# Why method matters: temporal, spatial and physical variations in LCA and their impact on choice of structural system

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## Abstract

Life Cycle Assessment (LCA) is increasingly used as an early-stage design-decision tool to support choices of structural system. However LCA modellers must first make numerous methodological decisions, and the resultant wide variations in approach are often inadequately described by the modellers.

This paper identifies, and quantifies, the three major areas of methodological variation. These are: temporal differences in the stages considered; spatial differences in the material boundaries; and physical disparities in the data coefficients. The effects are then demonstrated through a case study of a student residential building in Cambridge. The cross-laminated timber (CLT) structure is compared with concrete frame, steel frame and load-bearing masonry, considering the influence that varying the temporal boundaries, the data coefficients, and the spatial boundaries has on the choice.

While for this building CLT is confirmed as the lowest impact material, the paper demonstrates that varying the methodological choices can change the results by an alarming factor of 10 or even more. The findings confirm the need for the utmost clarity and transparency with all LCA calculations. Making wider industry or policy decisions based on LCA results should be undertaken with extreme caution.

## *Key words*

# 1. Introduction

The significance of the built environment on anthropogenic climate change is well-known. For many years now national regulations have focused on reducing the operational impacts of buildings. However with improvements in energy efficiency being achieved, both academic research and industry practice are becoming increasingly interested in measuring and reducing the embodied, as well as operational, impacts. The last two decades, and in particular the last five years, have therefore seen a rapid increase in the calculation of whole life (operational plus embodied) environmental impacts of buildings.

Life Cycle Assessment (LCA) is the most common approach to measurement [1], with three different methodological approaches used: process, input-output, and hybrids which incorporate elements of the previous two [2-4]. As well as these three main variations, all three methods are open to interpretation, particularly in the analysis of something as complex as a building. Without a closer look at the methodological choices being made, drawing clear conclusions from the multiple published detailed LCAs of individual case study buildings is highly problematic.

Nonetheless there are some broad conclusions that can be drawn. One of these is the widespread agreement that it is the materials used in a building that have the major impact on the total embodied carbon and this is therefore the most frequently identified mitigation strategy within the academic literature [5]. Of the high number of materials included in a building, the structural frame and foundation elements are frequently the major component both in terms of mass and embodied impacts, and the structural material is often identified as one of the most obvious routes to reduction of environmental impacts [6, 7].

While academic work on increasing accuracy and understanding of LCA of buildings is important, industry practice is clearly where major savings could be being made right now, with the right approach and advice. It is therefore important to understand both what is currently being calculated in practice, and how this could be better informed by academic research.

This paper therefore considers three questions: What are the key variations within the academic literature? What are the current industry approaches to reducing embodied impacts of buildings? And, What impact do both academic and industry methodological choices have on the choice of structural material in practice?

In the following section the paper reviews the existing literature to identify three key areas where there are methodological variations, the temporal boundaries provided by the choice of life cycle stages, the choice of coefficients used for materials and different life cycle stages, and the material boundaries of the

physical elements included in assessment. An analysis of recent case studies is used to demonstrate the reported ranges within each of the three areas.

The focus then turns to look at how real world calculations are being conducted within industry. Section 4 describes a new building recently completed for a Cambridge University college. Rather than a detailed academic LCA of the building, this is offered as a case of how calculations are being carried out on the ground. For this building a simplified LCA was carried out at early design stage for four alternative structural solutions in order to identify the lowest impact solution. In section 5 this original calculation is then repeated using published data ranges to show how the three identified areas of methodological variation could affect the choice made of structural material. Section 6 offers concluding remarks with implications for policy, industry and academia are offered in the final section.

## 2. Identifying three key methodological variations

The academic literature shows a wide variation in published results for both embodied energy and embodied greenhouse gases of buildings. Early reviews such as those by Ding [8] and Sartori and Hestnes [9] published the range of embodied energy values found in multiple previous articles, but did not distinguish between the effects of differences in the buildings and the effects of differences in the analysis methods used. A few years later Dixit et al. [10] identified some of the methodological issues which contribute to the variation in results, including the system boundaries, the life cycle stages included, the consideration of either primary or delivered energy and inclusion or not of feedstock energy, and the age, source and completeness of data. This latter was also demonstrated in the range of values found by Hammond and Jones [11] in their development of the Inventory of Carbon and Energy at the University of Bath.

By 2012 academics were calling for uniformity of data and methodologies. Dixit et al. [12, p.3741] noted that 'the current state of research is plagued by a lack of accurate and consistent data and standard methodology'. Through a review of the literature up to 2010, with a particular focus on that published since the updated ISO standards on LCA in 2006, they noted the variation in system boundaries, methods of measurement, geographic location, consideration of primary/ delivered/ feedstock energy, source and completeness of data, manufacturing technologies, etc., and called for guidelines, followed by standards and a robust database. In the same year Moncaster and Song [13] reviewed the data and methodologies used in both academic and industry calculations, and identified the three main causes for the wide range of results as: diverse and non-comparable product data; different methodologies; and differences in building design.

Arguably we have come a long way since 2012, in particular in Europe with the publication of the CEN TC 350 standards [14, 15]. These define the life cycle of a construction product or project, including

buildings, and set out product category rules for the development of Environmental Product Declarations. Following a process LCA approach they define four principal life cycle stages, A, B, C and D, as shown in Figure 1. The impacts related to the operational energy use are defined by stage B6 and those to the operational water use by stage B7, with the other 14 sub-stages together making up the 'embodied' impacts. This is now the most common basis for calculating embodied impacts of buildings within academic studies from Europe.

In 2013 Moncaster and Symons [16] developed a tool which applied the newly published method to an assessment at an early design stage, such as could be carried out by a designer making initial decisions about structural materials. However they highlighted both the difficulties posed by applying the detailed method to the lack of detailed information at the early stage of a project, and once again reiterated the call for better data for all life cycle stages.

| 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 |

Figure 1: Life cycles stages of a building or construction work (adapted from EN 15978: 2011)

Both national and commercial databases have since been developed in line with the standards, but the picture remains unclear. Calculations continue to vary both for buildings [17] and individual materials [18, 19]. Frischknecht et al. [20, p.421], in an overview of the 57th LCA forum held in Zurich in 2015, concluded that 'unifying life cycle inventory methodology, environmental indicators and life cycle inventory background databases is most important'.

In a 2017 review Säynäjoki et al. [21] found methodological variations due to material boundaries, the inclusion of sequestered carbon, end of life assumptions and data sources. While their paper covered case

studies drawn from the last thirty years, reviews of more recent case studies find similar results [22-24]. Anand and Amor [23] identify numerous areas of current uncertainty and discrepancy which they suggest warrant future research, including impact category, functional unit, service life of building products, assumed life of the building (also known as reference study period), system boundaries, accuracy of material inventory, rebound effect, the time value of carbon, biogenic carbon emissions and other variations. Rasmussen et al. [24] identified 'multiple interacting methodological parameters' causing a range in results of up to a factor of 20 in embodied energy and a factor of 27 in embodied carbon. Collected as part of the International Energy Agency Annex 57, the authors found multiple differences in the system boundaries, including both within the life cycle stages considered, and within the building components included, and differences in both building and component service life assumptions.

Some papers have considered the impacts of specific methodological variations on results. For instance a review by Chau et al. [25] considers the variation in results due to the choice of impact factor, comparing full Life Cycle Assessment, Energy only and CO2 only. Säynäjoki et al. [4] apply both process-based (PB) and input-output (I-O) methodologies to the same building to assess the relative and absolute impacts of 8 key building systems. While the total (cradle to gate) impact for the I-O calculation is almost twice that for the PB, as also found by Crawford et al. [2], they also show that the proportion of the initial impacts for the main superstructure frame and roof is just over 50% for both methods. The impact of the mechanical systems is shown to be considerably lower for the PB methodology (5% as opposed to 11% for I-O), while that of the foundations was much more significant for the PB (10% of the total) than the I-O methodology (3%).

With the TC350 standards suggesting that only the product stage (A1-3) is mandatory, the choice of which life cycle stages to include within process-based analyses also varies considerably between authors. Pomponi and Moncaster [5] demonstrated the variation in included life cycle stages through a review of 77 published LCAs, while Birgisdottir et al. [26] conducted a similar analysis in a study of over 60 international cases. Häfliger et al. [27] considered the effects of changing the life cycle system boundary in an analysis of four multi-occupancy residential buildings in Switzerland, with varying frame materials including reinforced concrete, cement-based masonry and timber.

Häfliger et al. [27] also conducted a sensitivity analysis using three alternative data sources, a database of EPDs, the KBOB [28] database and the commercially available Ecoinvent. Considerable discrepancies for the timber and insulation products in particular are demonstrated, with results varying even more between databases when different life cycle system boundaries are applied.

Rasmussen et al. [24] found a significant variation in the product data used within the published literature; within the 59 case studies analysed, 19 different databases were used, with a third of studies using two or

more data sources for the same analysis. Pomponi and Moncaster [22] analysed papers published since the CEN TC350 Standards, to quantify the variability in the data used for the material coefficients. While coefficients for key structural materials including concrete, steel, masonry and timber have been available for many years (see for example Hammond and Jones [11]), they showed that there is still a considerable variation in the data used in current academic publications.

Concentrating on recent papers, and even restricting the focus to the process-based calculations, it can be seen from this literature review that there are still three key areas of methodological variation in approach. These are, (1) *temporal* differences in the life cycle stages included, (2) *physical* disparities in the embodied carbon coefficients chosen, both for materials and specific life cycle stages, and (3) *spatial* differences in the physical building systems included in the assessment. The published ranges for each of these, focusing on their potential impact on the key structural materials, are identifed in the next section.

## 3. Analysis of published ranges

### 3.1 Temporal differences in life cycle stages included

Pomponi and Moncaster [5], in a systematic review of 77 academic publications on building LCAs, demonstrated that the majority of studies cover the initial life cycle stages up to the end of construction (A1-A5), while the end of life stages (C1-4), and stage D, the benefits and costs after the end of life of the building, are included in under a third of the papers. The in-use stages B1-5 are those least often included. A slightly different picture is found by Birgisdottir et al. [26], who reviewed 59 quantitative case studies collected as part of an international project. While they too find that the great majority of cases assess the product stages A1-3, the next most commonly assessed phase in their collection is B4 (replacement), and around 60% of cases assessed C3-4. However the case studies were drawn from responses to a request to provide examples of specific issues, including replacement and end of life scenarios, so this might explain the greater focus on cases looking at B4 and C3-4 compared with the literature analysed by Pomponi and Moncaster [5]. Both sets are plotted in Fig. 2, along with the findings from De Wolf et al. [29]. This third paper, rather than considering academic practice, used responses to interviews with industry practitioners to assess the life cycle stages commonly included in industry calculations.
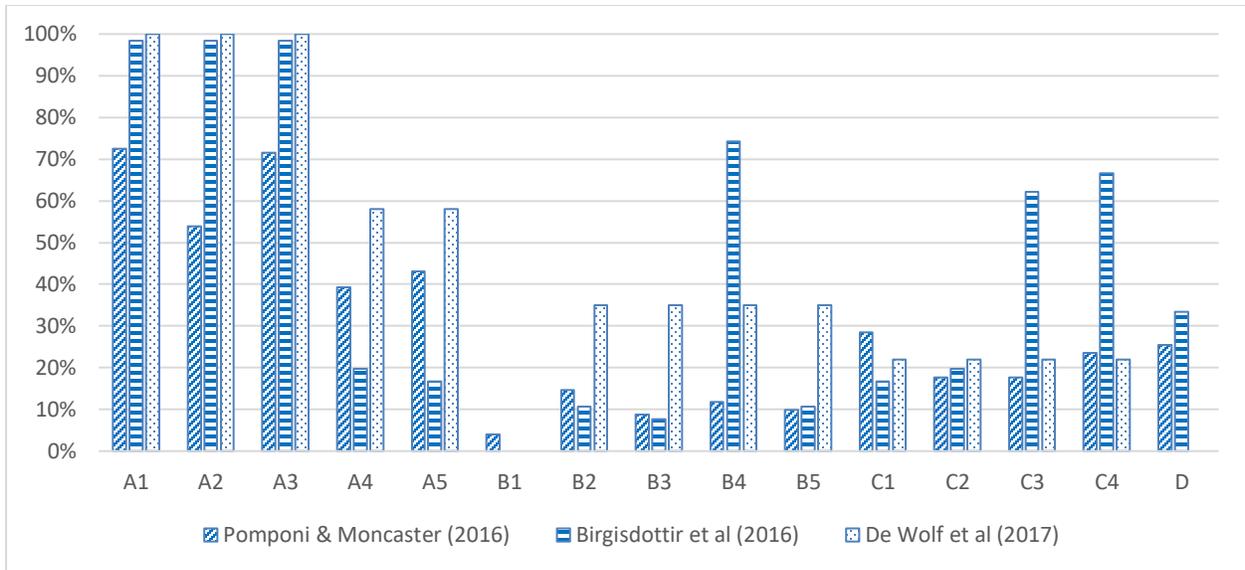
**Figure 2 - Life cycle stages included by academic authors reviewed by Birgisdottir et al. [25] and Pomponi and Moncaster [4], and as reported included by industry respondents (De Wolf et al. [28]).**

## 3.2    Data disparities in the embodied carbon coefficients

In their review of papers published since 2011, Pomponi and Moncaster [22] plot 105 data points for material coefficients for cement, concrete, load-bearing masonry, steel (virgin and including recycled content) and timber. This data has been revisited by this paper to give a revised version which plots the lower and upper quartiles and the mean for each of the structural materials (excluding cement), and this is given in Fig 3.
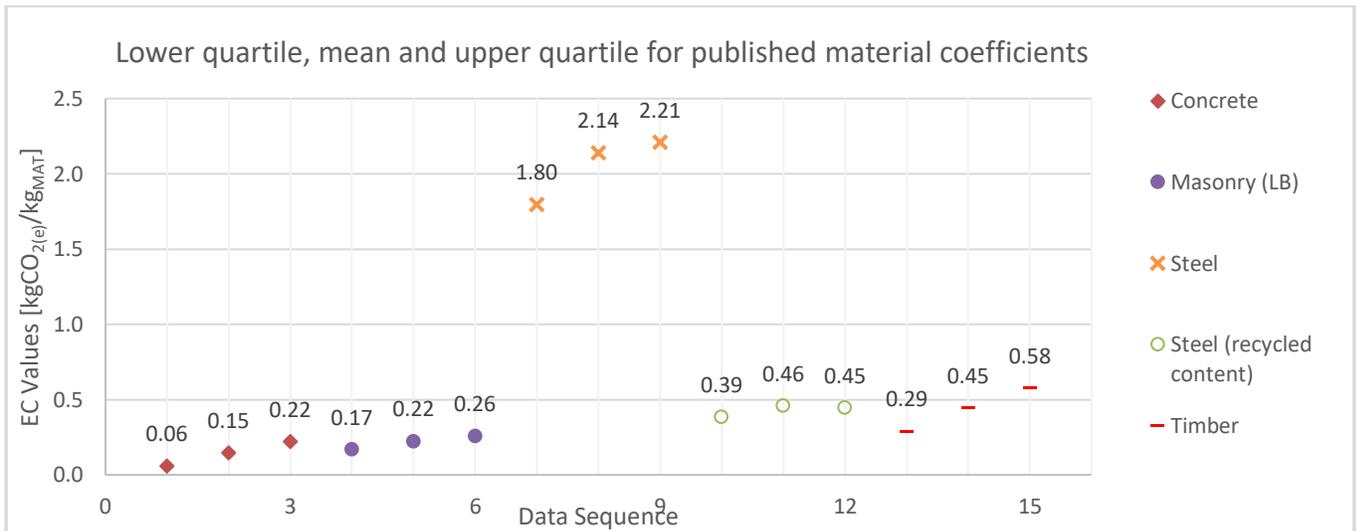


**Figure 3 - Distribution of EC coefficients used in academic literature for structural building materials, adapted from review in Pomponi and Moncaster [21]**

For calculating stage A4 (transport) at the early design stage, when exact suppliers and distances are not yet known, there are a range of methods in use in the academic literature. Some consider transport factors as proportional to the mass of construction material, in $kgCO_2/kg_{MAT}$, particularly where materials are

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likely to be sourced relatively locally such as concrete and masonry, but also frequently suggested for steel and general construction materials. Others require an estimate of distance travelled and sometimes also a knowledge of mode of transport, with values reported in $kgCO_2/t$ km. Similarly for calculating stage A5 (construction) multiple methods are used. Some authors assign a figure per $m^2$ of the building, and some suggest allowing between 16 and 32% of the whole life carbon. Yet another suggestion is that A5 should be calculated as a multiple of A4. Others suggest figures for the impact per kg construction material. There is the same variation in calculating the end of life stages C1-C4, which are sometimes related to the area of the building, or to the A1-A3, the A5, or the whole life impacts, or are simply expressed per kg material.

Table 1 shows the comparable reported alternative coefficients for stages A4, A5 and C, focusing on those which might vary with structural material choice.

**Table 1: Coefficients for stages A4, A5 and C adapted from analysis of literature in Pomponi and Moncaster [21]**

| Material | Transport coefficient A4 | units | Assumed distance (km) | **Construction coefficient A5 per kgMAT** | End of life coefficient C **per kgMAT** |
|---|---|---|---|---|---|
| concrete | 0.0133 | $kgCO_2/kg_{MAT}$ | 50 | -- | -- |
| masonry average | 0.0328 | $kgCO_2/kg_{MAT}$ | 50 | -- | -- |
| steel | 0.0127 | $kgCO_2/kg_{MAT}$ | 250[1] | -- | -- |
| timber | 0.15 | $kgCO_2/t$ km | 1500[2] | -- | -- |
| **All materials (lower)** | 0.032 | $kgCO_2/t$ km | -- | 0.000325 | 0.001 |
| **All materials (higher) per kgMAT** | 0.32 | $kgCO_2/t$ km | -- | 0.021 | 0.116 |
| **All materials (average) per kgMAT** | 0.0313 | $kgCO_2/kg_{MAT}$ | -- | -- | -- |
| [1] Distance from Port Talbot in Wales to Central England [2] Distance from Austria to Central England | | | | | |

### 3.3 Spatial differences in the physical building systems included
A third methodological variation identified in the literature review was that of the material boundaries of the assessments. **Error! Reference source not found.**Fig 4 shows the distribution of the number of reported EC coefficients in relation to the spatial boundaries of the assessments for the papers reviewed.
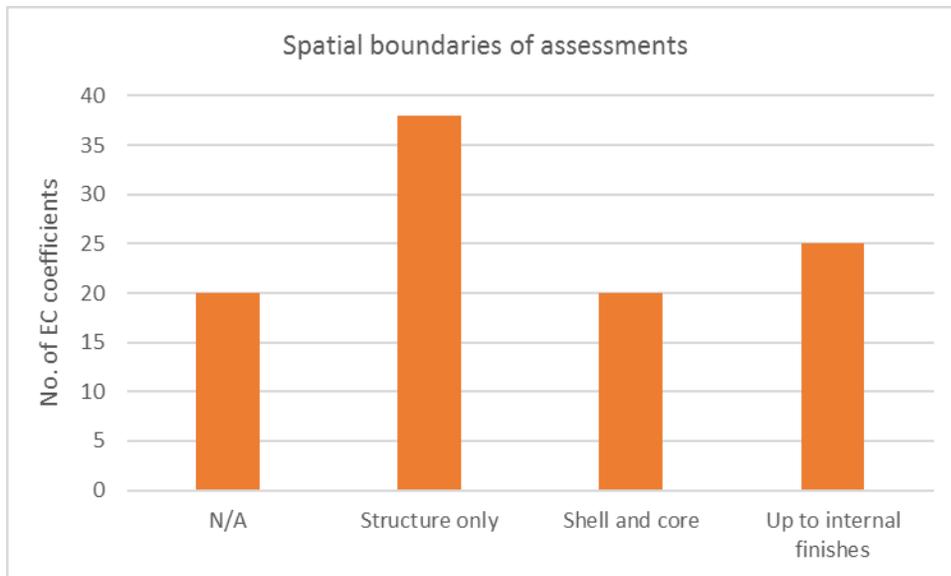
**Figure 4 - Distribution of EC coefficients across the spatial boundaries of the assessments.**

As can be seen, the majority of the assessments analysed only the structural elements of a building, including sub- and super-structure; however some included an analysis of the cladding envelope, often defined as the 'shell and core' [30], and some also included the internal finishes. None of the studies assessed included the fixtures and fittings or the services components. While the exact material boundaries are often not defined in the papers, it is assumed that 'structure only' refers to an assessment of the essential structural elements only, that 'shell and core' includes structural elements plus external cladding (walls, roof and windows), and the 'internal finishes' includes these plus internal non-load-bearing partitions and any internal linings to walls, floor and ceiling. The lack of definition of these boundaries in many papers reflects a common difficulty with reviewing published LCAs.

Not surprisingly in view of these results, words of caution about the use of LCA are sounded by many of the most recent authors. Anand and Amor [23, p.414] note that 'analyzing buildings … is one of the most complex applications of LCA'. Rasmussen et al. [24] note that the methodological discrepancies make it difficult to use individual case studies to inform practice or policy, unless the influence of the different choices is understood and taken into account, and Pomponi and Moncaster [22] call for a much greater transparency and conformity within the LCA community.

Despite the considerable problem identified above in the considerable differences in academic analyses of individual cases, which are often of exemplar low energy buildings as Cabeza et al. [18] point out, this is only part of the problem. The area in which major savings could be being made right now, with the right approach and advice, is in current industry practice. A rather smaller set of academic literature considers this. While Anand and Amor [23] acknowledge the increasing use of LCA in industry they see it as confined to building assessment tools such as BREEAM and LEED, in which it forms a small fraction of

a broad holistic sustainability assessment. The real state of understanding and practice, at least within the UK, is perhaps better revealed in a report on the 2014 UK Embodied Carbon Week [31]. While the analysis showed that transparent and openly available data, and consistent *measurement,* were the two main concerns of the industry attendees, there was also a clear belief that consistency in *method* already existed, and interestingly that there was no further need for research in this area. In 2016 De Wolf et al. [7] analysed a large number of case studies which were provided by major design firms from several countries. These all focused on the product stage (A1-3) and on the structural frame only, and formed a stand alone part of the design calculations, rather than part of an assessment tool. The existence of these analyses, and indeed of those captured by the WRAP Embodied Carbon Database [32], shows that as the Arup [31] report suggested there is some consistency within common industry calculations in the use of a limited method, focused often on product stage and on structural frame elements only. The authors of the current paper extended the picture of industry practice through qualitative research, including focus groups and interviews with industry consultants, as well as an analysis of the tools and databases which were identified as in common use.   De Wolf et al. [29] found additional evidence that the structural frame was the element of greatest interest, and confirmed that there was a prevalent focus on the product (A1-3) stage (see Figure 3 above). The transport and construction stages (A4 and 5) were the next most common stages calculated, with the use stages (B1-5) and end of life (C1-4) less likely to be included in the industry calculations.  Stage D, beyond the end of life, was not considered by the industry respondents or included in any of the tools reviewed [29].

While environmental assessment methods such as BREEAM and LEED do incorporate LCA, it appears that increasingly the design team are carrying out pared down calculations at the early design stage, mainly focused on the product stage A1-3, in order to support the choice of structural frame solution. These limited industry calculations are likely to be those that have the greatest real impact on embodied energy and greenhouse gas emissions.

## 4.  Case study

In order to investigate the potential impact of these three common methodological variations on the resultant choice of structural material, a case study was developed of the decision process which led to the choice of cross-laminated timber as the structural material for a building. For this building, as is increasingly common in design projects, the structural engineer had conducted an embodied carbon calculation at the early design stage and for the structural elements only, in order to identify an appropriate choice of structural material.

The building which was chosen for the case study is WYNG Gardens, a student residential block for Trinity Hall College, Cambridge, with a gross internal floor area (GIA) of 2250m$^2$. The block is 4 storeys

above ground; the basement has been excluded from the analysis assuming that it is identical for all four options. The building provides 71 student rooms plus a conference area, and is in the Cambridge Historic Core Conservation Area.

The Front (East) elevation is shown in Fig 5, and the ground floor plan in Fig 6. The building was completed in late 2016.



**Figure 5 - WYNG Gardens (previously St Clements Gardens): Front elevation (planning submission) Credit: Freeland Rees Roberts Architects**
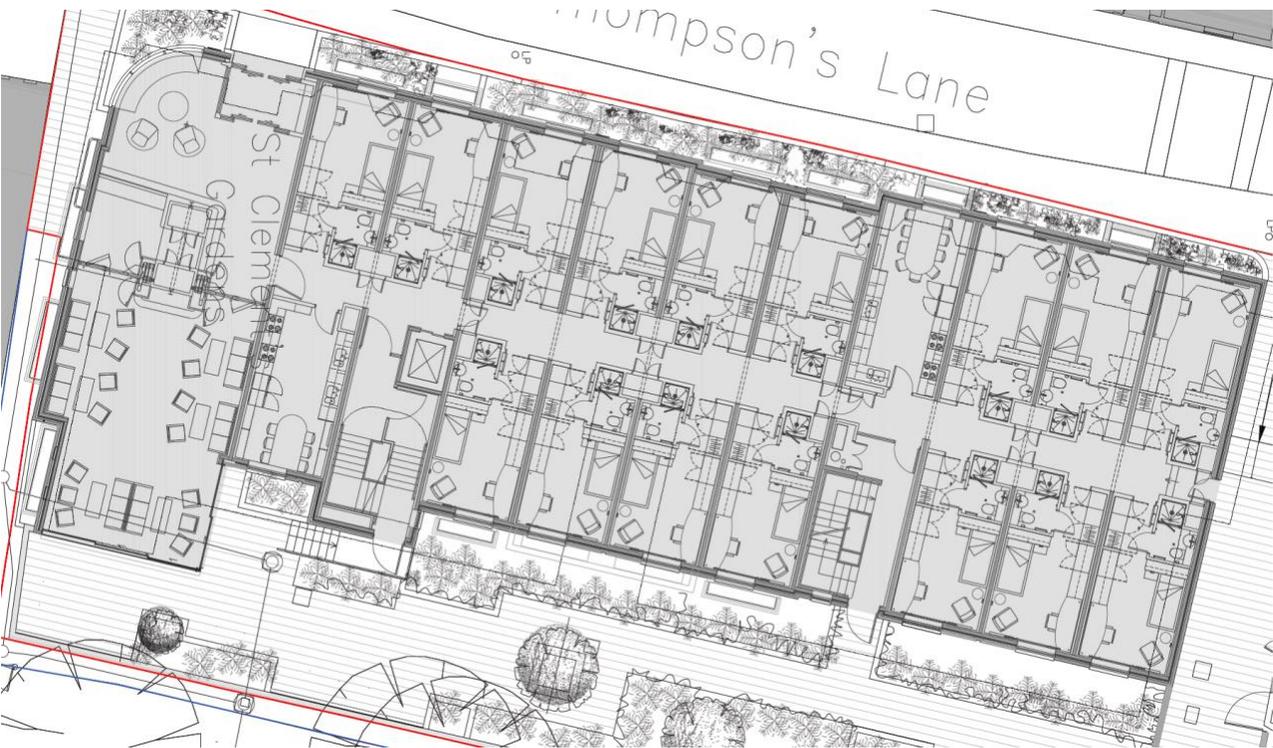


**Figure 6 - WYNG Gardens (previously St Clements Gardens): Ground floor plan (planning submission) Credit: Freeland Rees Roberts Architects**

Initial data collection included:

- The original calculations of material quantities and embodied carbon of three alternative structural frames – concrete frame, load bearing masonry, and cross-laminated timber

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(CLT) - which were provided by the structural engineer to the client as part of their tender stage documents in 2014.

- Additional calculations of material quantities and embodied carbon for a steel frame and slimdeck floor system provided by the structural engineer for this paper in 2016.

- The construction drawings for the CLT option showing detailed plans and elevations and the wall, floor and ceiling details.

- Email and face-to-face discussions with the structural engineer and the project architect.

The structural engineers' calculations of embodied greenhouse gases provided at Tender stage were based on estimates of material quantities for the above ground structural frame elements only, and used standard UK references for embodied carbon coefficients for stages A1-3 from the Bath/BSRIA Inventory of Carbon and Energy [33], with rounded quantities of materials and general specifications based on the limited design detail available at the time of calculation, reflecting an approach that is common within industry calculations as identified in the previous section and in an earlier paper [29]. Their results are replicated in Table 2 below. The internal walls for the four structural options differed; for the masonry and CLT structural systems the internal walls were load-bearing, and were therefore part of the structure, whilst for the reinforced concrete and steel frame options the internal walls were non-structural partitions. In these cases they were constructed of masonry in order to provide the acoustic separation needed between student bedrooms. In order to make the material boundaries of the comparative analyses equivalent, the non-load bearing masonry of the internal walls was included in the analysis of the structural elements in this case. However this is not always the case, as is discussed later in the analysis section of the paper. These calculations carried out by the structural engineer show the CLT solution to have considerably lower embodied carbon than all the other solutions.

Qualitative analysis is not the purpose of this study, but it is worth noting that in discussion both the engineer and architect stated that they were keen to use timber because they believed it to be more sustainable. The calculations produced supported this view. However the architect also suggested that the client was persuaded to use this material because it was both quicker to erect, and would be quieter to construct. These points are made as a side comment on the multiple reasons and values behind any decisions, in building projects as elsewhere.

Table 2: Comparing the embodied carbon of the four structural frame solutions: figures produced by structural engineers for the Tender stage report + additional information provided for this paper

| Description | Materials quantities (m³, uno) | Densities (kg/m³) | Total mass of material (t) | Coefficients (kgCO2e/kg) | Total Embodied (tCO2e) |
|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| **Concrete frame (CF)** | *RC columns and RC flat slab[1]* <br> *Internal walls: Masonry partitions[2]* | 600m³ concrete <br> 200m³ masonry | 2400 <br> 1950 | 1440 <br> 390 <br><br> **1830t** | 0.198 <br> 0.065 | 285t (concrete) <br> 25t (masonry) <br><br> **310t CO2e** |
| **Load-bearing masonry (LBM)** | *Masonry cross walls[2] and hybrid precast[3]/ in-situ RC[1] slab[4]* | 400m³ concrete <br> 400m³ masonry | 2400 <br> 1950 | 960 <br> 780 <br><br> **1740t** | 0.189 <br> 0.065 | 181t (concrete) <br> 51t (masonry) <br><br> **232t CO2e** |
| **Cross laminated timber (CLT)** | *Solid timber panel cross walls and slabs[5]* | 600m³ timber | 500 | 300 <br><br> **300t** | 0.42 | 126t (timber) <br><br> **126t CO2e** |
| **Steel Frame (SF)** | *Steel frame[6] (slimfloor) +hybrid precast[3] /in situ RC[1] slab[4]* <br> *Internal walls: Masonry partitions[2]* | 200t steel <br> 400m³ concrete <br> 200m³ masonry | - <br> 2400 <br> 1950 | 200 <br> 960 <br> 390 <br><br> **1550t** | 1.46 <br> 0.189 <br> 0.065 | 292t (steel) <br> 181t (concrete) <br> 25t (masonry) <br><br> **498t CO2e** |

**[1] In situ reinforced concrete spec: RC25/30+110kg/m³ reinforcement (p.41, Hammond & Jones [32])**
**[2] Masonry blockwork spec: 8MPa block, dense (1950kg/m³) (p.41, Hammond & Jones [32])**
**[3] Precast concrete spec: RC 40/50 (p.41, Hammond & Jones [32])**
**[4] Hybrid precast + in situ figure taken as average of [1] and [3] above**
**[5]Cross-laminated timber spec: 'glue laminated timber' (Glulam) used as no CLT figure available, carbon from fossil fuel only (p55, Hammond & Jones [32])**
**[6] Steel spec: General steel, UK typical, 59% recycled (p.50, Hammond & Jones [32])**

## 5. Analysis and discussion

The research carried out then reanalysed the figures for the building, as constructed in each of the four structural materials, varying the three key different methodological choices initially identified in the paper, including (1) the life cycle stages included in the analysis, (2) the embodied carbon coefficients for the main structural materials, and (3) the physical building elements included in the analysis.

### 5.1 Choice of life cycle stages included

As shown in Fig 2 it is common to calculate only the 'cradle to gate' A1-3 phases, as was the case in the original calculations for the WYNG Gardens building. A4 (transport to site) and A5 (construction) are the next most common stages to include, followed by the C (end of life) and then D (beyond end of life) stages, with the B stages (in use) most often omitted. This section considers what impact, if any, the inclusion or exclusion of the most common of these different stages, A4, A5 and C, might have on the choice of structural material for this particular building.

The resultant impacts of the transport stage for WYNG Gardens are given in Table 4, with the figures underlined being the lowest and highest calculated figures for each structural system.

Table 3: Resultant alternative figures for stage A4 depending on choices of transport coefficients for the different structural solutions

| Structural system | Volume | Mass | A4 (using coeffs for individual materials) | A4 (using All mats ave per kg$_{MAT}$) (tCO₂e) | A4 (using All mats (lower bound) per t km) | A4 (using ave per t km) | A4(using All mats (upper bound) per t km) |
|---|---|---|---|---|---|---|---|
| Units | (m³) uno | (t) | (tCO2e) | (tCO2e) | (tCO2e) | (tCO2e) | (tCO2e) |
| | 600m3 concrete | 1440 | 19.15 | 45.07 | 2.30 | 21.53 | 23.04 |
| | 200m3 masonry | 390 | 12.81 | 12.21 | 0.62 | 5.83 | 6.24 |
| **Concrete Frame (CF)** | **1830** | **32** | | **57** | **3** | **27** | **29** |
| | 400m3 concrete | 960 | 12.768 | 30.05 | 1.54 | 14.35 | 15.36 |
| | 400m3 masonry | 780 | 25.61 | 24.41 | 1.25 | 11.66 | 12.48 |
| **Load-bearing masonry (LBM)** | **1740** | **38** | | **54** | **3** | **26** | **28** |
| | 585m3 timber | 300 | 67.5 | --- | 14.4 | 134.55 | 144 |
| **Cross-laminated Timber (CLT)** | **300** | **68** | | --- | **14** | **135** | **144** |
| | 200t steel | 200 | 2.54 | 6.26 | 1.6 | 14.95 | 16 |
| | 400m3 concrete | 960 | 12.77 | 30.05 | 1.54 | 14.35 | 15.36 |
| | 200m3 masonry | 390 | 12.81 | 12.21 | 0.62 | 5.83 | 6.24 |
| **Steel Frame (SF)** | **1550** | **28** | | **49** | **4** | **35** | **38** |

The impact of the low and high figures for WYNG Gardens for the construction stage A5, and for the end of life stage C, where these are calculated per kg of construction material, are given in Table 5.

Table 4: Resultant alternative figures for construction stage A5 and end of life stage C for the different structural solutions

| Structural system | Mass | A5 (low) 0.000325 kgCO₂/kg$_{MAT}$ | A5 (high) 0.021 kgCO₂/kg$_{MAT}$ | C1-4 (low) 0.001 kgCO₂/kg$_{MAT}$ | C1-4 (high) 0.116 kgCO₂/kg$_{MAT}$ |
|---|---|---|---|---|---|
| Unit | (t) | (tCO2e) | (tCO2e) | (tCO2e) | (tCO2e) |
| Concrete Frame (CF) | 1830 | 0.6 | 38 | 1.8 | 212 |
| Load-bearing masonry (LBM) | 1740 | 0.6 | 37 | 1.7 | 202 |
| Cross-laminated Timber (CLT) | 300 | 0.1 | 6 | 0.3 | 35 |
| Steel Frame (SF) | 1550 | 0.5 | 33 | 1.6 | 180 |

## 5.2 Choice of embodied carbon coefficients for structural materials

As shown in Figure 3 there are a wide range of figures in use for embodied carbon of the basic structural frame materials. It should be noted that all of these figures have been used in recently published academic

papers. For WYNG Gardens, the average figures for the four materials compared are mostly fairly close to those chosen by the structural engineers. However, similar calculations at an early design stage using other choices of coefficient could make a radical difference to the result. While the highest figures in each case are the steel frame, and the lowest in each case are the timber structure, the relative impacts of load-bearing masonry or concrete frame change, so if this had been the consideration it would have been highly dependent on choice of coefficients. More importantly, for this building the choice of the lowest coefficients for each of the other materials, concrete, masonry and steel, would produce results – 76, 89 and 93 $kgCO_2e/kg$ - <u>lower</u> than the structural engineer's result for the timber structure of 126 $kgCO_2e/kg$.

Therefore extending the results of a single case study calculation such as this, or comparing two or more disparate case study calculations, or extending a limited comparative calculation to understand the full extent of embodied carbon of buildings, would not be valid.

**Table 5: A1-A3 Embodied carbon for different structural material systems, based on the boundaries used by the structural engineers, comparing the impact of different material embodied carbon coefficients**

| | Materials (tonnes) | Structural engineer's figures | | Low **values** | | Average **values** | | High **values** | |
|---|---|---|---|---|---|---|---|---|---|
| | | kgCO$_2$e/kg | Total tCO$_2$e | kgCO$_2$e/kg | Total tCO$_2$e | kgCO$_2$e/kg | Total tCO$_2$e | kgCO$_2$e/kg | Total tCO$_2$e |
| **Concrete frame** | 1440 concrete | 0.198 | | 0.033 | | 0.149 | | 0.295 | |
| | 390 masonry | 0.065 | 310 | 0.074 | 76 | 0.224 | 302 | 0.550 | 639 |
| **Load-bearing masonry** | 960 concrete | 0.189 | | 0.033 | | 0.149 | | 0.295 | |
| | 780 masonry | 0.065 | 232 | 0.074 | 89 | 0.224 | 318 | 0.550 | 712 |
| **Cross laminated timber** | 300 timber | 0.42 | | 0.200 | | 0.448 | | 0.720 | |
| | | | 126 | | 60 | | 134 | | 216 |
| **Steel Frame** | 200 steel | 1.46 | | 0.160 | | 0.46 | | 1.670 | |
| | 960 concrete | 0.189 | | 0.033 | | 0.149 | | 0.295 | |
| | 390 masonry | 0.065 | 498 | 0.074 | 93 | 0.224 | 322 | 0.550 | 832 |

## 5.3 Choice of physical building elements included

The third aspect to be considered is the material boundaries, the building elements included in life cycle analysis assessments. As shown earlier, often analyses are classified as 'structure only', 'shell and core', or 'up to internal finishes', frequently with inadequate description of what is included. The calculations produced by the structural engineers in this case study were of the structural elements, and in this case only the superstructure elements. The analysis was based on the early design stage information from the

structural engineer and architect, and has not been extended to quantify the impact of adding further material elements. However this section considers the potential impact that changing the material boundaries would have.

Firstly it is important to point out that alternative 'structure only' calculations might in other cases also include the substructure (foundations, basement). These have a major impact on the embodied carbon figures, as concrete (almost always the major or only component) is a carbon-intensive material, but nevertheless the impact would be the same for all four options. However if the building had been erected with no basement, the lighter timber structure would need smaller foundations, and therefore the carbon impact of this element would also be reduced.

'Shell and core' calculations would incorporate additional elements including cladding and non-load-bearing external walls, windows and doors, and internal partitions. The WYNG Gardens building is within a conservation area of Cambridge, and so the external appearance is defined by planning requirements and the external cladding would be the same for all options.  Therefore, again in this case, this would make no difference to the choice of structural framing option.

However, the internal walls <u>would</u> vary between the solutions, as would their carbon impact. As stated earlier, the structural engineers in this case chose to include calculations for the non load-bearing internal walls for the concrete and steel frame solutions, in order to compare 'like with like' with the two solutions which included load-bearing internal walls. The non load-bearing walls are identified as masonry, of the same specification as for the load-bearing masonry solution, which is a valid assumption because of the client's requirements for acoustic separation between the student rooms. However the detail drawings of the chosen CLT structural material show that the CLT internal walls were also layered with additional cementitious materials for acoustic separation. The architect confirmed that this was at the specific request of the client who was concerned about noise penetration through timber walls. Masonry walls would not require this detail. Therefore the comparison of the structural solutions missed this additional element, which would have increased the impact of the CLT option.

An additional issue occurred for the floor slabs. In the CLT option the floor slabs were also timber, and again were combined with additional non-structural cementitious layers for acoustic separation which were not included in the original calculations. The other solutions included concrete slab floors (either in situ reinforced concrete or hybrid pre-cast and in situ concrete) which would not have required the additional cementitious layers for acoustic separation. As with the additional layers on the internal walls, this would have again increased the overall embodeid impact of the CLT option.

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The third level of analysis considered by other authors is described as 'up to internal finishes', and includes additional elements of the wall, floor and ceiling linings and finishes. External works, fixtures and fittings, and services components are also sometimes included in calculations. Each of these elements are assumed to be equal for the four structural solutions and so can be assumed to have no impact on the comparative results. However since these are the elements which are most likely to require replacement, possibly several times, over the lifetime of the building, these elements would have a significant impact on the whole life embodied carbon if the in use B stages (Fig 1) are included in the calculation, showing another example in which limited calculations can misrepresent the real impacts of different elements.

In summary the points to be noted in considering the material boundaries of the assessment in this particular case are:

a) That the perceived difference in acoustic performance of the CLT internal walls and floors required an additional cementitious layer, which is not included in the current calculations, but which would increase the impact of the CLT option relative to the others;

b) That the existence of a heavy concrete basement in this case would add a considerable embodied impact equally to all four options;

c) That, however, if there was no basement, it is likely that the foundations for the timber building would be lighter and have a relatively lower embodied impact;

d) That the addition of the cladding to the calculation could add a significant proportion to the A1-3 stage embodied impact, which again would be the same for all four options, and

e) That the addition of the fixtures, fittings and services elements could add a significant proportion to the impacts over the lifetime of the building (the B stages) as these are elements which wear out and need to be replaced.

## 5.4 Combined impact

Table 6 combines the results from the initial analysis carried out by the structural engineer Smith and Wallwork (S&W), with the separate analyses in the previous section, in order to show the lower and higher results which could be obtained using different coefficients published in recent academic literature, for the A1-3, A4, A5 and C life cycle stages. Common combinations of stages found in the literature, A1-5, and A+C, are added as additional columns. Figure 8 plots these results in clustered bars, with the original A1-3 results from the structural engineer (column a) plotted on the left, followed by the three common temporal boundaries and the low and high choices of coefficients taken from the recently published literature, in the order of A1-3 (columns b and c), A1-5, (columns h and i) and A+C (columns l and m).

**Table 6: Resultant alternative figures for stages A1-A5**

| (tCO$_2$ e) | A1-3 S&W | A1-A3 low | A1-A3 high | A4 low | A4 high | A5 low | A5 high | A1-5 low | A1-5 high | C1-4 low | C1-4 high | A+C low | A+C high |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | a | b | c | d | f | e | g | h = b+d+e | i = c+f+g | j | k | l=h+j | m= i+k |
| Concrete frame (CF) | 310 | 76 | 639 | 3 | 57 | 0.6 | 38 | 80 | 734 | 1.8 | 212 | 81 | 946 |
| Load-bearing masonry (LBM) | 232 | 89 | 712 | 3 | 54 | 0.6 | 37 | 93 | 803 | 1.7 | 202 | 94 | 1005 |
| Cross laminated timber (CLT) | 126 | 60 | 216 | 14 | 144 | 0.1 | 6 | 74 | 366 | 0.3 | 35 | 74 | 401 |
| Steel Frame (SF) | 498 | 93 | 832 | 4 | 49 | 0.5 | 33 | 98 | 914 | 1.6 | 180 | 99 | 1094 |
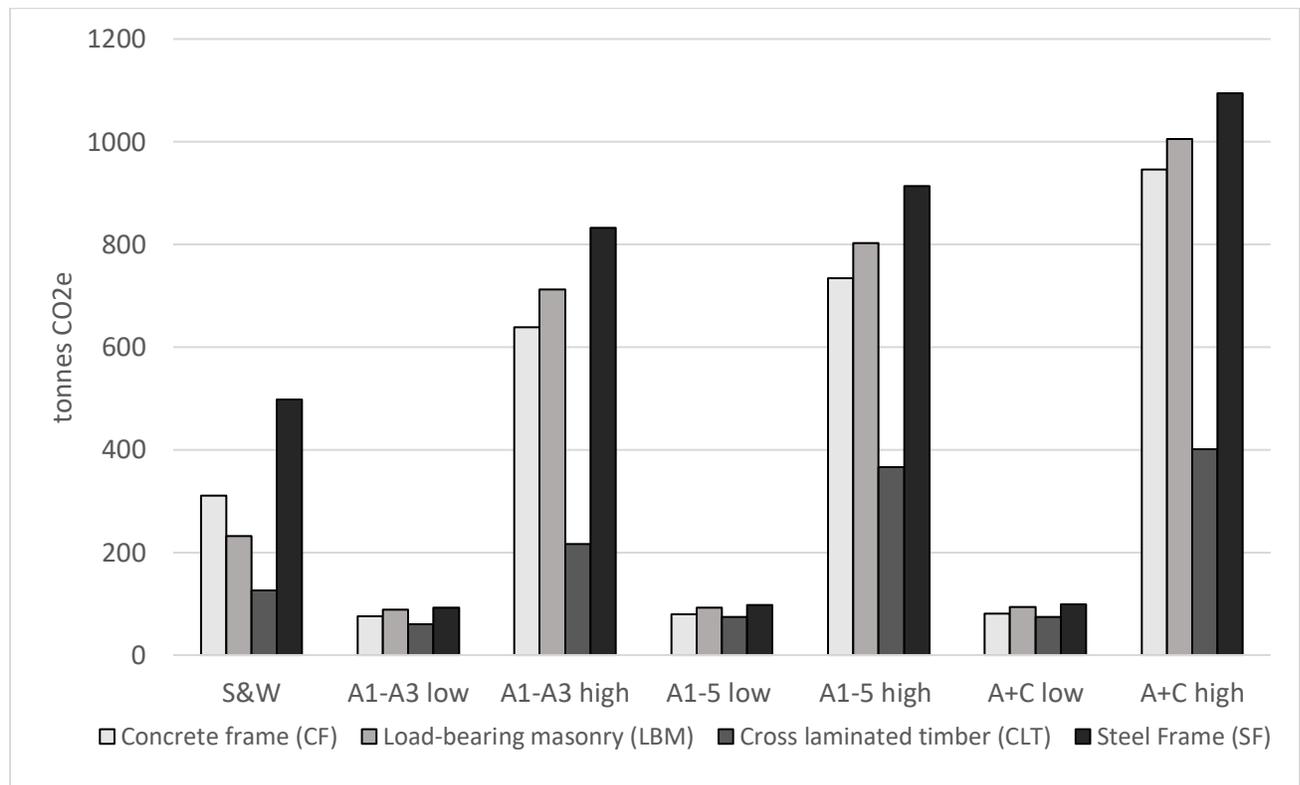


Figure 8: Bar chart of possible results for the comparative frame analyses using different published coefficients

The graph demonstrates that the choice of coefficients has a very significant impact on the results. For the material coefficients, A1-3, the higher values are up to 9 times the lower values for the steel frame. The

differences in the A+C analyses are even greater, with the higher assessments for both the concrete and steel frames being over 11 times the lower assessments.

Although the impacts of the transport (A4) and construction (A5) stages are generally considered to be small, it is clear that for some choices of material and of coefficient adding these stages to the assessment can make a considerable difference. The values shown here are approximated by a simple pro rata coefficient, which may not fully capture the reality. However they show that the impact of transporting timber is potentially as much as a third of the total A1-A5 impact for a CLT building. Using the higher figures for stages A1-A5 for the CLT system would give a figure of 366 $tCO_2e$, or almost three times the figure reported by the structural engineer of 126 $tCO_2e$ for stages A1-A3 only. The figure for A4 for steel would increase considerably if the steel was shipped from China, as is generally the case for larger building projects in the UK, but not calculated for this building. The figures for construction, A5, chosen for comparison here, are relatively low, but the published literature gave a far wider range and again this pro rata assessment is based on little evidence.

Both Table 6 and Fig 8 therefore demonstrate the problem with comparing multiple analyses by different authors, even where these are of the same building and using the same initial information. If the different authors had chosen different material coefficients, even if they had considered the same temporal and material boundaries, the results produced would have been quite different. It would be quite possible to, say, find an analysis of a steel frame giving a total figure for A1-5 of 98 $tCO_2e$, and compare it with an analysis of a concrete frame giving a total of 743 $tCO_2e$ and come to the conclusion that the steel solution clearly had the lower impact; or to find an analysis of a cross-laminated timber structure giving a total for A+C of 401 $tCO_2e$ compared with an A+C analysis of a load-bearing masonry structure giving a total of 94 $tCO_2e$, and conclude that the CLT solution had a higher impact than the masonry.

Nevertheless, within each group of analyses the CLT remains the lowest impact option and the steel frame the highest, suggesting that the advice from the structural engineer to the client for this building was correct.

## 6. Concluding remarks

It is acknowledged that there are multiple different reasons for choosing different structural systems, in addition to their embodied impacts, including their suitability to the use of the building, the cost and availability of that material, risk limitations and cost certainty, the speed of erection, the appearance (where exposed), the available experience in designing and constructing in that material, and several others. However choosing a structural system with lower greenhouse gas emissions has clear implications for the mitigation of climate change and for contributing to national environmental targets, and should always therefore be a consideration.

This paper has first identified the most common methodological approaches and choices used in the life cycle assessment of buildings. Using the published academic literature from the last five years it has identified three particular variations: the temporal boundaries provided by the choice of life cycle stages, the choice of coefficients used for materials and different life cycle stages, and the material boundaries of the physical elements included in assessment. The three most common temporal boundaries are found to be A1-3, A1-5, and A+C; a very wide range of coefficients are found for the key structural materials, and both coefficients and calculation methods vary for the A4, A5 and C stages; and material boundaries commonly vary between 'structure only', 'shell and core' and 'up to internal finishes'. In all of these it is also apparent that many authors fail to state clearly what the assumptions underpinning their analyses are.

A case study of a residential college building in Cambridge has then been used to consider the impacts that these methodological choices might have on the calculated embodied carbon, and hence on the choice of structural material. For this case study building the structural engineers developed four alternative structural solutions including concrete frame, load-bearing masonry, cross-laminated timber, and steel frame, and calculated the product stage (A1-3) embodied carbon for each. This paper then used the various methodological approaches from the literature to re-analyse the building for each structural material.

The results are quite remarkable. This is not a large or complex building, and the analyses have been based on the limited information available at the design stage, as were the original structural engineers' calculations. Nevertheless it is possible to demonstrate differences between the lowest figures for the A1-3 stages, and the highest figures for the A+C stages, from a factor of 6.5 for the cross-laminated timber up to much as 11.5 for the steel frame solutions. The range for the CLT solution is between 60 and 401 tonnes $CO_2e$, which is between 27 and 178 kg $CO_2e$ /$m^2$, and for the steel frame solution is between 93 and 1094 tonnes $CO_2e$, or 41 and 486 kg $CO_2e$ /$m^2$. These figures can be compared with a benchmarking exercise of multiple buildings by [7], which found figures ranging between 150 and 600 kg $CO_2e$ /$m^2$. The figures found in this paper are therefore relatively low in comparison, but this is likely to be due to the omission of the foundation structures from this analysis, combined with the fact that this is a straightforward low-rise building. What is important to point out, however, is that De Wolf et al. [7] were comparing several hundred very varied buildings to consider the impact that different designs have on the embodied carbon. What this analysis shows is that *the impact of difference in methodology*, *for calculations on a single building,  can be higher than the impact of different design using the same methodology.*

It should be stressed furthermore that these differences are by no means the greatest that could be calculated. They are based on a limited review of coefficients used in the published literature over the last

five years; apply them to a single case study; do not include consideration of any of the B life cycle stages or stage D; and have not quantified the impact of changing the material boundaries analysed.

While the paper suggests that the chosen solution of cross-laminated timber, as the lowest embodied carbon material, is likely to have been correct, it also demonstrates clearly that *any of the most common structural materials could appear to be preferable to the others, if limited and poorly defined calculations are offered for comparison*. Life cycle assessment is a tool which is only as good as the data and methodological assumptions underpinning the calculation, and, most importantly, rational conclusions can only be drawn from a detailed understanding of what these data and assumptions are.

The findings have very serious implications for the responsibility of the authors of LCA calculations to be absolutely clear about their assumptions and about the conclusions that can be drawn. Guidelines, including the TC350 standards and the newly published RICS Professional Statement [34], exist to support the production of transparent assessments based on realistic assumptions, and it is the responsibility of academics and practitioners in the field to ensure that these guidelines are followed. It is perhaps even more critical that all assumptions and data choices are clearly stated in the calculation, and that any use of the results takes these assumptions and choices into account.

This is particularly important for embodied carbon calculations; while inaccuracies in operational energy analysis will be apparent as soon as the first energy bills come through, and also allow the possibility of rectifying the problem, the true embodied carbon and energy impacts of individual buildings will remain invisible until they have an irreversible impact on the global environment. In order to meet our mid-century carbon targets it is therefore essential that we identify, and rectify, the disparities in embodied carbon calculations as a matter of urgency.

## Acknowledgements

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