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Scrutinising embodied carbon in buildings: The next performance gap made manifest



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ABSTRACT

Life cycle assessment (LCA) is becoming increasingly mainstream as an early-stage design-decision tool for buildings. Still, there are considerable variations in how the method is currently used, leading to limitations in comparing the results and the conclusions that can be drawn. These variations are due to several factors and LCA modellers must make multiple methodological decisions during an assessment. This has resulted, unsurprisingly, in a variety of approaches, and a wide range of outcomes. Academics have produced numerous case studies on particular buildings, aiming towards a detailed understanding of the energy and carbon impacts. However, very few case studies are detailed enough to allow for an in-depth comparison. This article investigates in detail these embodied carbon assessments, considering the data used and the methodological assumptions made. An in-depth analysis shows that there are still considerable variations in how the methodology is applied, leading to substantial limitations in comparing results and drawing conclusions. Results may differ by two orders of magnitude, thus limiting the understanding of how real mitigation might best be achieved. Without immediate action, embodied carbon will become a ‘second wave’ of performance gap in environmental assessments of buildings. Both greater transparency and greater conformity must be embraced by the LCA community and enforced by policymakers and professional bodies.

1. Introduction

The importance of the impacts of the built environment on global greenhouse gas emissions is undisputed. The impacts of buildings in particular can be considered in two distinct but inter-related divisions; those due to the operation of the building (lighting, heating and so on), and those due to the physical construction of the buildings (including processing of materials and material waste and their transport, assembly and disassembly).

Since the start of this century there has been a considerable political focus on reducing the first of these, the operational energy and carbon of buildings, through for instance the enacting of the EU Energy Performance of Buildings Directive [1] and its enforcement via national building regulations. This has led to the encouragement of specific design measures including higher levels of fabric insulation and increasing uptake of on-site low carbon energy technologies. The

impact on the building industry has been significant, with new processes and materials and even new professions emerging as a result.

While operational impacts have indeed reduced, however a significant ‘performance gap’ between the modelled and the actual values from occupied buildings has become apparent. The extent of this gap was one of the most important findings in built environment research at the start of this century see, for instance, [2] and its discovery has resulted in expanded efforts to identify the reasons behind it. The application of the now well-known concept of the ‘rebound effect’ to the energy performance of buildings [3], later followed by the development of the idea of the ‘prebound effect’ [4], demonstrate the developing maturity of academic research in this area, which is helping the move towards increased actual reductions in operational energy.

The original regulatory focus on operational impacts was justified by the assumption that they were highly dominant; however, increasingly detailed calculations over the last decade have shown that

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embodied carbon¹ and energy make up a significant proportion of whole life impacts of buildings e.g. [5–12]. With the increasing move towards nearly zero energy buildings (NZEBs), both the relative and the actual extent of these impacts is likely to increase [13]. It is becoming increasingly obvious, therefore, that attention must now turn to first calculating, and then reducing the embodied impacts of buildings. As a first step towards this end, the European Committee for Standardisation (CEN) published three key standards in 2011 and 2012 (Fig. 1) [14–16] formalising the methodology for calculating whole life impacts of buildings and other construction works.

However although the new standards provide a rigorous methodology they do not dictate its use. An international assessment of 80 recent building case studies from around the world [17–19] has demonstrated the continuing variability in approach. Developed for different purposes, conducted by authors from different disciplinary backgrounds, and using different data and assumptions, drawing coherent conclusions from multiple studies remains extremely difficult. Furthermore the calculations carried out at design stage are often very different to the actual embodied impacts of the building. This second performance gap appears to be significant, and should be of grave concern.

Industry is keen to see embodied impacts included in building regulations (see for example the UK Green Building Council activities [20,21] in this area). The recognition of a gap between modelled and actual embodied impacts should serve as a catalyst to develop increasing research to support this desire as it has with operational impacts. Instead, the variation in and complexity of the calculations, and the subsequent plethora of results, seems to have had the opposite effect. No building regulations in Europe yet require reduction of embodied energy or carbon, and the variation in the calculations is used as an excuse for their continued exclusion [22].

It is crucial for the academic community to work together to produce a detailed understanding of this area, and of the multiple reasons for the gap between embodied carbon modelled at the design stage and that emitted in reality. To this end this paper provides a meta analysis of studies published since the publication of the TC350 standards in 2011. By comparing both the approaches and data used by the different authors for different phases of the life cycle of the buildings, the paper reveals the wide variation in methodological choices, and sheds light on the reasons behind the various results.

With increased knowledge it is hoped that Governments will be encouraged to support appropriate regulations for an effective design-stage approach, not currently offered by the TC350 standards, which will both reduce the gap between calculated and actual embodied emissions, and produce the rapid increase in reduction needed.

2. Previous studies

Life cycle assessments of conventional, low-energy and low-carbon buildings have been subjected to academic reviews on several occasions over the last decade.

Sartori and Hestnes [23] reviewed 60 cases from nine countries, and found a quasi-perfect linear correlation (i.e. an R^2 coefficient close to 1) between operational energy and whole life energy, which was valid across climates and other contextual differences. At the time of their review, however, embodied energy and carbon were seldom assessed and generally disregarded under the belief that their share of the whole

life figures would be negligible. It was also noted that measures targeted at reducing operational side have often a negative impact (increase of emissions) on the embodied side [23]. This particular aspect resurfaced more recently e.g. [13,24] and it is growingly becoming of great concern – especially since the focus of current regulations remains on operational energy and carbon of buildings. Ramesh et al. [25] also undertook a review of case studies, totalling 73 cases from 13 countries. Their work is also solely focused on energy, and not carbon, of buildings, and – similarly to Sartori and Hestnes [23] – they also found that operational energy accounts for 80–90% of the whole life energy, and that measures aimed at its reduction might be counterproductive from a whole life perspective [25].

The review from Dixit et al. [26] also focused on embodied energy, embodied carbon being not yet a widespread concept in 2010. They reviewed the then available scientific literature, highlighting the inaccuracy and unreliability of energy data that led to incomplete and incomparable assessments. Their work identified a set of parameters that, if addressed and adopted by scholars, could reduce variability or at least harmonise terms and definitions within the field [26]. Such focus on parameters was also part of a follow-on work of the authors [27] two years later, which updated the list of parameters and, again, called for harmonisation, and globally accepted protocols and guidelines. Though the sector has certainly moved forward, harmonised global approaches are yet to be reached [28].

It was Moncaster and Song [29] who first reviewed in detail existing data and methodologies in terms of embodied carbon and not just embodied energy. Their study coincided with the final stages of the development of the new standards produced by the European Committee for Standardisation Technical Committee 350 (CEN/TC 350), which perhaps are the most comprehensive set of tools to calculate and evaluate sustainability of buildings [15,16,30]. Moncaster and Song [29] found for embodied carbon issues similar to those identified for embodied energy, such as variability and unreliability of data, incomparability of results, and the need for consistent and transparent databases and methodologies. Cabeza et al. [31] also focused on embodied carbon in their literature review, though their focus was at the material level and not concerned with whole buildings. Their study drew attention on the still very debated field of low carbon materials since it included cement, concrete and bricks as well as wood and rammed earth [31]. Their review looked at how the embodied energy and carbon of such materials can be reduced but ignored the great variability, and the potential reason for it, of the numbers utilised in the assessments.

Pomponi and Moncaster [28] systematically reviewed the literature on embodied carbon in buildings from the past ten years in order to identify mitigation strategies and to conduct a ‘health check’ of LCAs of buildings. They found that the vast majority of LCAs show an incomplete and short-sighted approach to life cycle studies. Over 90% of the LCA studies reviewed only look at the manufacturing stage whereas just over 50% go up to the end of the construction stage, with future activities and impacts mostly neglected – in particular the embodied impacts related to the use stage [28]. Their review highlights the importance that various actors of the built environment, and their mutual collaboration, play in ensuring that knowledge on embodied carbon can be rapidly advanced. Lately, Anand and Amor [32] have reviewed recent developments and future challenges in LCAs of buildings based on the decennial environmental management and life cycle standards of the 14,000 series [33,34]. They have found that the main issues still lie with the comparability of the studies, the system boundaries, and the data used in the assessment both in terms of sources and collection procedures used [32]. Similar to Pomponi and Moncaster [28], Anand and Amor [32] also call for further developments of industry/academia collaborations to address the gaps in many of the areas identified.

While most of these existing studies offer valuable insights into the current issues of embodied carbon and explain the potential reasons

¹ Embodied carbon is a shorthand for embodied greenhouse gas emissions, calculated as ‘embodied carbon equivalent’ and measured in kgCO_2e , which includes carbon dioxide emissions plus all other greenhouse gases normalised to the equivalent amount of carbon dioxide which would produce the same global warming potential over a 100-year period. The term ‘carbon’ is used throughout the paper to mean embodied carbon equivalent. Clearly, greenhouse gas emissions form just one of the many environmental impacts of the built environment. However they are undoubtedly one of the critical issues the world is facing at the moment. Their calculation, and subsequent reduction, is critical to the future of the global climate.

PRODUCT stage			CONSTRUCTION PROCESS stage		USE stage					END OF LIFE stage				BEYOND
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction Demolition	Transport	Waste Processing	Disposal	Reuse Recovery Recycling Potential
					B6									
					Operational energy use									
					B7									
					Operational water use									

Fig. 1. Life cycle stages of a building (adapted from BS EN 15978:2011).

behind and/or the solutions for the variability of the results, none looks directly into the variations in the numbers used in the assessments in order to (attempt to) increase both understanding and transparency.

3. Methods

This study follows on a previous systematic review of the scientific literature on embodied carbon [28]. The review utilised a structured and systematic approach which is common in many disciplines [35] and it is recently becoming popular in built environment research too [36] as a way of ensuring consistency and avoiding any bias in sampling publications.

The articles included in this further study were those with adequate information about the embodied carbon coefficients, the data sources and system boundaries, and the life cycle stages considered in the assessment. That number further reduced due to the choice of limiting inclusion of articles from the last five years, and the reason is manifold. Indeed, as shown in the literature review it was only in 2011 that embodied carbon started being discussed in the scientific literature, a couple of years after the publication of the first publicly available inventory of embodied carbon for building products [37]. Before the main focus was on embodied energy, and studies on embodied carbon were few and far between, with an average of circa five per year [28], characterised by little or no data disclosed. The years 2011 and 2012 also mark the publication of the TC350 standards [15,16]. Therefore, one would expect to find more standardisation in the work which has been published since, at least in Europe.

The articles remaining after the scrutiny guided by the above criteria became the secondary data used in the present study. This part of this research can be methodologically seen as ‘secondary analysis’ and ‘meta-analysis’ as defined by Glass [38]. In particular secondary analysis involves “the re-analysis of data for the purpose of answering new [research] questions with old data” whereas meta-analysis is understood as the “analysis of results from individual studies for the purpose of integrating the findings” [38, p.3].

The impacts throughout the different life cycle stages have been mapped and assessed against the framework developed by the TC350 Committee [16]. In terms of system boundaries, detailed classifications exist to cluster building elements into defined categories [39]. However, such detailed classifications would not match the loosely defined data in the original studies. Therefore, this study adopts a simplified approach with three macro-categories; namely (1) structure

only, (2) shell and core, (3) up to internal finishes, and a further category (4) when the specification of the system boundaries lacked in the original paper.

4. Results

The results and analyses are organised by the macro stages of the TC350 standards – namely, the production stage, the construction and installation stage, the use stage, and the end of life stage. The production stage is further divided into sub-sections for each of the most common construction materials – namely, cement, concrete, load-bearing masonry, steel, and timber.

4.1. Production stage (A1-A3)

This stage includes the extraction and processing of raw material, including the processing of secondary material input (A1), the transportation of those materials to the manufacturing plant(s) (A2), and the manufacturing of the product, component, or assembly (A3). There is a tendency to have these three individual stages grouped together in terms of embodied carbon coefficients. Additionally, the first publicly available embodied carbon database [37] was limited to ‘cradle to manufacturing gate’ impacts, which are exactly represented by the A1-A3 boundaries. It has therefore become a *de facto* standard for impacts related to the manufacturing stage and it is indeed the one used in the rapidly growing body of Environmental Product Declarations (EPDs) [40].

4.1.1. Cement

Table 1 presents the results for cement. It can be seen that in some cases there were further specifications about the material but this is not the norm. The majority of the assessments were limited to the production and construction stages, and focused solely on the structural system of the building.

4.1.2. Concrete

Table 2 presents the results for concrete, which is also the most numerous category out of the structural materials assessed. In the case of concrete, the further specification on which specific type was being assessed is more common. Concrete (together with steel) is also the material, which more often has an assessment that includes the end of life (C) stage. Perhaps, this is because it is at the end of life that such carbon intensive material can have an environmental benefit; crushed

Table 1
Embodied carbon analysis of cement.

Source	Macro category	Further Description [*]	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[41]	Cement	C30	A1-A4	A1-A3	(1)	0.196
[41]	Cement	C40	A1-A4	A1-A3	(1)	0.222
[41]	Cement	C50	A1-A4	A1-A3	(1)	0.242
[41]	Cement	C60	A1-A4	A1-A3	(1)	0.267
[41]	Cement	C70	A1-A4	A1-A3	(1)	0.290
[41]	Cement	C80	A1-A4	A1-A3	(1)	0.313
[42]	Cement		A1-A4	A1-A3	(2)	0.394
[43]	Cement		A1-A5	A1-A3	(2)	0.698
[44]	Cement		A + B4 + C	A1-A3	(4)	0.770
[45]	Cement	Portland	A + C	A1-A3	(4)	0.819
[46]	Cement		A1-A4	A1-A3	(1)	0.819
[47]	Cement		A + C1	A1-A3	(2)	0.860
[48]	Cement		A + B2, B5 + C	A1-A3	(3)	0.860
[40]	Cement		A1-A3	A1-A3	(4)	0.880
[49]	Cement		A + C1, C3	A1-A3	(3)	0.894
[50]	Cement		A + C	A1-A3	(1)	1.050

* This column includes the exact description in the original studies – when available.

Table 2
Embodied carbon analysis of concrete.

Source	Macro category	Further Description [*]	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[52]	Concrete	Precast	A1-A3 + B2, B5 + C3	A1-A4	(2)	0.033
[45]	Concrete	80% BFS	A + C	A + B + C + D	(4)	0.044
[45]	Concrete	35% FA	A + C	A + B + C + D	(4)	0.050
[45]	Concrete	50% BFS	A + C	A + B + C + D	(4)	0.050
[52]	Concrete		A1-A3 + B2, B5 + C3	A1-A4	(2)	0.053
[45]	Concrete	35% BFS	A + C	A + B + C + D	(4)	0.054
[45]	Concrete	20% FA	A + C	A + B + C + D	(4)	0.055
[45]	Concrete	Standard	A + C	A + B + C + D	(4)	0.061
[41]	Concrete	C30 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.072
[41]	Concrete	C40 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.080
[41]	Concrete	C50 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.086
[41]	Concrete	C60 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.094
[53]	Concrete		A1-A4 + B4 + C1, C2	A1-A3	(3)	0.1
[41]	Concrete	C70 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.101
[41]	Concrete	C80 25% + 75% GGBS	A1-A4	A1-A3	(1)	0.108
[44]	Concrete	Normal	A + B4 + C	A1-A3	(4)	0.111
[54]	Concrete		A + C	A1-A3	(1)	0.113
[43]	Concrete	Ready-mix	A1-A5	A1-A3	(2)	0.12
[41]	Concrete	C30 65% + 35% FA	A1-A4	A1-A3	(1)	0.133
[46]	Concrete		A1-A4	A1-A3	(4)	0.137
[55]	Concrete	Reinforced	A1-A3 + B4	A1-A3	(3)	0.15
[41]	Concrete	C40 65% + 35% FA	A1-A4	A1-A3	(1)	0.151
[47]	Concrete		A + C1	A1-A3	(2)	0.159
[56]	Concrete		A + B5	A1-A3	(3)	0.159
[42]	Concrete		A1-A4	A1-A3	(2)	0.1741
[41]	Concrete	C50 65% + 35% FA	A1-A4	A1-A3	(1)	0.176
[41]	Concrete	C60 65% + 35% FA	A1-A4	A1-A3	(1)	0.180
[41]	Concrete	C70 65% + 35% FA	A1-A4	A1-A3	(1)	0.195
[50]	Concrete	C40	A + C	A1-A3	(1)	0.200
[48]	Concrete		A + B2, B5 + C	A1-A3	(3)	0.2
[41]	Concrete	C80 65% + 35% FA	A1-A4	A1-A3	(1)	0.210
[40]	Concrete		A1-A3	A1-A3	(4)	0.212
[53]	Concrete	Precast	A1-A4 + B4 + C1, C2	A1-A3	(3)	0.22
[54]	Concrete	15 storey Lat Load 2	A + C	A + C	(1)	0.221
[54]	Concrete	10 storey Lat Load 2	A + C	A + C	(1)	0.224
[54]	Concrete	3 storey Lat Load 2	A + C	A + C	(1)	0.229
[54]	Concrete	10 storey Lat Load 1	A + C	A + C	(1)	0.231
[54]	Concrete	15 storey Lat Load 1	A + C	A + C	(1)	0.237
[49]	Concrete		A + C1, C3	A1-A3	(3)	0.242
[54]	Concrete	3 storey Lat Load 1	A + C	A + C	(1)	0.243
[57]	Concrete		A1-A4	A1-A3	(4)	0.295
[58]	Concrete	Ready-mix, reinforced	A + B2, B5 + C1, C2	N/A	(1)	0.033

* This column includes the exact description in the original studies – when available.

Table 3
Embodied carbon analysis for load bearing masonry.

Source	Macro category	Further Description*	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[52]	Masonry (LB)	Brick/block	A1-A3 + B2, B5 + C3	A1-A3	(2)	0.074
[55]	Masonry (LB)	Med dense block	A1-A3 + B4	A1-A3	(3)	0.078
[59]	Masonry (LB)	Fly ash concrete blocks	A1-A4	A1-A4	(1)	0.099
[59]	Masonry (LB)	Fly ash concrete blocks_RTb	A1-A4	A1-A4	(1)	0.101
[59]	Masonry (LB)	CSSB	A1-A4	A1-A4	(1)	0.103
[46]	Masonry (LB)	Sand-lime brick	A1-A4	A1-A3	(2)	0.120
[50]	Masonry (LB)	Brick	A + C	A1-A3	(1)	0.140
[60]	Masonry (LB)	Perforated ceramic brick	A1-A3	A1-A3	(3)	0.170
[48]	Masonry (LB)	Hollow blocks	A + B2, B5 + C	A1-A3	(4)	0.171
[40]	Masonry (LB)	Brick	A1-A3	A1-A3	(4)	0.180
[59]	Masonry (LB)	Solid concrete block	A1-A4	A1-A4	(1)	0.184
[44]	Masonry (LB)	Cement mortar	A + B4 + C	A1-A3	(4)	0.200
[48]	Masonry (LB)	Clay brick	A + B2, B5 + C	A1-A3	(4)	0.200
[49]	Masonry (LB)	Brick	A + C1, C3	A1-A3	(3)	0.200
[59]	Masonry (LB)	Clay bricks_RTb	A1-A4	A1-A4	(1)	0.220
[44]	Masonry (LB)	Brick	A + B4 + C	A1-A3	(4)	0.220
[59]	Masonry (LB)	Clay bricks	A1-A4	A1-A4	(1)	0.221
[59]	Masonry (LB)	Hollow concrete block	A1-A4	A1-A4	(1)	0.223
[53]	Masonry (LB)	Bricks	A1-A4 + B4 + C1, C2	A1-A3	(3)	0.230
[55]	Masonry (LB)	Dwarf walls brick	A1-A3 + B4	A1-A3	(3)	0.240
[43]	Masonry (LB)	Brick	A1-A5	A1-A3	(2)	0.246
[59]	Masonry (LB)	FaL-G bricks_RTb	A1-A4	A1-A4	(1)	0.252
[59]	Masonry (LB)	Fly ash clay bricks_RTb	A1-A4	A1-A4	(1)	0.258
[59]	Masonry (LB)	FaL-G bricks	A1-A4	A1-A4	(1)	0.259
[59]	Masonry (LB)	Fly ash clay bricks	A1-A4	A1-A4	(1)	0.266
[46]	Masonry (LB)	Ordinary brick	A1-A4	A1-A3	(2)	0.271
[60]	Masonry (LB)	Aerated concrete block	A1-A3	A1-A3	(3)	0.320
[59]	Masonry (LB)	AAC blocks	A1-A4	A1-A4	(1)	0.367
[42]	Masonry (LB)	Brick	A1-A4	A1-A3	(3)	0.518
[53]	Masonry (LB)	Bricks	A1-A4 + B4 + C1, C2	A1-A3	(3)	0.550

* This column includes the exact description in the original studies – when available.

and recycled concrete being, for instance, often suggested as a low-carbon way to build pavements [51].

4.1.3. Load-bearing masonry

Table 3 shows the results of the analysis for load-bearing masonry. Most of the assessments are limited to production and transportation stages, which are also the boundaries of the embodied carbon coefficients. It appears that the material boundaries of the assessments are almost evenly distributed across the four categories, without one prevailing over the others.

Table 4
Embodied carbon analysis of steel.

Source	Macro category	Further Description*	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[44]	Steel	Reinforcing	A + B4 + C	A1-A3	(4)	1.340
[46]	Steel	Reinforcing	A1-A4	A1-A3	(4)	1.526
[54]	Steel		A + C	A1-A3	(1)	1.53
[41]	Steel	crude DRI	A1-A4	A1-A3	(1)	1.540
[56]	Steel	Galvanized	A + B5	A1-A3	(3)	1.75
[56]	Steel	Tubing	A + B5	A1-A3	(3)	1.8
[61]	Steel	Rebar	A1-A5 + B3 + C	A1-A3	(3)	1.86
[61]	Steel	Sections	A1-A5 + B3 + C	A1-A3	(1)	1.95
[62]	Steel	Lean	A1-A5 + C2	A1-A5	(1)	1.950
[62]	Steel	Standard	A1-A5 + C2	A1-A5	(1)	2.015
[41]	Steel	crude pig iron	A1-A4	A1-A3	(1)	2.090
[49]	Steel		A + C1, C3	A1-A3	(3)	2.208
[47]	Steel		A + C1	A1-A3	(2)	2.210
[50]	Steel	10% recycled content	A + C	A1-A3	(1)	2.210
[53]	Steel	Rebar	A1-A4 + B4 + C1, C2	A1-A3	(3)	2.27
[53]	Steel	Galvanized	A1-A4 + B4 + C1, C2	A1-A3	(3)	2.82
[48]	Steel	Bar	A + B2, B5 + C	A1-A3	(4)	3.15
[42]	Steel		A1-A4	A1-A3	(3)	3.809

* This column includes the exact description in the original studies – when available.

Table 5
Embodied carbon analysis for steel (recycled content).

Source	Macro category	Further Description*	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECs
[41]	Steel (recycled content)	plate	Al-A4	Al-A3	(1)	0.160
[41]	Steel (recycled content)	rebar	Al-A4	Al-A3	(1)	0.160
[41]	Steel (recycled content)	section	Al-A4	Al-A3	(1)	0.210
[41]	Steel (recycled content)	tube	Al-A4	Al-A3	(1)	0.250
[41]	Steel (recycled content)	wire	Al-A4	Al-A3	(1)	0.270
[54]	Steel (recycled content)	3 storey Lat. Load 2	A + C	A + C	(1)	0.356
[54]	Steel (recycled content)	3 storey Lat. Load 3	A + C	A + C	(1)	0.365
[43]	Steel (recycled content)		Al-A5	Al-A3	(2)	0.367
[54]	Steel (recycled content)	15 storey Lat. Load 2	A + C	A + C	(1)	0.386
[41]	Steel (recycled content)	crude (100% scrap)	Al-A4	Al-A3	(1)	0.390
[54]	Steel (recycled content)	3 storey Lat. Load 1	A + C	A + C	(1)	0.391
[54]	Steel (recycled content)	15 storey Lat. Load 3	A + C	A + C	(1)	0.395
[54]	Steel (recycled content)	10 storey Lat. Load 3	A + C	A + C	(1)	0.399
[54]	Steel (recycled content)	10 storey Lat. Load 2	A + C	A + C	(1)	0.405
[54]	Steel (recycled content)	10 storey Lat. Load 1	A + C	A + C	(1)	0.409
[52]	Steel (recycled content)	15 storey Lat. Load 1	A + C	A + C	(1)	0.448
[52]	Steel (recycled content)	Rebar/Structural	Al-A3 + B2, B5 + C3	Al-A4	(2)	0.460
[40]	Steel (recycled content)		Al-A3	Al-A3	(4)	0.618
[52]	Steel (recycled content)	Galvanized	Al-A3 + B2, B5 + C3	Al-A4	(2)	0.675
[63]	Steel (recycled content)	Bars	Al-A3	Al-A3	(2)	0.920
[41]	Steel (recycled content)	crude (30% scrap)	Al-A4	Al-A3	(1)	1.670

* This column includes the exact description in the original studies – when available.

4.1.5. Timber

Table 6 illustrates the results for timber, which is also the least numerous group out of the structural materials assessed. This is not surprising because timber has only relatively recently become object of scientific scrutiny as a structural material that can compete with concrete and steel, despite it being – along with bricks – perhaps the most ancient material for human dwellings and sheltering.

4.1.6. Discussion

The previous sub-sections have analysed the different carbon coefficients and calculation methods to evaluate the embodied carbon content of common building materials. This section discusses the findings holistically. Fig. 2 shows the data clustered for each material, namely cement, concrete, load-bearing masonry, steel, and timber. Steel has been further divided between virgin and recycled due to the very different values of embodied carbon between the two. For each set the average and median values have also been calculated and plotted.

Fig. 2 reveals some interesting findings. Apart from virgin steel which lays well above all other materials, there seems to be a good degree of overlap between the embodied carbon content of the other materials. In other words, if one imagines a horizontal line at around the value of 0.25 kgCO_{2e}/kg_{MAT}, that line would cross all sets of values, meaning that for each material there will be values both above and below that line. This deserves great attention and care in comparative analyses of different materials because such variety of data would allow to ‘handpick’ the most appropriate embodied carbon coefficient to drive the results. This would not happen if embodied carbon coefficients were strictly related to a specific context (e.g. geographical, technological, etc.) but this is not yet the case and there is too big a room for manoeuvring when it comes to choose embodied carbon coefficients for an LCA of a building. It is worth remarking that comparative assessments of structural materials should be based on units of performance (e.g. how much steel vs. how much concrete one needs to guarantee the same intended performance for a specific project) and not units of mass but far too often the claims of greater environmental friendliness of one material over the others are simply based on its embodied carbon content, and just at the production stage.

Another element that is immediately evident is the very broad range of values that characterises each set of embodied carbon coefficients. This might seem more the case of some materials over the others but it should be noticed that those with a flatter dataset (e.g. concrete) are also those with lower values closer to zero and therefore the variation in percentage is equally remarkable as the numbers in Table 7 show.

The upper part of Table 7 shows the minima and maxima in terms of embodied carbon coefficients for each of the materials assessed, as well as the ratio between the minimum and maximum value for each material. All values are significantly high, ranging from 284% to 1044%. The lower part shows an example of assessing 1 t of each material by means of the minima and maxima showed in the upper part. The last row presents the difference in the assessments by using one coefficient or the other. In the case of steel (either virgin or recycled) the choice of minimum or maximum embodied carbon coefficients produces a difference in mass of embodied carbon greater than the mass of the material assessed (2.4 and 1.5 t CO_{2e} for 1 t of steel assessed, respectively). However, differences are very significant for any of the materials assessed.

A final element worth of analysis is the difference between the mean (average) and the median in the datasets. In some cases, these differences appear moderate (concrete and load-bearing masonry) whereas for other materials they are more pronounced. A more objective, numerical, way to assess the mutual relation between mean and median and how it influences the distribution is given by Pearson’s skewness coefficient, defined as in Eq. (1) [64]:

$$C_{SK} = \frac{3 \cdot (\mu - M)}{\sigma} \tag{1}$$

Table 6
Embodied carbon analysis for timber.

Source	Macro category	Further Description [*]	Boundaries of the assessment (EN 15978)	Boundaries of EC coefficients	Material boundaries of the assessment	ECCs
[49]	Timber		A + C1, C3	A1-A3	(3)	0.200
[47]	Timber	Lumber	A + C1	A1-A3	(2)	0.275
[46]	Timber	Softwood	A1-A4	A1-A3	(2)	0.3
[40]	Timber	OSB	A1-A3	A1-A3	(4)	0.300
[40]	Timber	Wood	A1-A3	A1-A3	(4)	0.330
[40]	Timber	Particleboard	A1-A3	A1-A3	(4)	0.379
[50]	Timber	Wood	A + C	A1-A3	(1)	0.410
[40]	Timber	Gluelam	A1-A3	A1-A3	(4)	0.415
[54]	Timber	Plywood	A + C	A1-A3	(4)	0.450
[46]	Timber	Gluelam	A1-A4	A1-A3	(4)	0.541
[42]	Timber	Gluelam	A1-A4	A1-A3	(2)	0.685
[40]	Timber	Fibreboard	A1-A3	A1-A3	(4)	0.69
[56]	Timber		A + B5	A1-A3	(3)	0.72

^{*} This column includes the exact description in the original studies – when available.

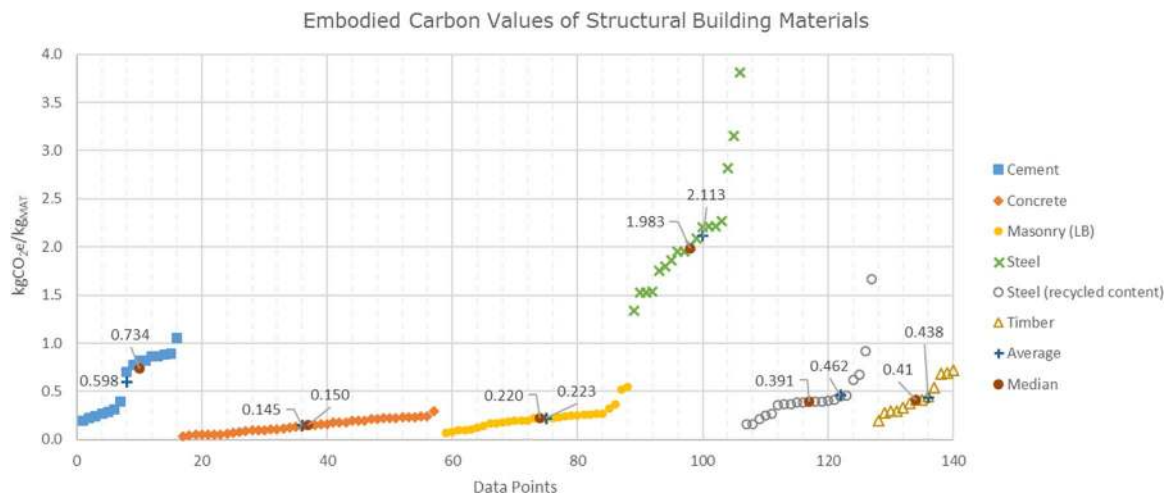


Fig. 2. Embodied carbon coefficients for the main structural materials.

where μ is the mean value, M is the median, and σ is the standard deviation. The coefficient can be either positive or negative and serves the purpose of giving a trend of the shape of the data distribution in terms of its symmetry [64] as shown in Fig. 3.

Table 8 gives the numerical values of average, median, standard deviation, and Pearson's skewness coefficient for all materials assessed.

The closer the coefficient is to zero the more the data can be safely approximated by a normal distribution, but this seems only possible for concrete and load-bearing masonry. For all other materials the skewness cannot be neglected, with cement and recycled steel showing the highest values of the Pearson's coefficient. This piece of information could be particularly useful to build statistical distribution for the embodied carbon coefficients based on, for example, Monte Carlo modelling techniques. These values could also be used for other, simpler forms of uncertainty analysis or the inclusion of data varia-

bility. These are, for instance, the min/max approach - which adopts the minima and maxima for a scenario analysis related to the best and worst cases - or the three points estimate, which in addition to the minima and maxima includes the mean value to also assess the most likely scenario and not just the two extreme cases.

4.2. Construction process stage (A4-A5)

The TC350 standard [15] divides the construction stage into two groups of activities:

- Transportation from the manufacturing gates to the construction site; and
- Installation of building's assemblies and components into the building.

Table 7
Minima and Maxima ECCs and EC values for 1 t of each structural material.

ECCs [kgCO _{2e} /kg _{MAT}]	Cement	Concrete	Masonry (LB)	Steel	Steel (recycled)	Timber
Minima	0.196	0.033	0.074	1.340	0.160	0.200
Maxima	1.050	0.295	0.550	3.809	1.670	0.720
Ratio M/m	536%	894%	743%	284%	1044%	360%
EC [kgCO _{2e} /1 t _{MAT}]	Cement	Concrete	Masonry (LB)	Steel	Steel (recycled)	Timber
Minima	195.88	33.00	74.00	1340.00	160.00	200.00
Maxima	1050.00	295.00	550.00	3808.76	1670.00	720.00
Difference [kgCO_{2e}]	854.12	262	476	2468.76	1510	520

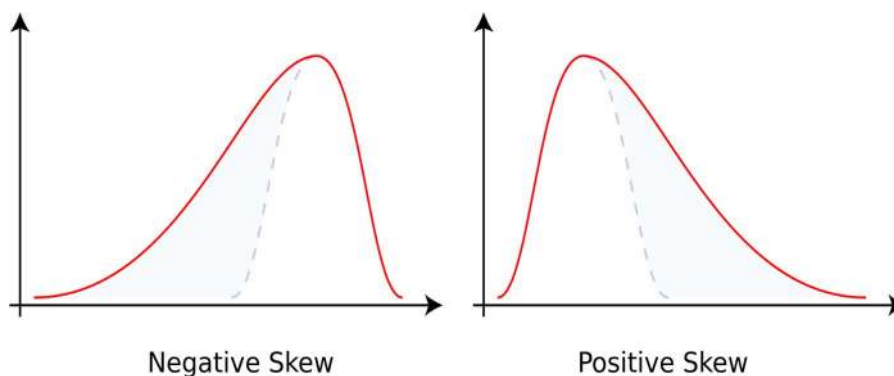


Fig. 3. Negative and positive skew according to Pearson's coefficient.

According to the standards, the construction stage should also include all materials, products, and energy that are necessary to the construction of the building even if they do not form part of the final building. The site waste processing as well as the final residues resulting out of construction processes should also be accounted for in here. Finally, any losses of building materials and/or ancillary products that may happen during transportation or installation activities have to be included too.

The analysis has attempted to reveal as much information and data as possible on both sub-stages. Table 9 shows the results for the transportation stage (A4). Where the transportation impacts were considered for a specific material this has been noted in the table but many studies have adopted a one-size-fits-all approach for transportation regardless of the material being transported.

It can be seen that for the EC of transportation activities there is a relatively large agreement on the measuring units, with two being those primarily used:

- kgCO₂/kg_{MAT}, and
- kgCO₂/t_{MAT} km

The main difference between the two lies in the fact that the first measure already includes an assumption on the transportation distance embedded in the embodied carbon coefficient and, therefore, it is only the mass being transported that will influence the overall EC for A4. The second measure, instead, requires not just the mass being transported as input but also the distance that is to be covered. As such the same mass transported over two different distances would produce two values with the second unit while it would be the same overall EC for the first unit. Fig. 4 shows graphically the sets of EC coefficients for transportation impacts.

Table 10 gives results for the EC analysis of construction and installation activities (A5). There is less information available in literature on this matter, as the size of the table clearly highlights. Also, any agreement on how to best measure the EC of A5 is yet to be reached. In some cases EC_{A5} is simply calculated as a percentage of other life cycle stages, mainly A1-A3 or even A4. It is worth remembering that, apart from some benchmarks that exist as a result of previous calculations, there has been no evidence of correlation – to the authors' knowledge – between A5 and impacts of other life cycle stages.

In other cases, and solely at material level for concrete and steel,

Table 8
Statistical values for most common building materials.

	Cement	Concrete	Masonry (LB)	Steel	Steel (recycled)	Timber
Average (mean value)	0.598	0.145	0.223	2.113	0.462	0.438
Median	0.734	0.150	0.220	1.983	0.391	0.410
Standard deviation	0.305	0.070	0.109	0.616	0.326	0.171
Pearson's skewness coefficient	-1.330	-0.196	0.077	0.632	-2.211	0.490

Table 9
Embodied carbon analysis for the transportation stage (A4).

Source	Element	Further description [*]	A4 stage
[41]	Any material	Railway	0.017 [t CO ₂ /kg _{MAT} km]
[41]	Any material	Marine shipment	0.033 [t CO ₂ /kg _{MAT} km]
[42]	Any material		0.094 [kgCO ₂ /t km]
[47]	Any material		0.12 [kgCO ₂ /t km]
[49]	Any material	50 km distance	0.168 [kgCO ₂ /t km]
[44]	Any material		0.17 [kgCO ₂ /t km]
[46]	Any material	20–28 t lorry 100 km	0.193 [kgCO ₂ /km]
[48]	Any material	Truck	0.278 [kgCO ₂ /t km]
[61]	Any material		0.32 [kgCO ₂ /t km]
[41]	Any material	Medium goods vehicle (15–20 t)	0.75 [kgCO ₂ /km]
[41]	Any material	Medium goods vehicle (20–24 t)	1.10 [kgCO ₂ /km]
[41]	Any material	Heavy goods vehicle (24–38 t)	1.22 [kgCO ₂ /km]
[43]	Cement	60 km distance	0.207–0.288 [kgCO ₂ /t km]
[54]	Concrete		0.0133 [kgCO ₂ /kg _{MAT} km]
[45]	Concrete		0.1 [kgCO ₂ /t km]
[43]	Concrete	80 km distance	0.207–0.288 [kgCO ₂ /t km]
[59]	Masonry (LB)	Hollow concrete block	0.0159 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	FaL-G bricks	0.0208 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Solid concrete block	0.0210 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Fly ash clay bricks	0.0225 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Clay bricks_RTb	0.0228 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Fly ash concrete blocks_RTb	0.0247 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	CSSB	0.0267 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Fly ash clay bricks_RTb	0.0319 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Fly ash concrete blocks	0.0326 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	AAC blocks	0.0461 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	FaL-G bricks_RTb	0.0480 [kgCO ₂ /kg _{MAT} km]
[59]	Masonry (LB)	Clay bricks	0.0810 [kgCO ₂ /kg _{MAT} km]
[54]	Steel		0.0127 [kgCO ₂ /kg _{MAT} km]
[62]	Steel		0.106 [kgCO ₂ /t km]
[43]	Steel	120 km distance	0.207–0.288 [kgCO ₂ /t km]
[50]	Timber		0.15 [kgCO ₂ /t km]

^{*} This column includes the exact description in the original studies – when available.

Embodied Carbon Coefficients for A4

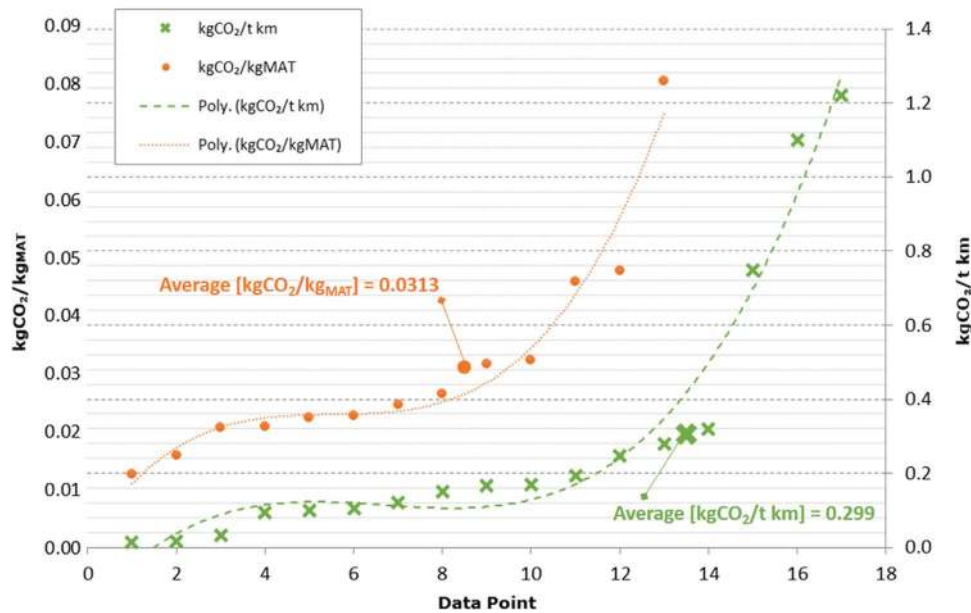


Fig. 4. Embodied carbon coefficients for A4.

Table 10
Embodied carbon analysis for the construction and installation stage (A5).

Source	Element	Further description*	A5 stage
[47]	Any material		2 ⁺ EC _{A4}
[45]	Concrete		0.000325 [kgCO ₂ /kg _{MAT}]
[54]	Concrete		0.016 [kgCO ₂ /kg _{MAT}]
[61]	Concrete	Reinforced	0.019 [kgCO ₂ /kg _{MAT}]
[62]	Steel	Assessment of equipment	0.007–0.01% of A1–A3
[54]	Steel		0.021 [kgCO ₂ /kg _{MAT}]
[48]	Whole building	Electrical equipment	0.969 [kgCO ₂ /kWh]
[43]	Whole building	Electrical equipment	1.018 [kgCO ₂ /kWh]
[44]	Whole building		16–32% of WLC
[43]	Whole building	Diesel equipment	2.617 [kgCO ₂ /litre]
[48]	Whole building	Diesel equipment	2.645 [kgCO ₂ /litre]
[58]	Whole building	Structure only (cast-in-place)	362.60 [kgCO ₂ /m ²]
[49]	Whole building		8.30 [kgCO ₂ /m ²]
[58]	Whole building	Structure only (full prefabrication)	93.90 [kgCO ₂ /m ²]

* This column includes the exact description in the original studies – when available.

EC_{A5} is calculated in the form of kgCO₂/kg_{MAT} – a form that would ensure consistency with how EC_{A1–A3} and EC_{A4} are calculated. Two other means of calculating the impacts of A5 are used:

- EC related to the energy inputs necessary for the construction of a building (in litres of fuel used or kWh of energy used); and
- EC related to area units of the buildings (which would require the specification of which area is being considered² though this information often lacks in literature).

4.3. Use stage (B1–B5)

The use stage is rather loosely defined in the standards themselves [15] compared to the detail of the A stage and this might or might not be the reason why it is the least considered in the assessment of EC of buildings as Pomponi and Moncaster [28] have shown. In this research, it was mentioned only in a handful of publications [44,52,56,58].

² A thorough definition of all different possible area measures can be found in [65].

Even when the B stage does get taken into account this takes primarily the form of including replacement rates for the main building elements or materials (B5) and – in some cases – the consideration of refurbishment activities (B4). Repair (B3), ordinary maintenance (B2), and use (B1) are usually completely neglected.

As such, there is simply not enough information in the scientific literature to analyse here how this very long life cycle stage characterised by significant impacts is dealt with, and how its EC is to be calculated. This is certainly a challenging area due to both high complexity and uncertainty but it also deserves urgent attention by the relevant communities in research and practice.

4.4. End of life stages (C1–C4)

Similarly to the use stage, the end of life stage (C) is defined in less detail than the product and construction stages in the TC350 standards [15]. It includes four main groups of activities, which occur once the decision that a building has reached the end of its useful life is taken. These are: deconstruction and demolition (C1), transportation to waste processing facilities (C2), waste processing (C3), and final disposal (C4). Table 11 shows the results of the analysis for the EC of the end of life stages.

Table 11
Embodied carbon analysis for the end of life stage (C1-C4).

Source	Element	Further description	EC ^c End of Life Value	Boundaries of EC coefficients
[53]	Any material	Demolition	0.2% of WLE	C1
[53]	Any material	Transport	empirical formula	C2
[44]	Any material		0.01 [kgCO ₂ /kg _{MAT}]	C1-C4
[61]	Concrete	Selective demolition	0.116 [kgCO ₂ /kg _{MAT}]	C1
[61]	Concrete	Mass demolition	0.011 [kgCO ₂ /kg _{MAT}]	C1
[52]	Concrete		3% of A1-A3	C
[45]	Concrete		0.001 [kgCO ₂ /kg _{MAT}]	C1
[45]	Concrete		2.37·10 ⁻⁴ [kgCO ₂ /kg _{MAT}]	C3
[54]	Concrete		0.0080 [kgCO ₂ /kg _{MAT}]	C1-C2
[49]	Concrete	Reinforced concrete	88.78 [kgCO ₂ /m ²]	C1
[49]	Concrete		30 km by truck	C2
[52]	Masonry (LB)		3% of A1-A3	C
[52]	Steel		5% of A1-A3	C
[62]	Steel	Lean	0.4% of WLC	C2
[62]	Steel	Standard	0.6% of WLC	C2
[54]	Steel		0.0093 [kgCO ₂ /kg _{MAT}]	C1-C2
[47]	Whole building		90% of A5	C1
[54]	Whole building	Demolition energy	51.5 MJ/m ²	C1
[54]	Whole building	Waste generated	0.845 t/m ²	C1
[54]	Whole building	Based on mass from C1	40 km by truck	C2
[48]	Whole building		7.8 [kgCO ₂ /m ²]	C1
[58]	Whole building	Structure only (full prefabrication)	94.647 [kgCO ₂ /m ²]	C1-C2
[58]	Whole building	Structure only (cast-in-place)	94.648 [kgCO ₂ /m ²]	C1-C2

^c Not in all cases the coefficients refer to EC but this is due to the original studies.

It can be seen from the table that the ways to assess EC_{C1-C4} are extremely varied, similar to the EC_{A5}. It goes from percentages of whole life impacts (all below 1%) to percentages of other life cycle stages, such as 3–5% of EC_{A1-A3} or 90% of EC_{A5}. The other methods used include:

- EC related to the energy inputs necessary for the deconstruction of a building (either in litres of fuel used or kWh of energy used);
- EC related to the area of the buildings (which would require the same specification explained before²);
- EC related to the mass of building elements or components in kgCO₂/kg_{MAT} – though such values have only been found for concrete and steel.

It is also worth noting that in the vast majority of cases, the end of life was merely represented by the deconstruction or – more realistically – demolition of the building (C1). If the assessment of the building's end of life is limited to the fuel that goes into the demolition equipment, it is likely to produce a significantly reduced figure, which could mislead judgement and evaluation. This is also an area that certainly requires further work.

5. Discussion and conclusions

Embodied carbon assessments in buildings has rapidly grown as a research field due to the timeliness and importance of the topic with respect to issues such as climate change and global warming. If on the one hand the concept of embodied carbon is established and well known, the science behind it is yet to reach maturity and current assessments are often incomplete, not transparently defined, and therefore hard to verify, replicate, and compare. The context is very similar to that which led to the energy performance gap in the operational phase of buildings. In fact, significant discrepancies are already being seen between embodied carbon assessments at the design stage and 'as built'.

This phenomenon, if not addressed to promptly, will inevitably lead to a second wave of performance gaps in buildings. The only difference is that this time the gap is related to the embodied rather than operational impacts, and the two bear a fundamental difference: while discrepancies in operational performance can be somewhat addressed later on through simulations, assessment and post – occupancy

evaluations (POEs), the same does not hold true for embodied impacts. Once the building has been completed and the 'as built' embodied carbon is assessed there is no room for reducing it. In fact, any action or intervention on the building – even if beneficial – instantly provokes an additional growth to its embodied carbon. For this reason it is imperative to increase the accuracy of embodied carbon assessments at the design stage.

To this end, the objective of this article was to investigate how embodied carbon calculations of buildings are done, and what the data behind are, in order to enable a more transparent understanding of embodied carbon calculations and avoid significant gaps between the estimated and actual values. Results have shown that data scarcity is a problem only in some life cycle stages, primarily those related to the use stage of a building and its end of life impacts – which are the activities more distant in the future and therefore less predictable. However, where data are abundant – such as in the case of embodied carbon coefficients of common construction materials – they are characterised by a remarkable variability, which is not easily linked to contextual variations such as geographical location or technological level. For instance, the analysis of minima and maxima embodied carbon coefficients for the manufacture of the main structural building materials show variations in the range of 284–1044%. Such a high variation range cannot be justified solely by technological and geographical differences in the production processes of those materials. The numerical analyses offered for the production and construction stages, as well as the embodied carbon coefficients of common construction materials, represent a stepping stone to promote a more objective approach to the science behind embodied carbon assessments. For example, more detailed and harmonised ways to quantify environmental impacts of construction and end of life activities could be proposed in order to reduce the high number of different metrics currently being utilised. The analysis of the data variability also paves the way for further work on scenario and uncertainty analysis.

The main limitation of this article is that it is based on secondary data from published studies, and therefore it does not discuss the merit of existing databases, but rather how the data are used by the LCA community of practice. Future work should broaden and deepen the understanding of the variability of embodied carbon data to further reduce the gap between 'as designed' and 'as built' embodied carbon assessments. A number of stakeholders, including governments as well

as professional bodies, bear the responsibility to speed up on promoting the importance of embodied carbon and increasing its knowledge base – a task that so far has been left in the hands of a small group of academics and practitioners. An important step in this direction would be the inclusion of embodied carbon calculation at the design stage in national building regulations. If this is not done, the built environment can expect a second wave of performance gap in the environmental assessment of buildings, with even more detrimental environmental consequences as well as unmet carbon targets, both nationally and internationally.

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