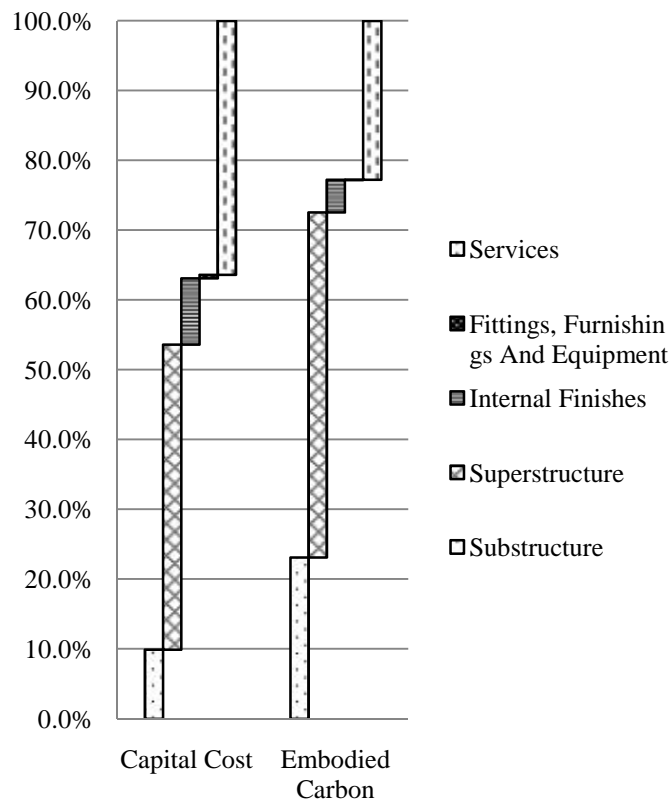


Figure 3: CC and EC Contribution by Elements

Services are the second most significant cost hotspot in the case study building contributing up to 36%. On the other hand, services and substructure both contribute almost equally towards the EC of the building. Internal finishes contribute up to 10% and 5% towards CC and EC, respectively. Fittings, furnishings and equipment are the least significant in terms of both CC and EC contributing less than 1%.

Table presents the hierarchy of cost and carbon hotspots of the case study buildings. The elements that are coloured in greyscale are the elements that contribute up to 80% of the CC and EC. The Carbon and cost hotspot analysis revealed that not all the identified cost hotspots are carbon hotspots and Substructure, Frame and Services are identified as both cost and carbon hotspot at different significant levels - Services

being the most cost significant and the Frame being the most carbon significant. On the other hand, Fittings, Furnishings and Equipment, Stairs and Ramps and Internal Doors are found to be the least cost and carbon significant in the case study building. The findings inform the designers that more attention is needed when designing Substructure, Frame and Services for this kind of office buildings. EC can be reduced by sourcing materials that are recycled or with lower carbon content which again needed to be compared with the cost to arrive at an informed decision of the optimum solution for the project considered.

Table 4: Carbon and Cost Hotspots of the Case Study Building

Cost Hotspot Hierarchy	Cumulative %	Carbon Hotspot Hierarchy	Cumulative %
Services	36.4	Frame	26.2
Frame	61.8	Substructure	49.3
Substructure	71.8	Services	72.1
Windows and External Doors	77.6	Upper Floors	84.6
Ceiling Finishes	83.0	Internal Walls and Partitions	89.0
Upper Floors	87.1	External Walls	91.8
External Walls	89.8	Ceiling Finishes	93.9
Internal Walls and Partitions	92.5	Roof	96.1
Floor Finishes	94.9	Floor Finishes	97.9
Roof	96.8	Windows and External Doors	98.6
Wall Finishes	98.5	Wall Finishes	99.3
Fittings, Furnishings and Equipment	99.1	Stairs and Ramps	99.8
Stairs and Ramps	99.5	Internal Doors	99.9
Internal Doors	100	Fittings, Furnishings and Equipment	100

In addition to that CC per GIFA and EC per GIFA were also calculated for individual elements to get insights in to the findings and presented in Figure. Even though CC and EC demonstrate a similar pattern when analysing at main elements level, differences can be noticed at individual element level. Clearly, Services is the most Significant cost hotspot in the building followed by Frame and Substructure while Frame is the most carbon significant element followed by Substructure and Services. This showcases that the Substructure, Frame and Services are the most carbon and cost critical elements in the case study building. Further, Figure also clarifies that not all Superstructure elements are cost and carbon significant. For instance, contribution of Stairs and Ramps and Internal Doors are almost negligible. While Windows and External Doors are found to be cost significant, EC contribution of the same is very low. The reason for this is CC of timber is high while EC of timber is very low making this enormous difference. Hence, specification of the building elements plays a major role in dictating CC and EC of the building and their relationships. In terms of Internal Finishes, Ceiling Finishes are the most carbon and cost significant and Wall Finishes are the least carbon and cost significant of the three following a similar rhythm. Fitting, Furnishing and Equipment are found to be insignificant in terms of both cost (0.51%) wise and carbon (0.04%).

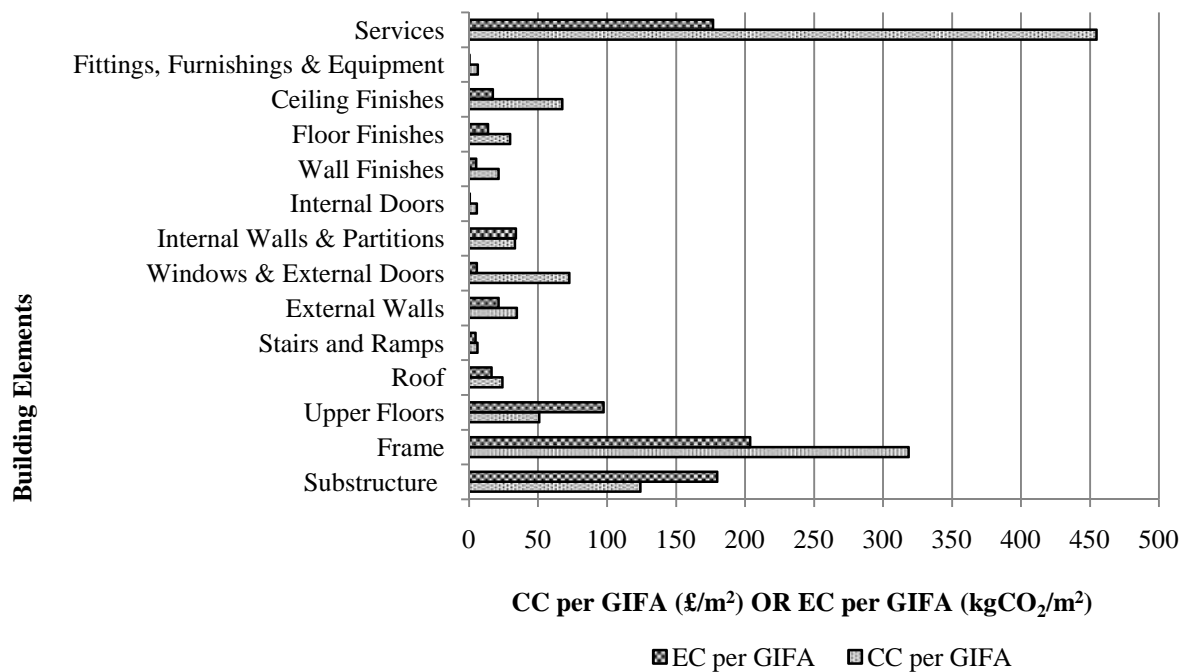


Figure 4: CC per GIFA vs. EC per GIFA by Elements

The significance of this analysis is that it informs the design team about the elements whose design has greater impact on the CC and EC of the building. For instance, in the case study building, Substructure, Frame and Services are identified as both cost and carbon critical elements. Hence, it is possible to select the optimum design solution from various possible alternatives, which does not compromise the function and aesthetics of the building element, when designing those elements in the future. Hotspot analysis also demonstrates that certain building elements are not worth investing time in optimising cost and carbon as its contribution to total EC and CC is almost negligible. Therefore, it is important that this kind of knowledge is developed and utilised during design development. However, this is based on a single case study and hence, no inferences can be drawn from the findings. Nevertheless, a foundation is laid in this paper to expand this type of research with a larger sample to arrive at generic prepositions and recommendations.

5. SUMMARY

The aim of the study was to identify the cost and carbon critical elements in the case study office building. Even though there is a general say that foundations, frame, roof, walls, and floors are to be carbon hotspots it cannot be taken for granted without thorough analysis. Also hotspots will vary for buildings with different functions and design features. Subsequently, an office building located in London was studied in detail to identify and draw insights about the cost and carbon significant elements in the building. Accordingly, the case study findings reveal that both CC and EC are significant in Substructure, Frame and Services. The Frame is identified as the most carbon significant element in the superstructure followed by Substructure, Services and Upper Floors while Services is identified as the most cost significant followed by Frame, Substructure, Windows and External Doors and Ceiling Finishes. Further, some elements impact hugely than others and some elements like Fittings, Furnishings and Equipment, Stairs and Ramps and Internal Doors have minimal impact on CC and EC compared to other elements. The implication of this analysis is that it enlightens the design team with the knowledge about the elements whose design has greater impact on the CC and EC of the building. Hence, it is possible to select the most optimum design solution from various possible alternatives which does not compromise with the function and aesthetics of the building element when designing building elements in the future.

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