Furthering embodied carbon assessment in practice: results of an industry-academia collaborative research project

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Abstract

In order to meet the mid-century carbon reduction targets and to mitigate climate change and global warming it is imperative that embodied carbon in the built environment receives immediate attention from policy, industry and academia. To shed light on how to accelerate a wider uptake of embodied carbon assessments in buildings, an industry-academia collaboration was funded by Innovate UK and the Engineering and Physical Sciences Research Council (EPSRC). Implementing Whole Life Carbon in Buildings (IWLCiB) has been the resulting project, a cooperative endeavour led by key academics and practitioners in the UK. Over the course of the project, three independent environmental consultants have produced a total of fifteen embodied carbon assessments across various building types, all starting from the same information including building specification and bill of quantities. These assessments have then been reviewed and analysed in detail by the academic team to establish similarities, differences, and common challenges and pitfalls.

This paper reports on the project's numerical findings by life cycle stages and building type. Detailed results are presented for each of the five case studies, showing elements of agreement and, most often, of variation. Additionally, each of the life cycle stages as defined by the TC350 standards is analysed both numerically and in terms of its contribution towards the whole life embodied carbon. The results show that significant discrepancies consistently exist even when the initial information available to the assessors is the same. The many assumptions that are necessary throughout the assessments inevitably present a barrier to consistency and convergence of the outputs. The numerical analysis also reveals that all life cycle stages account for important shares of the whole life carbon, and that therefore partial assessments – e.g. cradle-to-gate - are not sufficient if carbon reductions are to be realistically achieved. Yet, life cycle assessment remains the best tool for environmentally informed decision making. Future research in the field should continue to address the challenges identified in this article and work towards greater understanding and reliability of the numbers produced.

Keywords: embodied carbon; life cycle assessment; buildings; industry academia collaboration.

1. Introduction

While embodied carbon emissions are a key element of the global carbon conversation for imports, exports, and most manufactured products [1], this is yet not the case for buildings [2]. Current regulations still focus solely on the operational impacts of buildings although some national strategies have started to suggest a focus on a whole-life (embodied + operational) carbon approach [e.g. 3].

The assessment of embodied carbon presents many challenges in both research and practice [4, 5] despite a growing set of available guidance [6]. The latter is available in many forms, such as European standards [7-9], briefings from national organisations [10, 11] and professional bodies [12], as well as publications by international teams of researchers such as those who worked on the International Energy Agency Annex 57 [13-15] and the subsequent and recently launched Annex 72 [16].

Yet, it remains very difficult to achieve a complete coverage of all life cycle stages of a building [17] and many published assessments lack the necessary transparency to fully understand system boundaries as well as modeller's assumptions [18]. Future events and decisions are characterised by high uncertainty which decreases the reliability of predictions and estimates [19] and there is great underestimation of how much influence methods have on the final numbers.

Consequently, published results vary greatly in scope and magnitude [2, 17, 18, 20], and such variations are influenced by many parameters. A review of all such parameters falls beyond the scope of the present work but the interested reader will find a thorough and comprehensive overview in recently published works [21-29]. In this complex scenario it is no surprise that academia and industry fail to communicate and collaborate effectively, and there is currently a lack of implementation of the available – and considerable – body of academic work amongst practitioners [18]. Moncaster et al. [30] showed an almost inverse trend between the most common media for dissemination used by academics and the most used sources accessed by practitioners, and concluded that it was necessary to move towards meaningful means of collaboration between industry and academia for effective knowledge transfer and co-production.

This paper reports on the numerical findings of a funded research project [31] that was designed following that recommendation. The project involved a number of professionals from various organisations in the construction industry, three firms operating in the 'embodied carbon consultancy and assessment' market, and the academic team that analysed the consultants' assessments and acted as a trustee for sensitive information. For privacy and confidentiality reasons, all names of the project partners and their firms will remain anonymous; the academic team was formed by the authors of this publication. Additionally, the three consultants will be referred randomly and alternatively as Consultant A, B, and C without any letter referencing to the same firm throughout the article. The readers should therefore not focus on the results from "A", "B", or "C" as they never refer to the same company. Rather, they should pay attention to the difference in the results, which is the main point and contribution of this article.

The numerical results presented in this article are based on the analysis of the three consultants' assessments of five different case studies. This study represents the first of its kind, that is, an extensive analysis of the differences in embodied carbon assessments in practice across different consultants and project types. At a time where the suitability of life cycle assessment (LCA) to guide policy guidelines is questioned [32], our findings suggest that LCA still represents the most appropriate tool for the environmental impact assessment of buildings – provided that an agreed methodology is used and methods are applied consistently and transparently.

This work provides a valuable insight into the challenges and barriers of embodied carbon assessment in practice. In addition, it offers a timely and novel starting point to bridge the gap between academics and practitioners and ensure both communities learn from what the other has to offer.

2. Methodological approach

To ensure this research would cover as broad a range of built assets as possible, the project was set up to assess five different project types. This was to establish the extent of the influence of all inputs to and choices during an embodied carbon assessment. The five case studies cannot be disclosed to retain the anonymity of the data providers but the project types they refer to are as follows:

1. Case Study 1 (CS1): Office Building
2. Case Study 2 (CS2): Residential Refurbishment
3. Case Study 3 (CS3): Infrastructure
4. Case Study 4 (CS4): Residential
5. Case Study 5 (CS5): Retail

It was agreed that consultants would use the BS EN 15978 standard [9] and its proposed division for the life cycle stages (Figure 1), and that they would be based on the consultants' current practice.

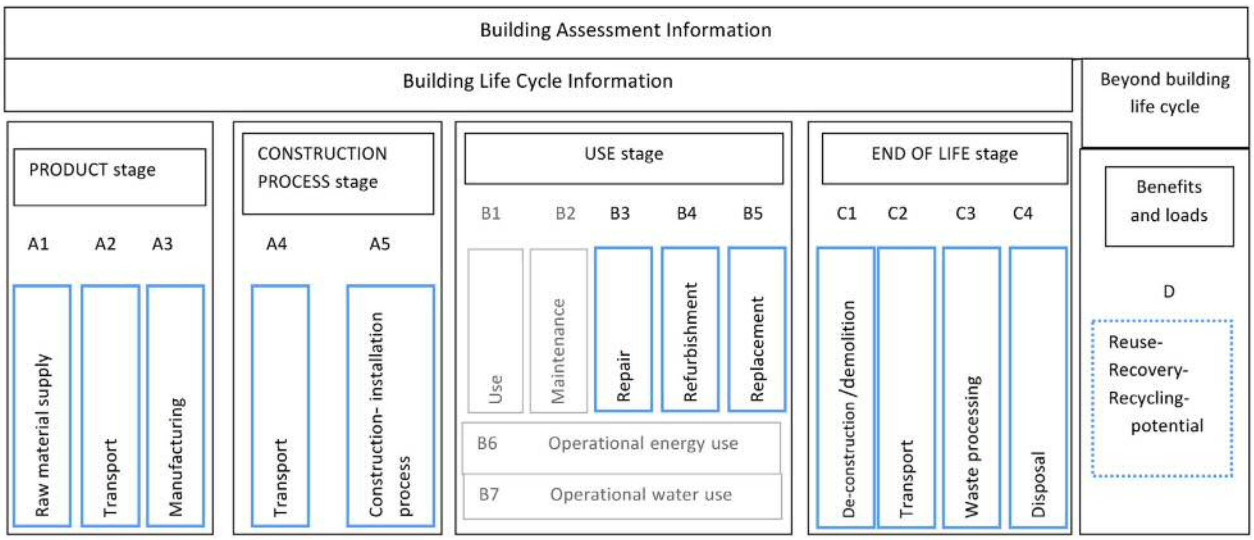


Figure 1: Life Cycle Stages [33]

A pre case study was conducted in March 2016 to assess the most notable differences amongst consultants and allow for an easier comparison of all subsequent case studies. The assessments of the five case studies by the three consultants were submitted to agreed deadlines. The gap between the submission of different studies allowed the academic team to analyse the consultants' work, seek clarification where necessary and produce individual reports for each case study that form part of the project deliverables.

It is important to note that the consultants submitted their calculation files (e.g. Excel spreadsheets) rather than a report with the results of their assessment. Such access to the raw data behind industry assessments of embodied carbon, from three firms that are normally competitors, is probably unprecedented in academic research on embodied carbon, and was only possible because of a genuinely collegial and collaborative spirit.

3. Results

The different nature of the projects related to the five case studies was aimed at covering a broad range of built assets. For this reason, detailed results on each of the five case studies are presented in turn in the following subsections, before being comparatively discussed in Section 4.

3.1 Case Study 1

Case Study 1 covered the embodied carbon assessment of a new metal frame office building with curtain walls in central London. The consultants all started their assessments from the same initial information. From the assessments submitted, the results were produced to demonstrate two main divisions:

1. Cradle-to-gate embodied carbon emissions divided according to the agreed-upon classification for the building layers
2. Whole life embodied carbon emissions divided according to the life cycle stages shown in Figure 1.

As for the second element, it is important to note that the B stage is often challenging to quantify due to the high uncertainty that characterise events and decisions over the useful life of a building. For this reason, there has been little consistency in reporting against individual sub-stages of the B cluster. Therefore, these will be presented in this article as grouped under the overall B stage. Further, to account for some of the aforementioned uncertainty and include equally possible scenarios, the consultants have produced assessments for two different timespans of useful life. These will be referred to in the remainder of this article as B_1 (shorter lifespan) and B_2 (longer lifespan).

Figure 2 shows the numerical results of the cradle to gate embodied carbon of the different building layers, while Table 1 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered. Results are shown for the three consultants to highlight the differences in the results that different assessors have produced starting from the same initial information.

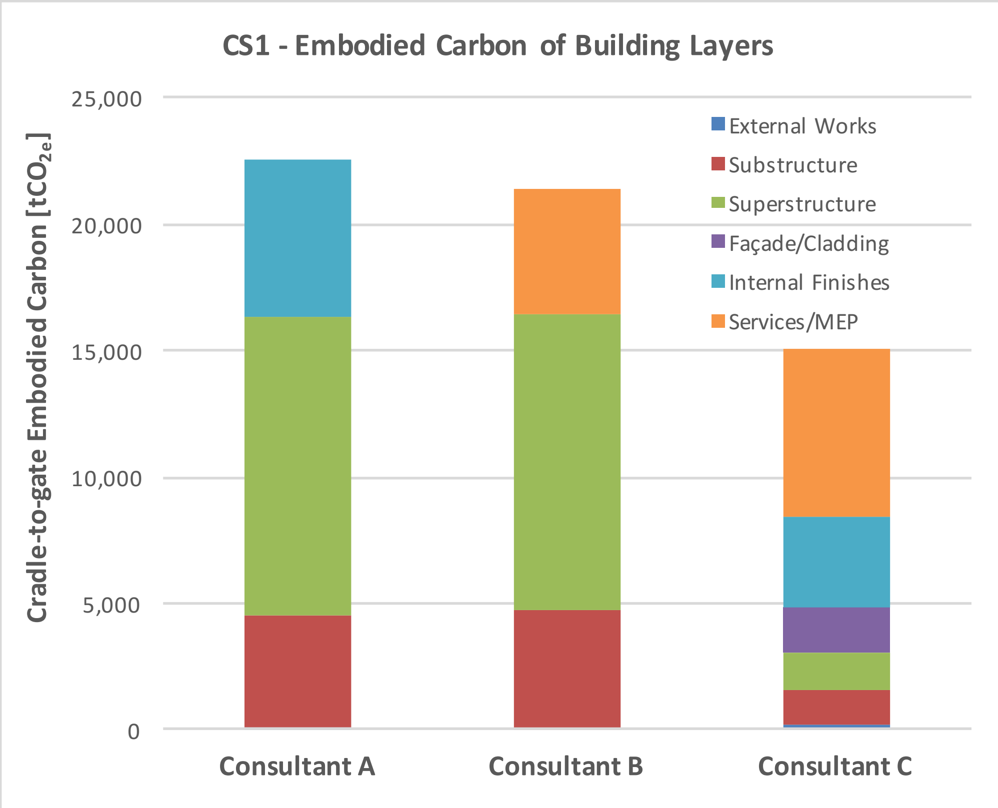


Figure 2 - Embodied carbon of the different building layers (CS1)

Table 1 - Numerical results of whole life embodied carbon for shorter and longer lifespans (CS1)

tCO_{2e}		CS1 [office]		
A1-A3	15,061	22,529	21,429	
A4	1,099	1,241	932	
A5	980	557	11,956	
B_1	6,257	7,799	1,059	Shorter Lifespan
B_2	18,603	20,747	2,460	Longer Lifespan
C1-C4	1,803	903	199	

It is interesting to analyse the contribution that different life cycle stages have towards the whole life embodied carbon. This is shown in Figure 3 for CS1.

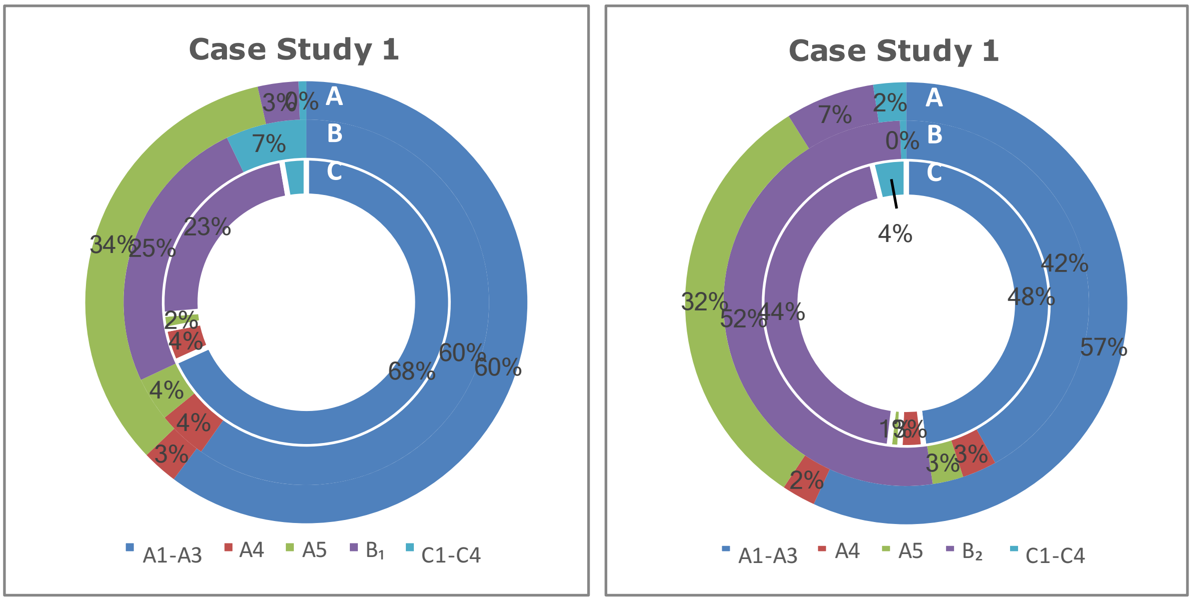


Figure 3 – Comparative results for Case Study 1 for both the shorter (left) and longer (right) lifespan

The range of variations for the impacts of different life cycle stages are shown in Table 2.

Table 2 – Ranges variations for different life cycle stages (CS1)

	Shorter lifespan	Longer lifespan
A1-A3	60% - 68%	40% - 58%
A4	3% - 4%	2% - 3%
A5	2% - 34%	1% - 32%
B	3% - 25%	7% - 49%
C1-C4	1% - 7%	1% - 5%

The results above show significant ranges of variations across consultants. They also challenge several myths in the embodied carbon literature and practice. For instance, whilst A1-A3 impacts are still the category which accounts for the greatest embodied carbon in the shorter lifespan case, impacts occurring in the B stage are considered by two consultants to be in the same order of magnitude for the longer lifespan case. These impacts are still seldom addressed in embodied carbon scientific research [17].

3.2 Case Study 2

Case Study 2 is a residential refurbishment. The building is a redeveloped terraced building over six storeys.

Similarly to the previous case study, Figure 4 shows the numerical results of the embodied carbon of the different building layers, while Table 3 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered. It should be noted that the building layers of a refurbishment project can be interpreted very differently and this increases the discrepancy even further. Results are again clustered around the three consultants. As mentioned in the introduction, the letters used in this case study to refer to the three firms do not match the letters used in Case Study 1.

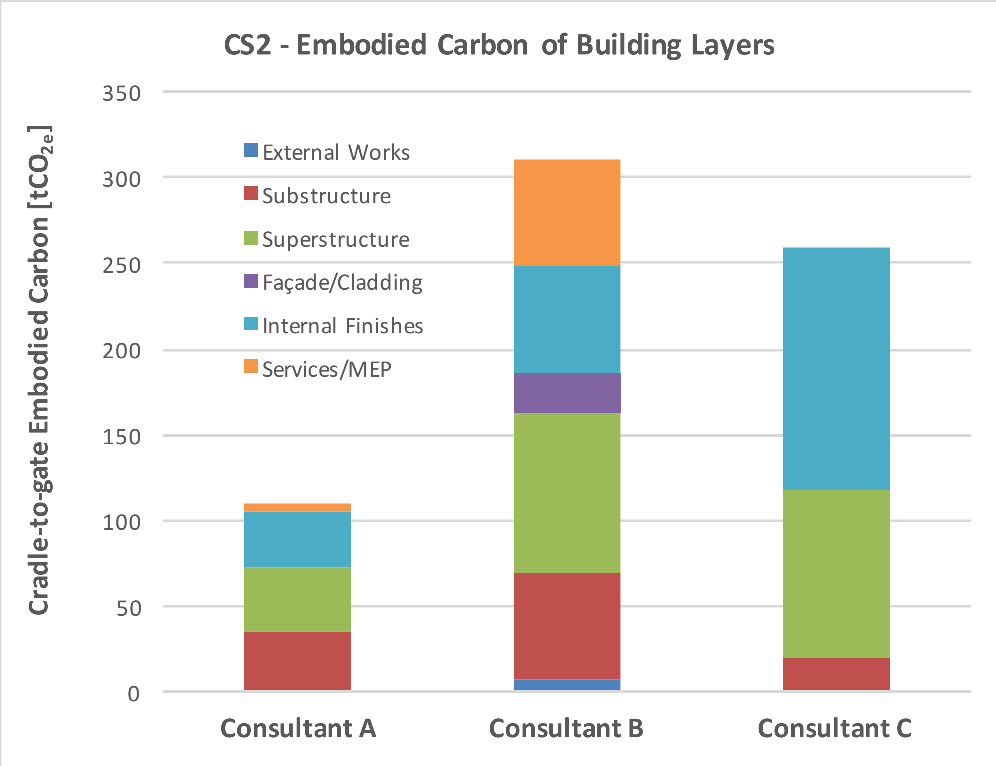


Figure 4 - Embodied carbon of the different building layers (CS2)

Table 3 - Numerical results of whole life embodied carbon for shorter and longer lifespans (CS2)

tCO_{2e}	CS2 [residential refurbishment]			
A1-A3	309.89	259.54	109.69	
A4	11.25	3.32	0.55	
A5	49.15	5.04	4.05	
B_1	0.00	70.98	12.75	Shorter Lifespan
B_2	409.56	202.97	29.61	Longer Lifespan
C1-C4	35.29	7.95	2.43	

The contribution that different life cycle stages have towards the whole life embodied carbon is shown in Figure 5 for CS2, while the ranges of variations across consultants are presented in Table 4.

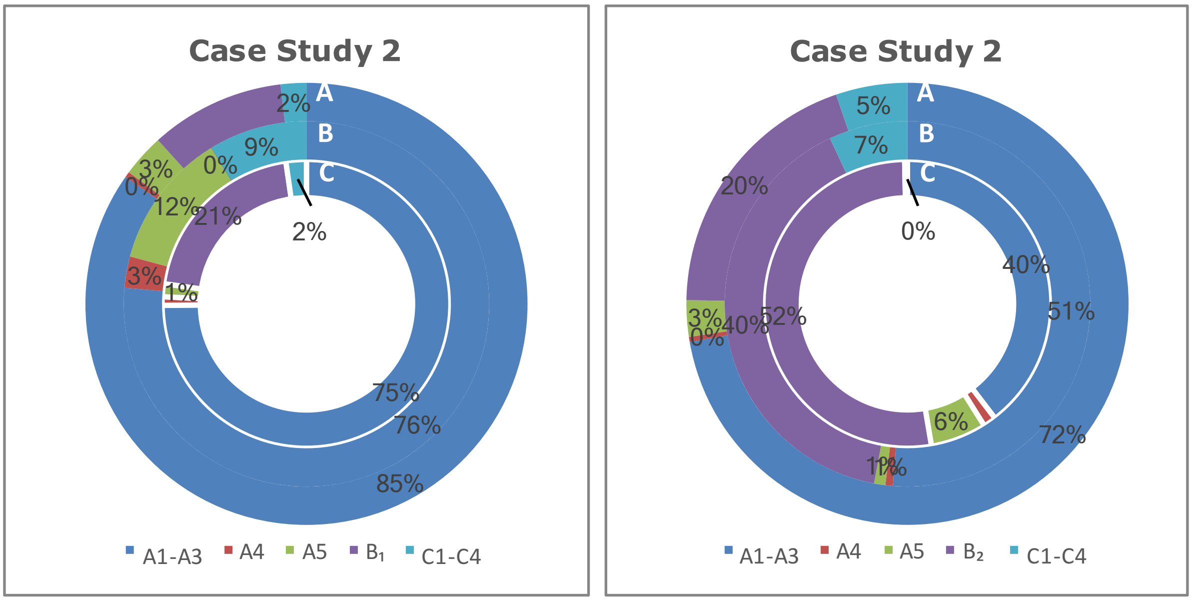


Figure 5 – Comparative results for Case Study 2 for both the shorter (left) and longer (right) lifespan

Table 4 – Ranges of variations for different life cycle stages (CS2)

	Shorter lifespan	**Longer lifespan**
A1-A3	76% - 85%	38% - 75%
A4	1% - 3%	1% - 2%
A5	1% - 12%	1% - 6%
B	10% - 21%	20% - 50%
C1-C4	2% - 9%	2% - 4%

For the second case study the results also show great variation. Impacts of categories usually overlooked such as A5, B and C are instead clearly worth of consideration. Once again this might be due to the nature of the project, i.e. a refurbishment, for which costing and assessment are harder than for new build.

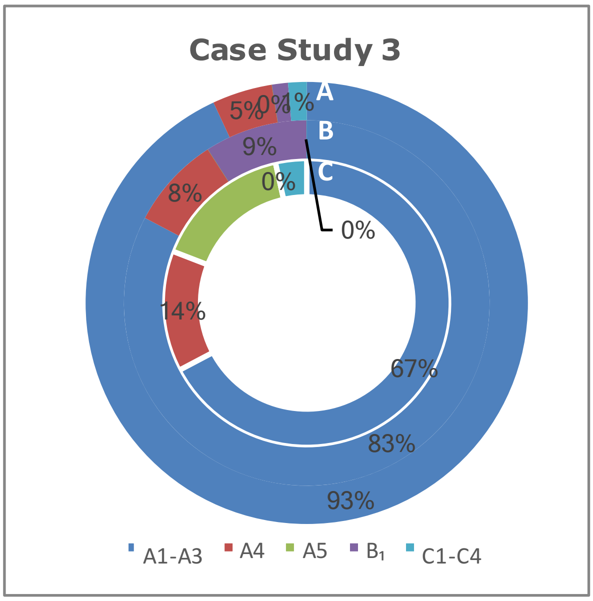
3.3 Case Study 3

Case Study 3 differs from the others as rather than a building it is an infrastructure project. As such, results for the building layers are therefore not given in this specific case. However, it is still possible to analyse the contribution of different life cycle stages as an infrastructure still follows the same production-construction-use-disposal path over its life cycle. These are given numerically in Table 5.

Table 5 - Numerical results of whole life embodied carbon for shorter and longer lifespans (CS3)

tCO_{2e}	CS3 [infrastructure]			
A1-A3	29,984	37,246	11,677	
A4	6,058	1,763	1,156	
A5	6,972	0.00	0.00	
B_1	0.00	469	1,285	Shorter lifespan
B_2	417	792	0.00	Longer lifespan
C1-C4	1,556	541	0.00	

Figure 6 shows the contribution that different life cycle stages have towards the whole life embodied carbon for CS3.



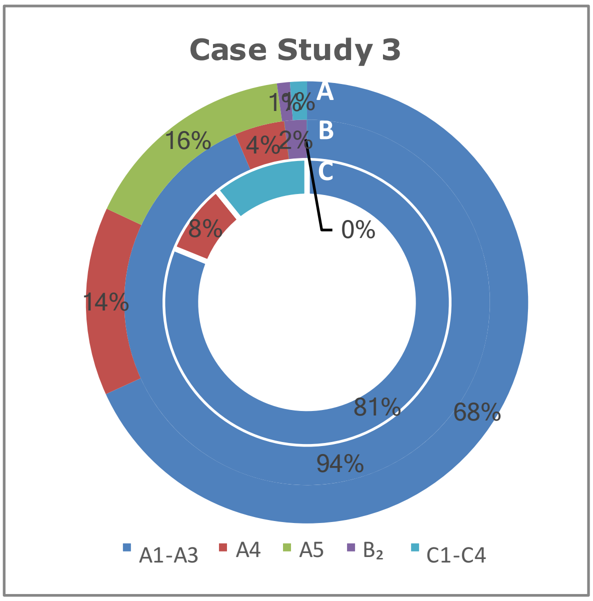


Figure 6 – Comparative results for Case Study 3 for both the shorter (left) and longer (right) lifespan

The ranges of variations across consultants are presented in Table 6 for both the shorter and longer timespans.

Table 6 – Ranges of variations for different life cycle stages (CS3)

	Shorter lifespan	**Longer lifespan**
A1-A3	67% - 93%	67% - 92%
A4	5% - 14%	5% - 13%
A5	16%	16%
B	1% - 9%	1% - 2%
C1-C4	1% - 3%	1% - 3%

It might be worth clarifying that when results for a specific life cycle stage are equal to zero it does not mean that those stages do not have an impact but simply that the consultants have not estimated it.

Results seem to vary less for the third case study, and this is probably due to a simpler assessment for an infrastructure project which is characterised by fewer materials and components, most of which are structural. Also refurbishment cycles are less relevant, and most of the maintenance is carried out on a scheduled basis which somehow facilitates its estimation. This likely reduces the uncertainty and the necessity for assumptions.

3.4 Case Study 4

Case study 4 is a new mixed use residential development, which includes not only residential units, but also commercial, educational, and industrial units and car parking. Figure 7 shows the numerical results of the embodied carbon of the different building layers.

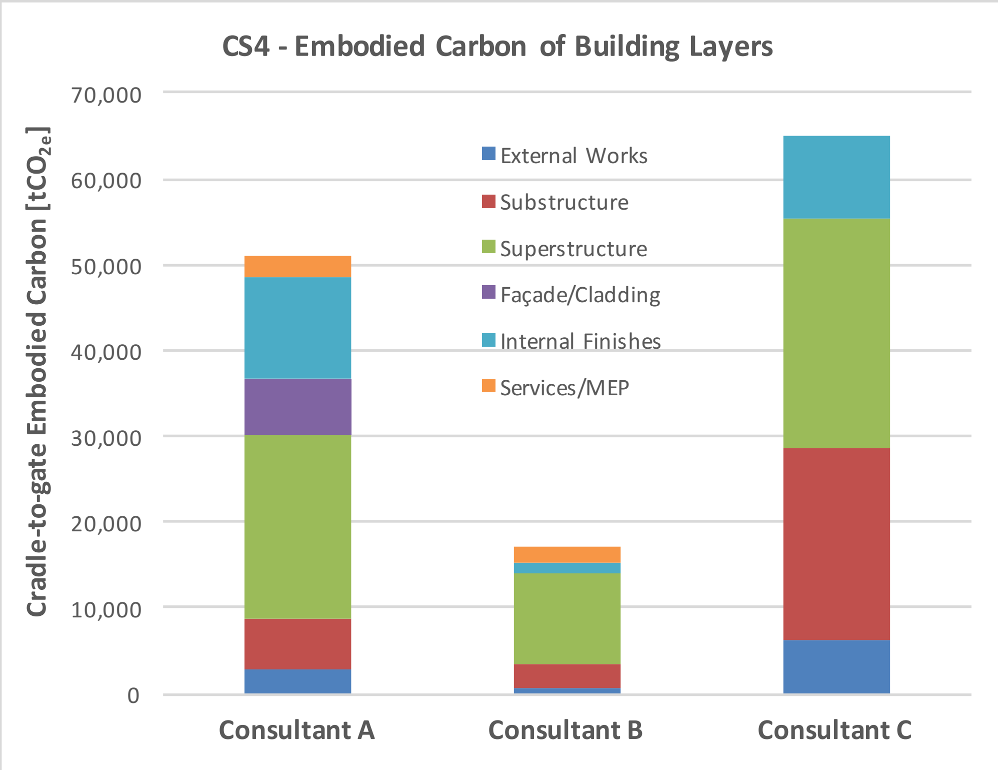


Figure 7- Embodied carbon of the different building layers (CS4)

Table 7 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered.

Table 7 - Numerical results of whole life embodied carbon for shorter and longer lifespans (CS4)

tCO_{2e}	CS4 [residential]			
A1-A3	34,023	45,992	17,155	
A4	2,162	2,192	2,616	
A5	1,320	617	300	
B_1	6,067	4,307	881	Shorter lifespan
B_2	13,531	19,174	2,048	Longer lifespan
C1-C4	2,991	1,872	264	

Figure 8 shows the results for the fourth case study (CS4) of the contribution of the different life cycle stages. The range of variations for the impacts of different life cycle stages are shown in Table 8.

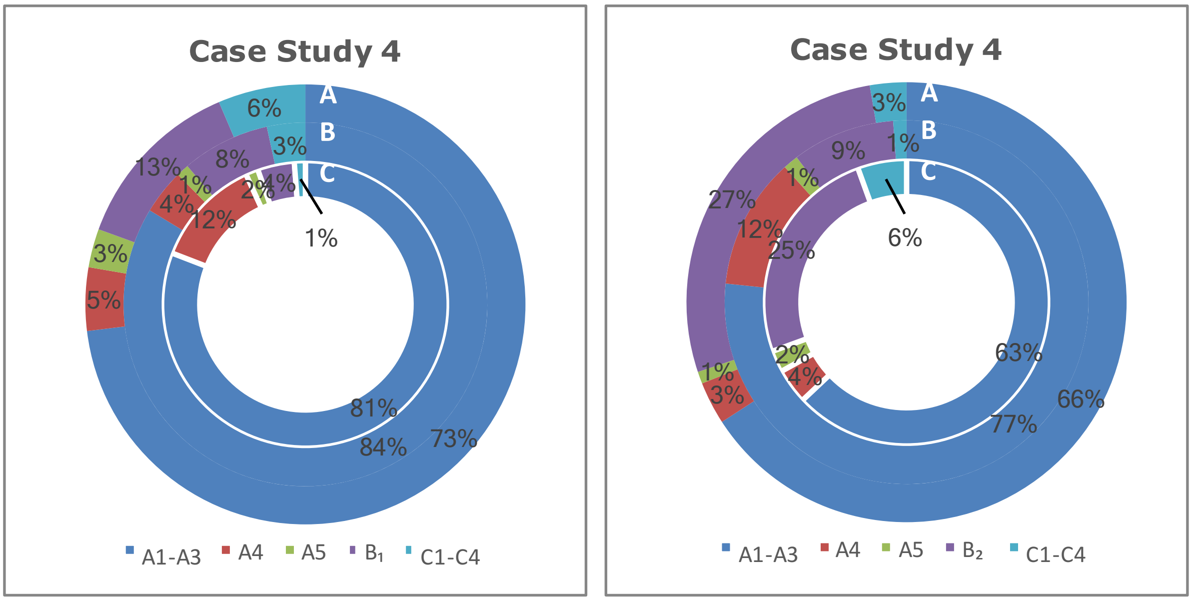


Figure 8 – Comparative results for Case Study 4 for both the shorter (left) and longer (right) lifespan

Table 8 – Ranges of variations for different life cycle stages (CS4)

	Shorter lifespan	**Longer lifespan**
A1-A3	73% - 84%	63% - 77%
A4	4% - 12%	3% - 12%
A5	1% - 3%	1% - 2%
B	4% - 13%	9% - 27%
C1-C4	1% - 6%	1% - 6%

For the fourth case study the results still show noteworthy variation but less than CS1 and CS2. Even in such case though, impacts for stages other than A1-A3 represent significant percentages reinforcing the need for a complete whole life assessment.

3.5 Case Study 5

Case Study 5 is a new retail building with multiple stores and car parks. Similar to all other case studies the consultants received the bill of quantities and technical drawings, which formed the basis for their assessments. Figure 9 shows the results for the cradle-to-gate emissions of the different building layers.

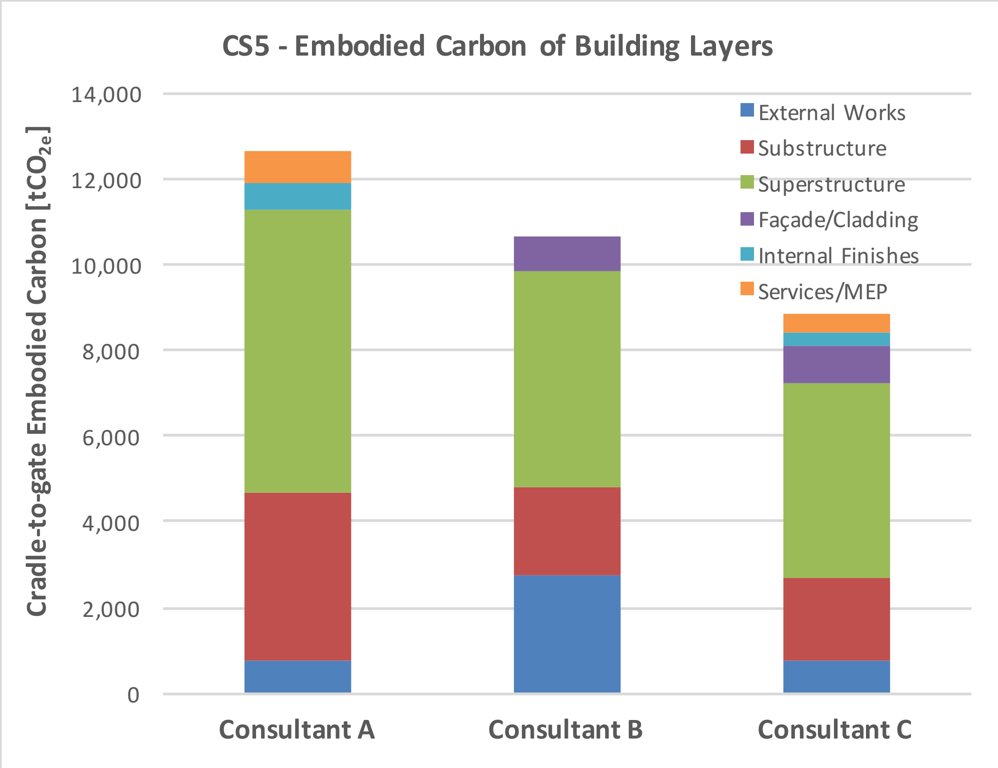


Figure 9 - Embodied carbon of the different building layers (CS5)

Table 9 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered.

Table 9 - Numerical results of whole life embodied carbon for shorter and longer lifespans (CS5)

tCO_{2e}		CS5 [retail]		
A1-A3	8,872	9,220	12,971	
A4	942	806	1,092	
A5	1,080	2,288	190	
B_1	0.00	766	569	Shorter lifespan
B_2	934	3,165	1,323	Longer lifespan
C1-C4	1,807	1,248	117	

Figure 10 gives the percentages of all life cycle stages towards the whole life embodied carbon. The range of variations for such percentages across the three consultants are presented in Table 10.

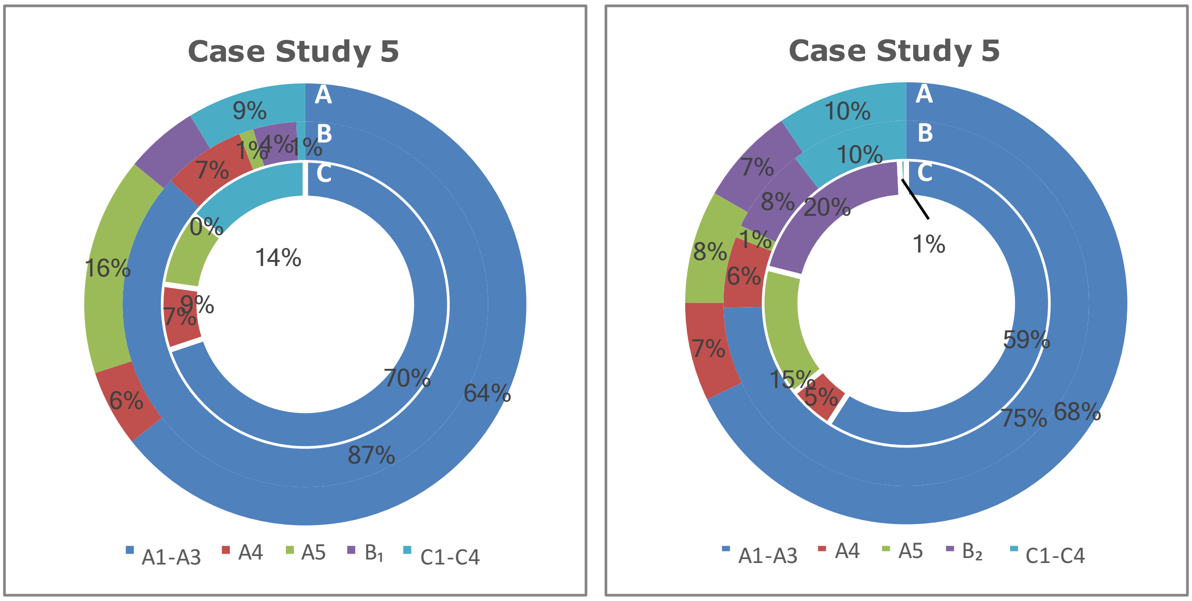


Figure 10 – Comparative results for Case Study 5 for both the shorter (left) and longer (right) lifespan

Table 10 – Ranges of variations for different life cycle stages (CS5)

	Shorter lifespan	**Longer lifespan**
A1-A3	70% - 87%	55% - 83%
A4	6% - 7%	5% - 7%
A5	1% - 16%	1% - 14%
B	4% - 5%	7% - 19%
C1-C4	1% - 14%	1% - 13%

Even the fifth case study, which was characterised by the lowest numerical variation across consultants, shows that percentages of the impacts of the different life cycle stages do vary significantly. Some consultants have indeed found that stages such as A5 and C account for as little as 1% but others have obtained much higher impact and therefore a careful assessment of those stages with the greater variation should always be undertaken.

4. Comparative overview and discussion

The previous sections of this article have extensively covered individual case studies. This section provides a comprehensive overview of the five case studies across the three consultants, and highlights the most pressing issues upon which the project has shed light. Comparative results for all case studies will be shown graphically to allow for an easier comparison of differences and similarities.

Figure 11 and Figure 12 show the absolute values for all life cycle stages of all case studies from all consultants for both the shorter and longer lifespans – respectively. Results for the second case study (refurbishment) are not really legible as they are extremely small to all others (new built). A solution could have been the use of a log scale but that would then make illegible all results for all stages subsequent to A1-A3 across all other case studies. The detailed results for CS2 can be however found in the previous sections of this article.

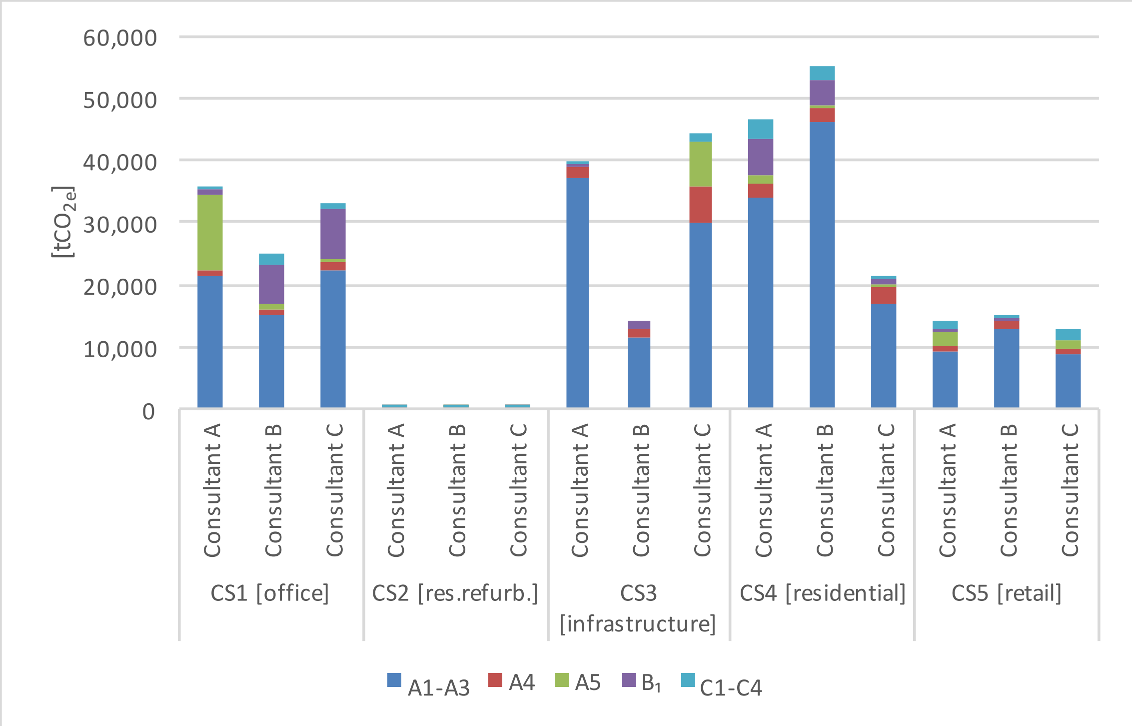


Figure 11 – Comparative view of absolute impacts [tCO_{2e}] (shorter lifespan B_1)

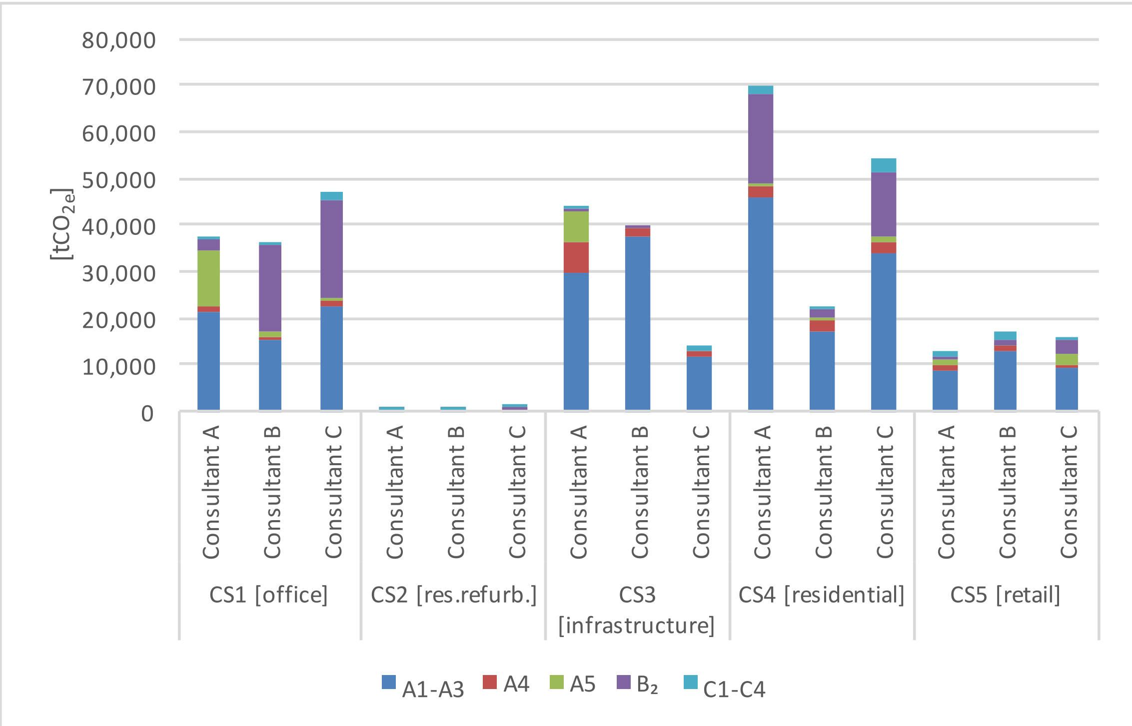


Figure 12 – Comparative view of absolute impacts [tCO_{2e}] (longer lifespan B_2)

Figure 13 and Figure 14 show the comparative overview of normalised impacts (please note that for CS3 the normalised unit is $kgCO_{2e}$/km).

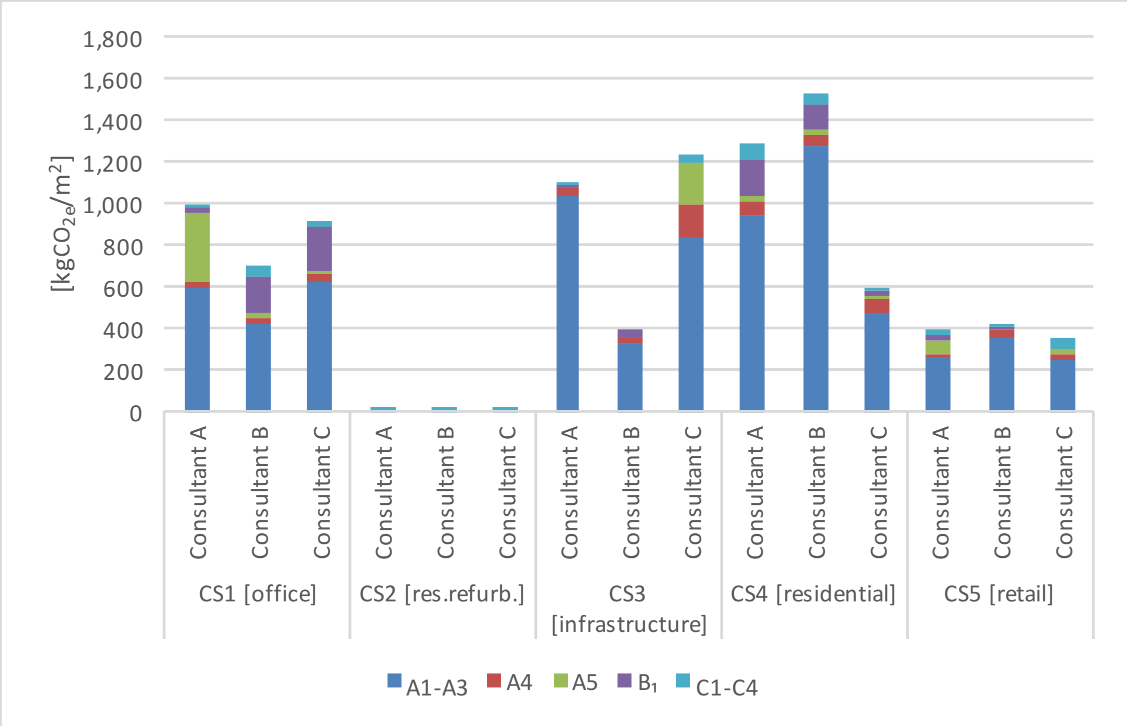


Figure 13 – Comparative view of normalised impacts [kgCO$_{2e}$/m^2] (shorter lifespan B$_1$)

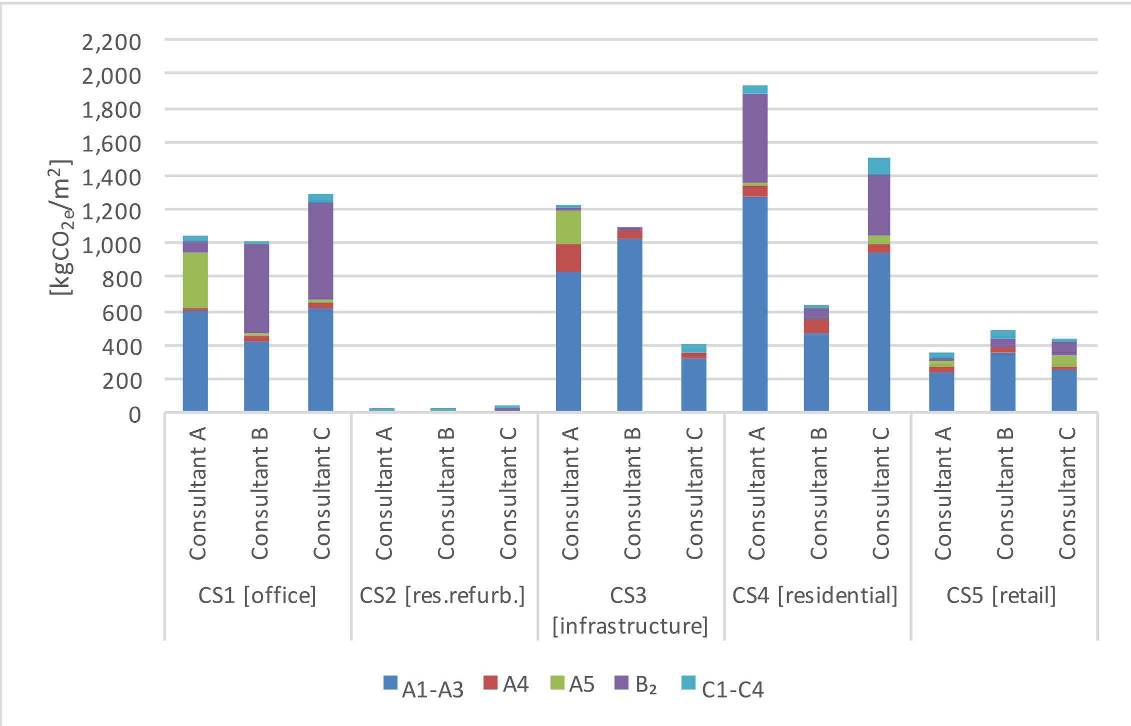


Figure 14 – Comparative view of normalised impacts [kgCO$_{2e}$/m^2] (longer lifespan B$_2$)

The projects are all individual case studies and the validity of the results in different contexts cannot be guaranteed. It is worth, however, to provide the ranges of normalised impacts for the different built assets that could serve as reference points for both academic and practitioners. These are shown in Table 10, and numbers have been rounded up to integers to avoid a false sense of accuracy given by decimal figures.

Values in [$kgCO_2/m^2$]	**Office**	**Residential refurbishment**	**Infrastructure***	**Residential**	**Retail**
A1-A3	418 –625	3 – 9	324 – 1033	476 – 1275	247 – 360
A4	26 – 35	1	33 – 168	60 – 73	23 – 31
A5	16 – 332	1 – 2	1 – 194	9 – 37	6 – 64
B	30 – 516	1 – 12	12 – 36	25 – 376	16 – 88
C1-C4	6 – 50	1	15 – 44	8 – 83	4 – 51

* Please note the normalising unit is km and not m^2 in this case.

These last four figures and the table above show very clearly that despite some agreement in the percentage of the different life cycle stages across the case studies, numerical outputs have been – at times – utterly different. Overall, several trends can be observed from the results and the comparative overview presented so far:

1. A1-A3 tends to be the life cycle stage with the highest impact. However, this is not always true as there have been exceptions in some of the case studies. It seems to average at around 60/70%, but can be as low as 40%, of the whole life carbon and therefore an A1-A3-only assessment would miss out on at least as much as one third of the whole life cycle carbon.

2. The lifespan of the building plays a determinant role. In some cases, a longer lifespan had the B stage impacts doubling, thus showing how sensitive impacts of those stages are to the time element. In addition, it occurred that impacts of the the use stage outweighed those of the product and construction stages, despite data for the B stage being scant. It would seem that this element deserves a great deal of attention and certainly further research.

3. Though some building types have shown a little less variation than others, the differences were not significant enough to conclude that certain buildings are 'harder' to assess than others. Significant variations occurred in all life cycle stages of all case studies by all consultants. The only exception is represented by the infrastructure project probably due to a bill of quantities made of fewer materials and components, most of which of a structural nature.

4. Impacts generally overlooked in embodied carbon practice and, even more, in scientific literature – such as those of A5 and C under the claim that they account for less than 1% of the whole life carbon – are instead certainly worth of assessment and further investigation. Though they seem to average at around 6/8% of the whole life carbon each, in some circumstances they were calculated to be as significant as 15%.

5. While substructure and superstructure still seem to be the building layers generally contributing the most to the cradle-to-gate embodied carbon emissions, it is also evident that other layers (e.g. façades, internal finishes, services, external works) can play a very significant role.

5. Conclusions

This article has presented the numerical results of funded research, which has seen three consultants in the UK assessing the embodied carbon of five built projects. Such a comparative insight into assessments of embodied carbon in practice is unprecedented in the academic literature, and has shed considerable light on current challenges and future needs in the field. We have shown that even with the same initial information (i.e. bill of quantities and technical drawings), all the subsequent subjective choices and assumptions that a modeller must make have a profound influence on the numerical outcome.

Considerable variation has been observed across all life cycle stages, that is, production, construction and installation, use, and end of life stage. Results have confirmed that the product stage (A1-A3) does indeed account, on average, for the most of the whole life carbon. However, a simple cradle-to-gate assessment leaves out about 30/40% of the whole life carbon emissions. As such, it is imperative that partial assessments are abandoned in favour of whole life analyses. Additionally, some life cycle stages that are generally labelled as insignificant in the scientific literature – such as construction and end of life activities – may instead account for a notable quantity of carbon emissions. This evidence should encourage the scientific community to develop more data for these stages and to consider complete life cycle assessments.

Notwithstanding the limitations, life cycle assessment (LCA) remains at present the best approach to guide towards an assessment, and a subsequent mitigation, of the carbon emissions and environmental impacts caused by buildings. This article has shed light on what the challenges are, and where the pitfalls are. Additionally, it shows where practitioners need help for more comprehensive and reliable assessments, and where academics can help.

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