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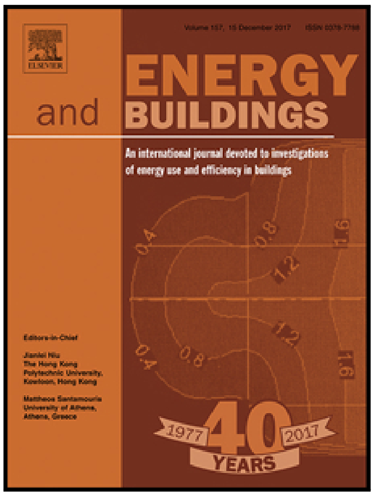

Furthering embodied carbon assessment in practice: results of an industry-academia collaborative research project

Francesco Pomponi , Alice Moncaster , Catherine De Wolf

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Highlights

- Three practitioners each assessed the embodied carbon of the same five projects
- Results show great variation across life cycle stages and component layers of buildings
- Cradle-to-gate assessments miss as much as a third of the whole life carbon
- This unprecedented approach sheds light on the need for effective collaboration between academia and industry

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

Authors: Francesco Pomponi[1*], Alice Moncaster[2] and Catherine De Wolf[3]

[1] REBEL (Resource Efficient Built Environment Lab) – Edinburgh Napier University, 10 Colinton Rd – EH10 5DT Edinburgh (UK)
[2] School of Engineering and Innovation Open University – MK6 7AA Milton Keynes (UK)
[3] EPFL – Structural Xploration Lab – CH-1015 Lausanne (Switzerland)

[*] Corresponding author: f.pomponi@napier.ac.uk

Abstract

In order to meet the mid-century carbon reduction targets and to mitigate climate change and global warming it is imperative that embodied greenhouse gases (GHGs) emissions in the built environment receive immediate attention from policy, industry and academia. While academic research has grown in recent years, the uptake of embodied carbon assessments in practice has been slower. This paper reports the findings of a collaborative project between industry and academia to shed light on how to accelerate a wider uptake of embodied carbon assessments in buildings. Five projects have been each examined by three assessors (independent environmental consultants) for a total of fifteen detailed assessments.

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 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. 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, 7]. The latter is available in many forms, such as European standards [8-10], briefings from national organisations [11, 12] and professional bodies [13], as well as publications by international teams of researchers such as those who worked on the International Energy Agency Annex 57 [14-16] and the subsequent and recently launched Annex 72 [17].

Yet, it remains very difficult to achieve a complete coverage of all life cycle stages of a building [18] and many published assessments lack the necessary transparency to fully understand system boundaries as well as modeller's assumptions [19]. Future events and decisions are characterised by high uncertainty which decreases the reliability of predictions and estimates [20] 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, 18, 19, 21], 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 [22-30]. 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 [19]. Moncaster et al. [31] 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 [32] 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 who were in charge of the embodied carbon assessments 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.

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 [33], 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 research was set up to assess five different project types at the design stage. This was to establish the extent of the influence of all inputs to and choices during an embodied carbon assessment.
The methodology developed for this research has seen three firms (i.e. environmental consultants) each assessing the same five projects starting from the same background information (i.e. bills of quantities and architectural drawings). This means that each firm produces five assessments and the total data for the project therefore resulted in 15 assessments, three for each of the five different projects. It is worth noting that the bills of quantities did vary in detail from project to project. In some occasions, for instance an adequate specification of concrete mixtures (e.g. RC 40 MPa with 20% PFA) was given where in others the descriptors were rather generic which necessarily implied the need to make assumptions by the assessors.

A further element of analysis was the useful lifespan of the built assets that was considered in the assessment. To account for the uncertainty of future events, each of the projects was characterised with two values: one for a shorter lifespan (SL) and a second for a longer lifespan (LL). The five projects cannot be fully disclosed to retain the anonymity of the data providers but relevant information is presented in Table 1.

Table 1 - Details of the five projects that have all been assessed by the three firms

Project Reference	*Location*	*Type*	*Further details*	*SL*	*LL*
1	London	Office building	17 storeys + 2 underground, steel frame with concrete core, curtain wall cladding	30 years	60 years
2	London	Residential refurbishment	6 storeys, floor area ~ 500m^2 , masonry with steel framing, brick cladding	60 years	100 years
3	UK	Transport infrastructure	Concrete decks, pier, and pile caps – Assessment normalised to distance units	60 years	100 years
4	UK	Residential	Large development with more	30	60

			than 300 new homes for a total of ~ 30,000m^2 of Gross Internal Area (GIA)	years	years
5	UK	Retail	Large shopping centre, 2 storey, precast concrete structure, lime-hemp wall with stone finishing	30 years	60 years

It was agreed that consultants would use the BS EN 15978 standard [10] and its proposed division for the life cycle stages (Figure 1), and that they would be based on the consultants' current practice.

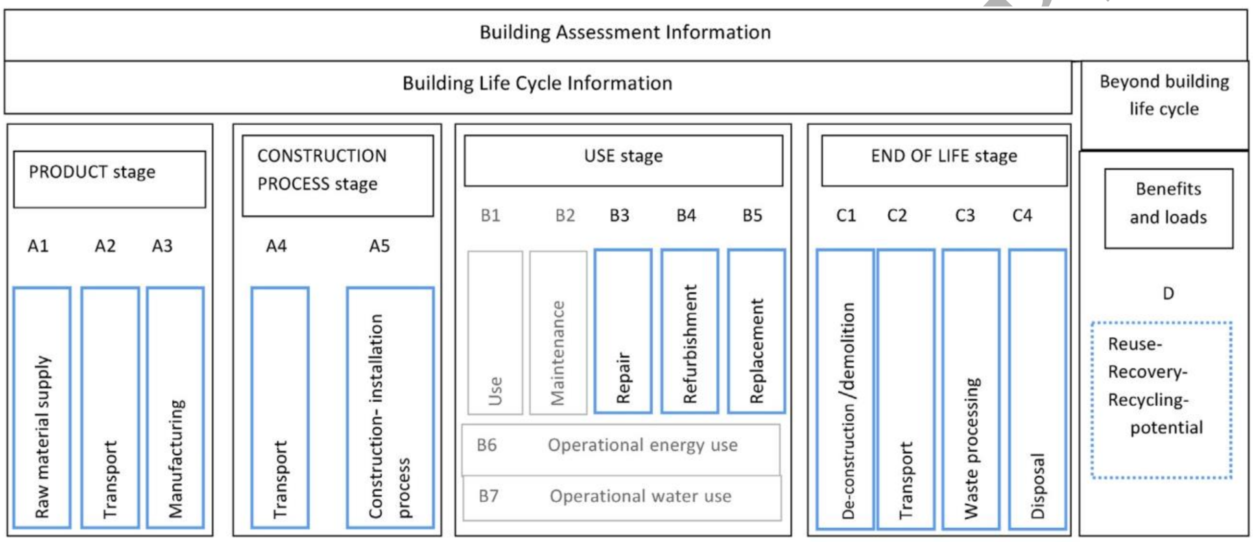

Figure 1: Life Cycle Stages [34]

A pre assessment on a further project was conducted in March 2016 to evaluate the most notable differences amongst consultants and allow for an easier comparison of all subsequent projects.
The assessments of the five projects by each of 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 assessment 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 projects was aimed at covering a broad range of built assets. For this reason, detailed results on each of the five projects are presented in turn in the following subsections, before being comparatively discussed in Section 4.

3.1 Project 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 2 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.

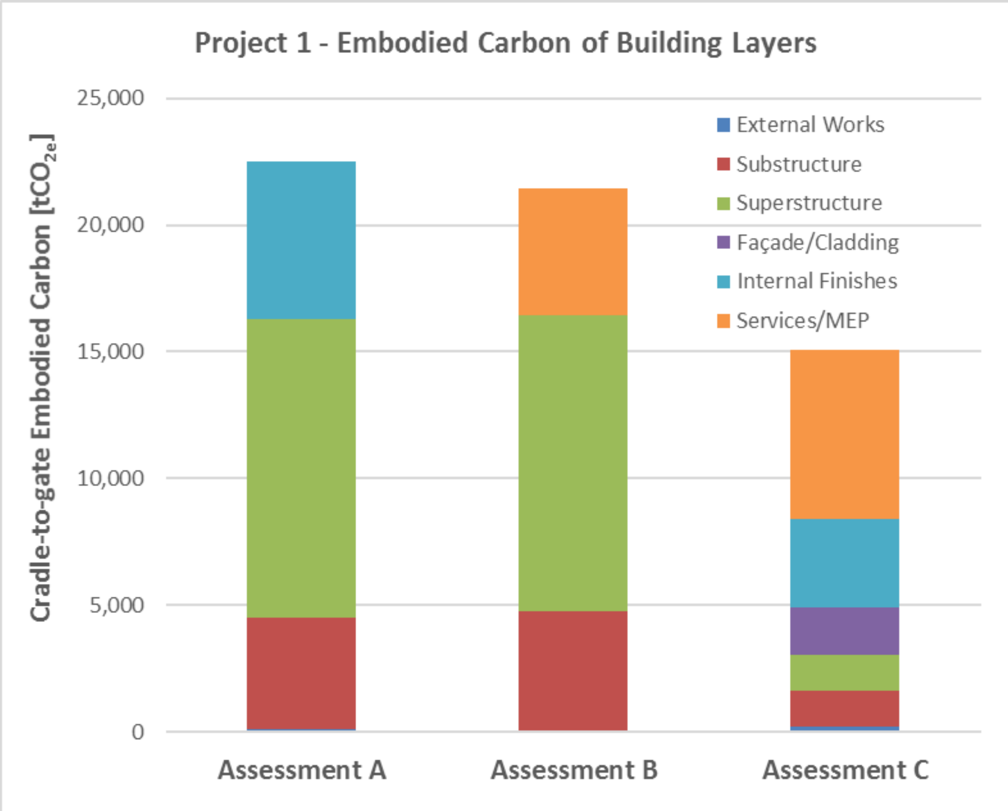

Figure 2 - Embodied carbon of the different building layers for the first project (P1)

Table 2 - Numerical results of whole life embodied carbon for shorter and longer lifespans for the first project (P1)

tCO_{2e}		P1 [office]		
A1-A3	15,061	22,529	21,429	
A4	1,099	1,241	932	
A5	980	557	11,956	
B STAGE	6,257	7,799	1,059	Shorter Lifespan (SL)
B STAGE	18,603	20,747	2,460	Longer Lifespan (LL)
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. The range of variations for the impacts of different life cycle stages are shown in Table 3.

Table 3 – Ranges variations for different life cycle stages for the first project (P1)

	Shorter lifespan (SL)	**Longer lifespan (LL)**
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 [18].

3.2 Project 2

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

Similarly to the previous project, Figure 4 shows the numerical results of the embodied carbon of the different building layers, while Table 4 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 project to refer to the three firms do not match the letters used in Project 1.

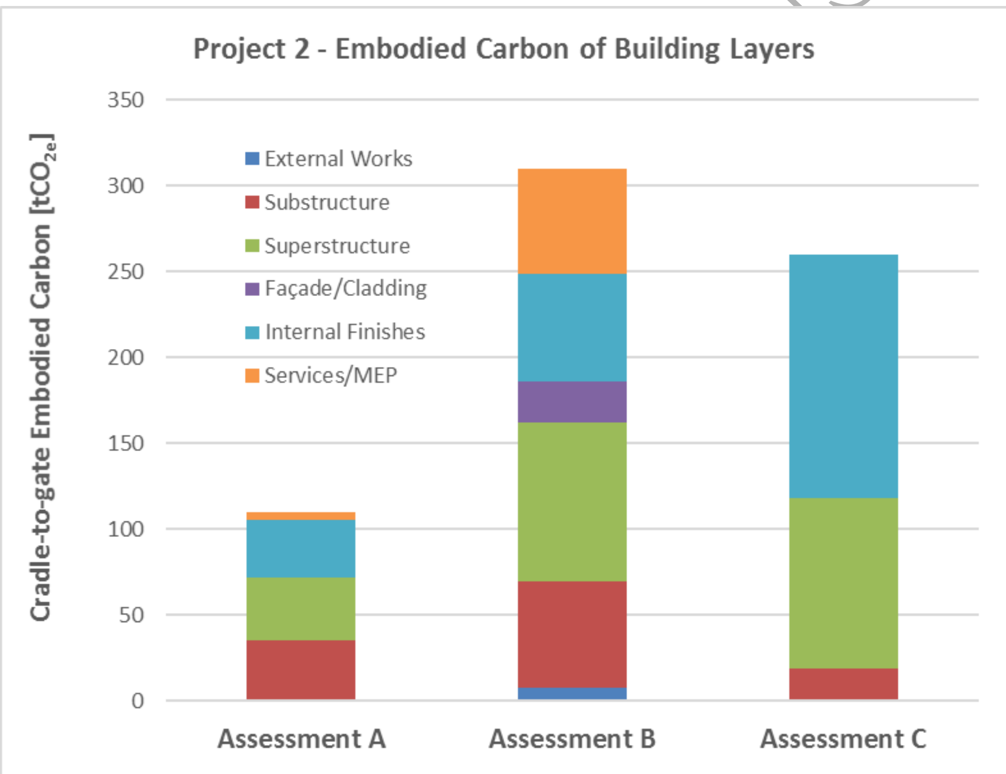

Figure 3 - Embodied carbon of the different building layers for the second project (P2)

Table 4 - Numerical results of whole life embodied carbon for shorter and longer lifespans for the second project (P2)

tCO_{2e}	P2 [residential refurbishment]			
	Ass. A	Ass. B	Ass. C	
A1-A3	309.89	259.54	109.69	
A4	11.25	3.32	0.55	
A5	49.15	5.04	4.05	
B	0.00	70.98	12.75	Shorter Lifespan

STAGE				(SL)
B STAGE	409.56	202.97	29.61	Longer Lifespan (LL)
C1-C4	35.29	7.95	2.43	

The ranges of variations across consultants are presented in Table 5.

Table 5 – Ranges of variations for different life cycle stages for the second project (P2)

	Shorter lifespan (SL)	**Longer lifespan (LL)**
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 project 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 Project 3

Project 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 6.

Table 6 - Numerical results of whole life embodied carbon for shorter and longer lifespans for the third project (P3)

tCO_{2e}	P3 [infrastructure]			
A1-A3	29,984	37,246	11,677	
A4	6,058	1,763	1,156	
A5	6,972	0.00	0.00	
B STAGE	0.00	469	1,285	Shorter lifespan (SL)
B STAGE	417	792	0.00	Longer lifespan (LL)
C1-C4	1,556	541	0.00	

The ranges of variations across consultants are presented in Table 7 for both the shorter and longer timespans.

Table 7 – Ranges of variations for different life cycle stages for the third project (P3)

	Shorter lifespan (SL)	**Longer lifespan (LL)**

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 in Table 7 seem to show that numerical variation for the third project are less than those for the previous two, 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 Project 4

Project 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.

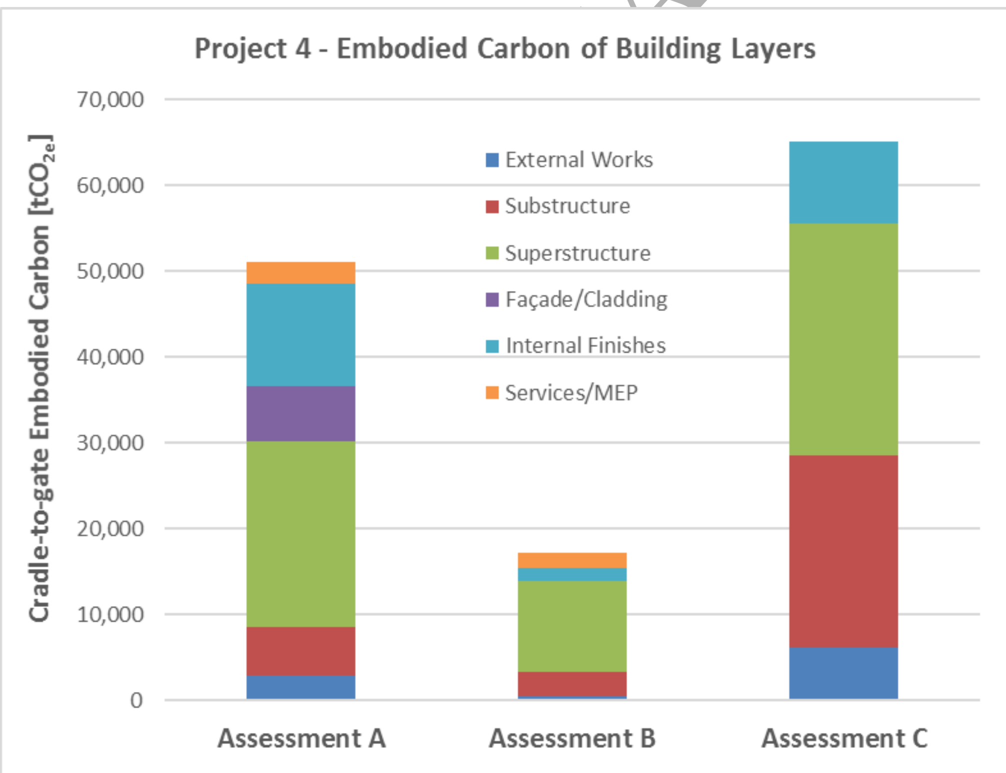

Figure 4- Embodied carbon of the different building layers for the fourth project (P4)

Table 8 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered.

Table 8 - Numerical results of whole life embodied carbon for shorter and longer lifespans for the fourth project (P4)

tCO_{2e}	P4 [residential]			
A1-A3	34,023	45,992	17,155	
A4	2,162	2,192	2,616	
A5	1,320	617	300	
B STAGE	6,067	4,307	881	Shorter lifespan (SL)
B STAGE	13,531	19,174	2,048	Longer lifespan (LL)
C1-C4	2,991	1,872	264	

The range of variations for the impacts of different life cycle stages are shown in Table 9.

Table 9 – Ranges of variations for different life cycle stages for the fourth project (P4)

	Shorter lifespan (SL)	**Longer lifespan (LL)**
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 project the results still show noteworthy variation but less than P1 and P2. 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 Project 5

Project 5 is a new retail building with multiple stores and car parks. Similar to all other projects 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.

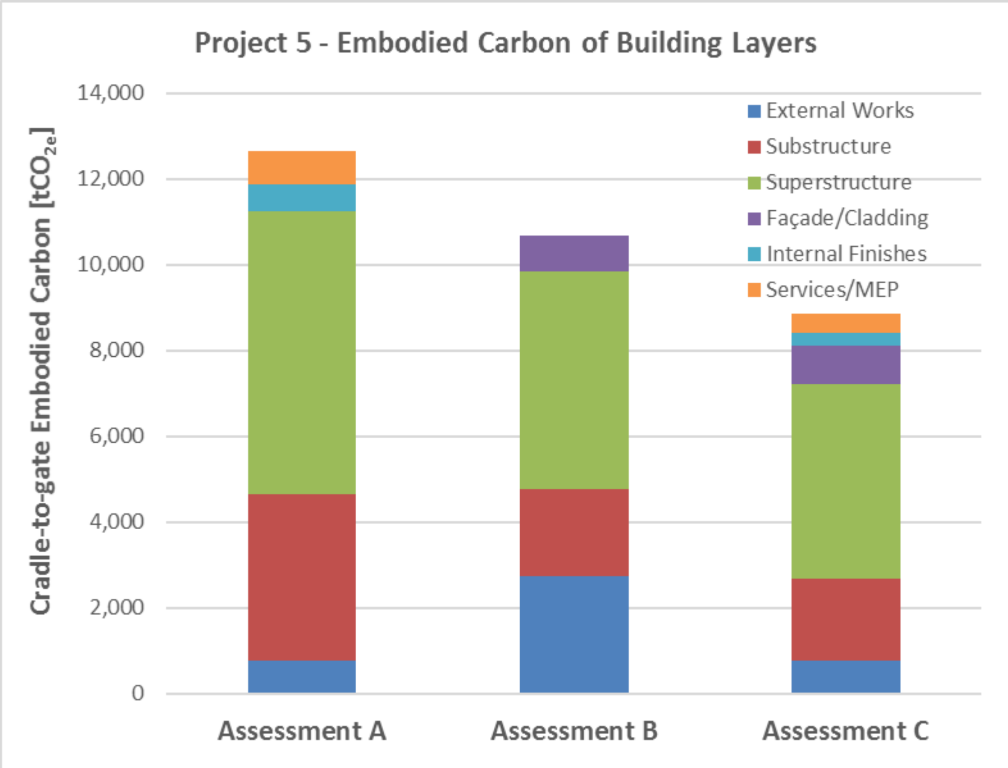

Figure 5 - Embodied carbon of the different building layers for the fifth project (P5)

Table 10 gives the numerical results of the whole life embodied carbon emissions across all life cycle stages and for both timespans considered.

Table 10 - Numerical results of whole life embodied carbon for shorter and longer lifespans for the fifth project (P5)

tCO_{2e}		P5 [retail]		
A1-A3	8,872	9,220	12,971	
A4	942	806	1,092	
A5	1,080	2,288	190	
B STAGE	0.00	766	569	Shorter lifespan (SL)
B STAGE	934	3,165	1,323	Longer lifespan (LL)
C1-C4	1,807	1,248	117	

The range of variations for such percentages across the three consultants are presented in Table 11.

Table 11 – Ranges of variations for different life cycle stages for the fifth project (P5)

	Shorter lifespan (SL)	**Longer lifespan (LL)**
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 project, 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 projects. This section provides a comprehensive overview of the five projects across the three consultants, and highlights the most pressing issues upon which the project has shed light. Comparative results for all projects will be shown graphically to allow for an easier comparison of differences and similarities. However, it is important to first analyse the different data used by the three firms in each of the five assessments as this aspect might reveal the causes for either discrepancies or similarities in the assessment. This meta-analysis is shown in Table 12.

Table 12 - Meta analysis on the data used in each of the assessment to determine the whole life carbon

Life Cycle Stages (BS EN 15978)	**Project 1 (3 assessors)**			**Project 2 (3 assessors)**			**Project 3 (3 assessors)**			**Project 4 (3 assessors)**			**Project 5 (3 assessors)**		
A1 [Raw material supply] A2 [Transport] A3 [Manufacturing]	1, 2	1, 2	1, 2, 3	1, 2	1, 2	1, 2, 3	1	1	1, 3	1	1	1, 3	1	1	3
A4 [Transport]	4, 7	4, 7	4, 5, 7	4, 7	4, 7	4, 5, 7	4, 7	4, 7	4, 7	4, 7	4, 7	4, 5, 7	4, 7	4, 7	4, 5, 7
A5 [Construction processes]	5, 6, 7, 10	4, 5, 7	5, 7	5, 6, 7, 10	7	5, 7	5, 6, 7, 10		7	5, 6, 7, 10	4, 5, 7	4, 5, 7	5, 6, 7, 10	4, 7	4, 5, 7
B1 [Use]															
B2 [Maintenance]	7, 8						7, 8			7, 8			7, 8		
B3 [Repair]															
B4 [Refurbishment]	7, 8	8	8	7, 8	8	8	7, 8	8	8	7, 8	8	7	7, 8	8	9
B5 [Replacement]			8			8						7			9
C1 [Deconstruction/ demolition]			7			7	9					7	9		7
C2 [Transport]	7	9	7	7	7	7	9	7		7	7	7	9	7	7
C3 [Waste processing]			7			7	7					7	7		7
C4 [Disposal]			7			7	7					7	7		7
D [Beyond life cycle]															

Notes:

1 = ICE | 6 = Environmental Agency Tool
2 = EPDs | 7 = Empirical factors/formulas (referenced and/or internal)
3 = Hutchins | 8 = Replacement rates (BCIS, RICS NRM 3, empirical)
4 = DEFRA | 9 = Percentages of WLC or other life cycle stages
5 = WRAP | 10 = Cost based method

It can be seen that whilst there are of course some differences in the data sources, there is also a remarkable consistency in either the databases used or the approaches followed. It should also be remembered that the three consultants were given the same initial information (i.e. bill of quantity) for each of the five projects prior to commencing their assessments.

Figure 11 and Figure 12 show the absolute values for all life cycle stages of all projects from all consultants for both the shorter and longer lifespans – respectively. Results for the second project (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 projects. The detailed results for P2 can be however found in the previous sections of this article.

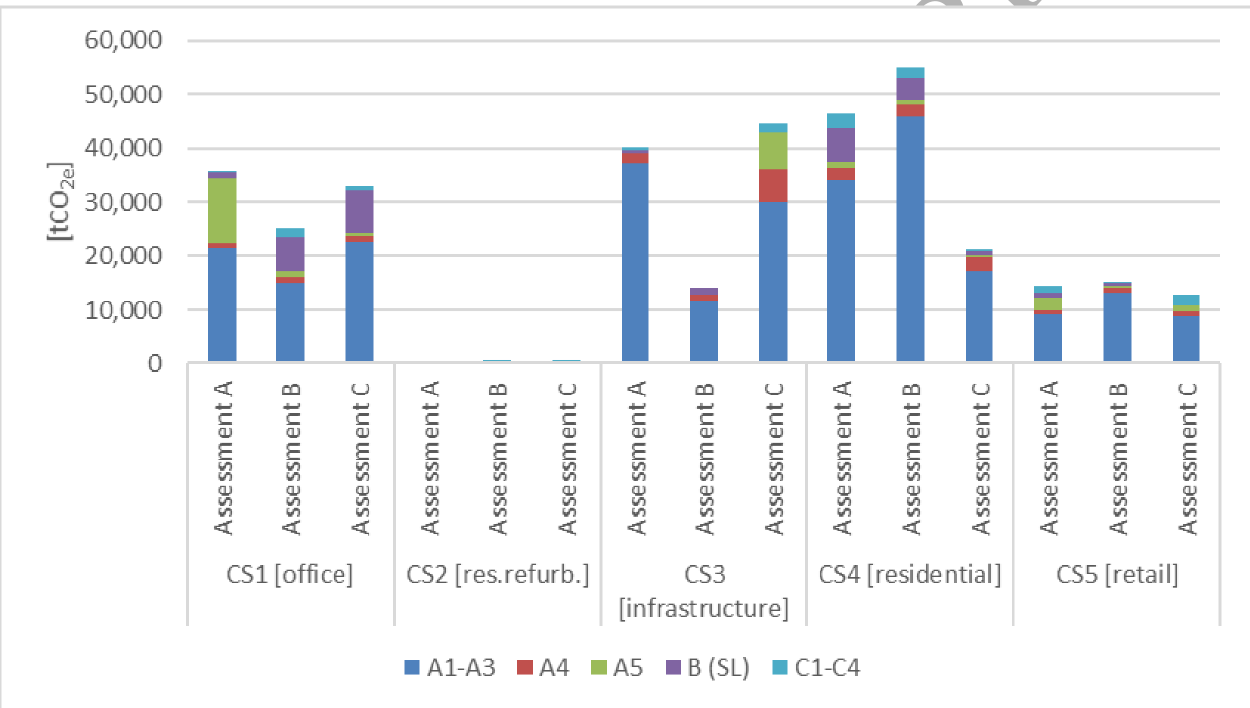

Figure 6 – Comparative view of absolute impacts [tCO_{2e}] (shorter lifespan BSL)

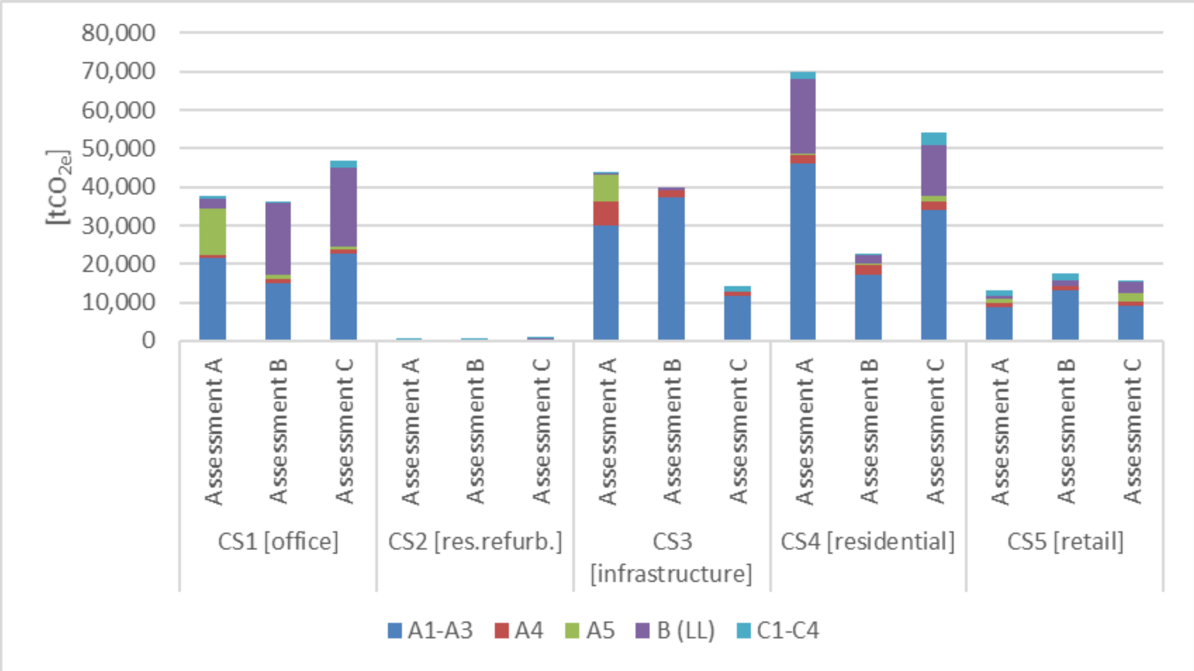

Figure 7 – Comparative view of absolute impacts [tCO_{2e}] (longer lifespan B LL)

Figure 13 and Figure 14 show the comparative overview of normalised impacts (please note that for P3 the normalised unit is $kgCO_{2e}/km$).

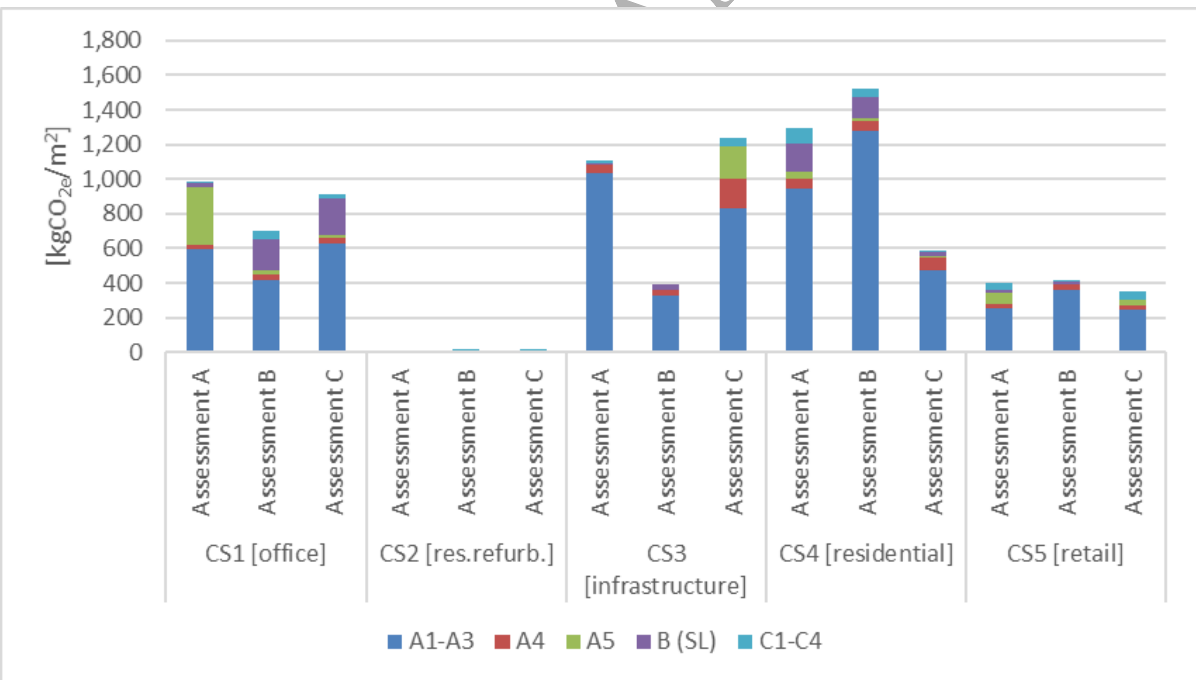

Figure 8 – Comparative view of normalised impacts [$kgCO_{2e}/m^2$] (shorter lifespan B SL)

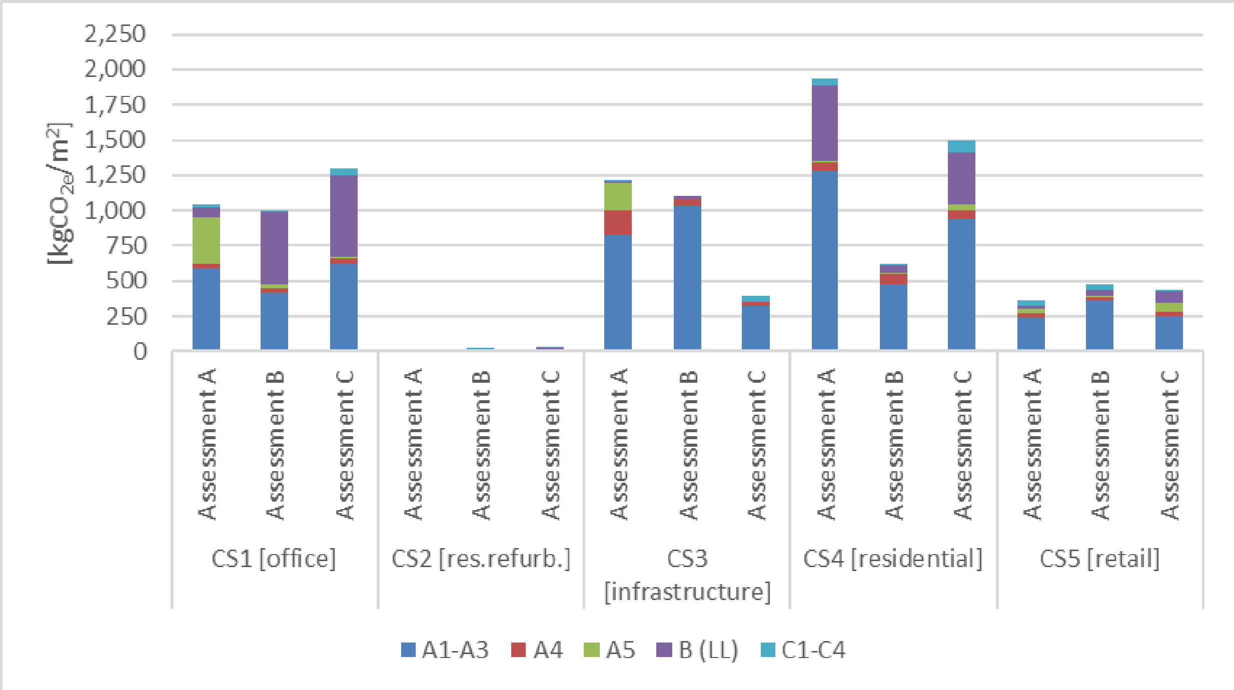

Figure 9 – Comparative view of normalised impacts [$kgCO_{2e}/m^2$] (longer lifespan B LL)

The projects are all individual and the validity of the results in different contexts cannot be guaranteed. In some cases the results for a specific life cycle stage are equal to zero but that does not mean that those stages do not have an impact, rather that the consultants simply have not estimated it. This is a boundary difference which means that the assessments of the projects are not exactly a like-for-like comparison and this certainly has an implication on the comparability of results. However, what we aimed to show is that even with the same exact initial information and very similar background data and data sources, results can still vary significantly due to the subjective choices that the assessors must make throughout the project. These might be due to lack of detailed specification in the bill of quantities for instance, or wrong perception about the significance of a specific element/life cycle stage that is excluded. This represents an important and necessary avenue for further work.

Additionally, even with the same data sources and initial information on quantities results can still vary due to a number of reasons. One such example is the recycled content of metals, whereby 1 kg of virgin steel has an average embodied carbon content of 2.113 $kgCO_{2e}$ which drops to 0.462 $kgCO_{2e}$ when 1 kg of recycled steel is considered [2]. Similarly, assumptions over carbon sequestration for natural materials – most notably timber – can also influence, and skew, results significantly.

Some life cycle stages further add to the variation in results as they are characterised by high variation due to the lack of enough information. The construction phase (A5) is one of these as it can be seen from the broad range of methods used in its estimation (Table 12). A5 is also often the stage where construction waste is estimated and accounted for (although in some assessments this was temporally shifted to the end of life stage). Bills of Quantities (BoQs) do not generally consider any construction waste and therefore it falls again on the modeller to make educated guesses.

As far as BoQs are considered, they sometimes lacked enough specification for key materials. For instance, there have been cases in which a loose specification of 'reinforced concrete' was given. However, this did not provide adequate specification over which concrete mix should actually be used, and again modellers' choices could likely produce a significant variability in the results.

Lastly, a further element of variation is to be found in the building layers considered by the assessors. This information is shown graphically in the bar charts for each project but can also be found summarised with more details in Table 13.

Table 13 - Comparison of the building layers considered by the assessors across all five projects

Categories	**Project 1**			**Project 2**			**Project 3**			**Project 4**			**Project 5**		
	3 assessors			3 assessors			3 assessors			3 assessors			3 assessors		
External Works	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
Substructure	✓	✓[3]	✓	✓	✓[3]	✓	✓	✓[3]	✓	✓	✓[3]	✓	✓	✓	✓
Superstructure	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Façade / Cladding	✓	[1]	[1]	✓	[1]	[1]		[1]		✓	[1]	[1]	✓	✓	
Internal Wall and Partitions	[2]	✓		[2]	[4]			[4]	✓[2]	[2]	[4]	[2]	✓	✓	✓
Fittings and Furnishing	✓			✓	[4]	✓		[4]	✓	✓	[4]	✓			✓
Services / MEP	✓		✓	✓	[4]	✓		[4]	✓	✓	[4]	✓	✓	✓	✓

Notes: [1] considered in superstructure, [2] this category is sometimes labelled as internal finishes, [3] foundations considered as a separate category from substructure, [4] considered in Fit-Out as a further, separate category

Despite the variation in the results, 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 14, and numbers have been rounded up to integers to avoid a false sense of accuracy given by decimal figures.

Table 14 – Normalise values divided according to life cycle stages and project types.

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 projects, 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 projects. 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 projects 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. Specifically, façades can make up as much as 12% of the total carbon (P1), internal finished up to 45% (P2), services up to 44% (P1), and external works up to 25% (P5).

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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