

Whole-life embodied carbon in multistory buildings

Steel, concrete and timber structures

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Abstract

Buildings and the construction industry are top contributors to climate change, and structures account for the largest share of the upfront greenhouse gas emissions. While a body of research exists into such emissions, a systematic comparison of multiple building structures in steel, concrete, and timber alternatives is missing. In this article, comparisons are made between mass and whole-life embodied carbon (WLEC) emissions of building superstructures using identical frame configurations in steel, reinforced concrete, and engineered timber frames. These are assessed and compared for 127 different frame configurations, from 2 to 19 stories. Embodied carbon coefficients for each material and life cycle stage are represented by probability density functions to capture the uncertainty inherent in life cycle assessment. Normalized results show clear differences between the masses of the three structural typologies, with the concrete frame approximately five times the mass of the timber frame, and 50% higher than the steel frame. The WLEC emissions are mainly governed by the upfront emissions (cradle to practical completion), but subsequent emissions are still significant—particularly in the case of timber for which 36% of emissions, on average, occur post-construction. Results for WLEC are more closely grouped than for masses, with median values for the timber frame, concrete frame, and steel frame of 119, 185, and 228 kgCO₂e/m², respectively. Despite the advantage for timber in this comparison, there is overlap between the results distributions, meaning that close attention to efficient design and procurement is essential. This article met the requirements for a gold–gold JIE data openness badge described in <http://jie.click/badges>.



KEYWORDS

building structures, construction, cross-laminated timber (CLT), embodied carbon, life cycle assessment (LCA), material efficiency

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1 | INTRODUCTION

1.1 | Background

The operation of buildings is responsible for 28% of global CO₂ emissions with a further 11% attributable to the construction industry, including the manufacture of building materials and components (IEA, 2019). Therefore, nearly 40% of global CO₂ emissions are linked to buildings and construction. The absolute totals from these sources continue to increase as the increase in global floor area offsets energy efficiency gains. These are also undermined by the rebound effect which, for instance, allows the benefits of energy efficiency to be taken as improved comfort rather than lower energy consumption and is acknowledged as an important consideration for policy-makers (Sorrell, 2007). If global emissions are to be reduced in support of the Paris agreement (United Nations, 2015) to limit global temperature rises to 1.5–2°C above pre-industrial levels, considerable progress must be made with buildings and construction.

The Global Status Report (IEA, 2019) identifies reduction of embodied energy and greenhouse gas (GHG) emissions as a priority for action but does not present evidence of systematic and coordinated action in this area. With continuing global population growth and increased urbanization, global floor area has recently (2010–2018) grown at more than 2.6% p.a. (IEA, 2019). If continued, this would result in a further doubling of floor area before 2050. In testing alternative decarbonization strategies for the English housing stock, Serrenho et al. (2019) highlighted the extent of the challenge of meeting GHG emissions reduction targets, focusing on operational carbon. A parallel effort is needed to explore strategies for reducing embodied GHG emissions (embodied carbon) in all new construction and the contribution this can make to reducing industry GHG emissions. While a plethora of options exist for building envelopes, only the three main structural systems that we analyze are viable, high-volume, short-to-mid-term solutions to accommodate population growth. Better understanding of the environmental impacts of such structural systems is therefore crucial.

The relative environmental merits of concrete and steel structural systems have been debated for at least 20 years (Jonsson et al., 1998). But engineered timber, such as glulam and cross-laminated timber (CLT), is increasingly recognized as a viable alternative, with examples of up to 14 stories already realized, 24 stories under construction, and even taller buildings planned (CTBUH, 2017; Teshnizi et al., 2018). Going beyond the sporadic case study approach commonly presented in the literature, there is a clear need for a systematic assessment of the climate change impacts or mitigation potential of different structural systems across a range of configurations. The Database of Embodied Quantity Outputs (DEQO) (De Wolf et al., 2020) goes some way toward addressing this, through secondary data collected from multiple industry stakeholders. This approach does not, however, offer transparency on system boundaries, data sources, and cut-off rules, and the underpinning data is not produced according to harmonized national or international methodologies. Even when agreed rules and common data are used, results from different assessors can be significantly different (Pomponi et al., 2018).

Understanding of the life cycle environmental impacts of buildings involves investigations at a range of levels from materials to buildings and developments. Life cycle assessment (LCA) of buildings offers insights into the relative importance of a wide range of building elements over a long time period. This holistic and necessary viewpoint does, however, require support from investigations with a tighter focus, such as structure and materials, as discussed in this article.

1.2 | Previous work

Previous studies have provided insight into the embodied carbon of building structures, exploring a range of building types, life cycle stages (for instance, cradle-to-gate or cradle-to-grave), and scopes (for instance, structural frame or whole building). Simonen et al. (2017) identified 384 kilograms carbon dioxide equivalent per square meter (kgCO₂e/m²) of floor area as a median value for embodied carbon across all types of building covered in their meta-analysis. In their cradle-to-gate analysis of structural frames, De Wolf et al. (2016) reported that timber frames had the lowest median value (~200 kgCO₂e/m²) compared to the steel and concrete systems (at ~350–380 kgCO₂e/m²). The ranges, however, are wide and overlapping, partly because of the variety of building types studied. A meta-analysis of non-residential, single, whole-building LCA studies found that in eight out of eight studies, wood frames achieved lower Global Warming Potential (GWP) than concrete, and in five out of six cases wood was better than steel. The exception here was a steel design credited with high optimization and durability (Saade et al., 2019).

Taking an approach closer to that followed in this work, other researchers have compared results for alternative structural systems for the same buildings. Nadoushani and Akbarnezhad (2015) assessed the cradle-to-grave embodied carbon of five steel and reinforced concrete (RC) structural variants for three structures of 3–15 stories in Atlanta, Georgia. The results were in the range of 148–233 kgCO₂e/m², with the upper end of the range corresponding to 15-story RC. Hafner and Schäfer (2018) assessed 13 timber residential buildings in Germany and Austria alongside mineral comparators, designed for the purpose, through a cradle-to-grave analysis (with omissions, e.g., construction and demolition processes) of the building structure. By their analysis, timber buildings had significantly lower embodied carbon (9–56%) than their mineral counterparts. Skullestad et al. (2016) compared cradle-to-gate impacts for timber and RC alternatives for four structures up to 21 stories: results were in the range 111–121 kgCO₂e/m² for mid-rise RC structures and 26–40 kgCO₂e/m² for timber. The strikingly low numbers in this study are at least partly attributable to the low emission factor of the Nordic electricity mix (0.139 kgCO₂e/kWh), and sensitivity analysis showed a narrowing of the gap between timber and concrete if a higher emission factor is assumed. Research for the UK's Committee on Climate Change (Spear et al.,

2019) has found embodied carbon savings in the range of 220 to 260 kgCO₂e/m² (internal area) for the structures of apartment buildings in CLT compared to concrete, along with the result that a high-growth scenario for timber usage can reduce the embodied carbon of UK domestic building construction by 0.8–1.0 MtCO₂e annually by 2050.

Some authors express any advantage that timber construction has over mineral alternatives as a displacement factor. This is presented in terms of tonnes of GHG emissions (as carbon) avoided per tonne of carbon in the timber itself. In their meta-analyses, Sathre and O'Connor (2010) calculate an average displacement factor of 2.1 tonnes of carbon emissions avoided per tonne of carbon in the timber (tC/tC) from a variety of studies, and Geng et al. (2017) identify a range of 0.25 to 5.6 tC/tC, including reference to a study comparing wood framed buildings to steel and concrete alternatives, for which the range was 0.9 to 2.2 tC/tC (Lippke et al., 2004). Some of the studies referenced in these articles are many years older than the articles themselves, and it is reasonable to expect that current displacement factors would be low compared to these ranges, as manufacturing efficiency improves over time.

Purnell (2012) investigated the embodied carbon of structural materials as a function of their load capacity. The importance of material selection was found to be dependent on the context and general conclusions were drawn that timber should be preferred for very light duty columns and longer, light duty beams, whilst other cases needed more careful assessment. In many cases, it was found that the lowest embodied carbon was achieved with RC made from a concrete mix optimized for low embodied carbon (C50/60 with 40% of cement substituted by pulverized fuel ash). However, the implications of using heavier columns and beams on the elements beneath them was not part of the analysis.

One case study of a 16-story concrete building in China (Zhang & Wang, 2016) finds that foundations (including a basement) and groundwork are responsible for emissions of 65 kgCO₂e/m² of floor area, with superstructure adding a further 275 kgCO₂e/m². Whilst the design of substructures and superstructures are closely linked, there is also a degree of independence, with multiple factors other than the weight of the superstructure contributing to the specification of the foundations. This may explain why researchers, as in this study, frequently assess the superstructure only—for instance Helal et al. (2020)—especially when pursuing a systematic approach. Others isolate the foundations, for example Sandanayake et al. (2016), who calculate the embodied carbon (including construction) of the foundations/basement of two high-rise buildings (48 and 52 floors): although the areas of the buildings are not given, the results imply a substantially smaller contribution per floor area than the 65 kgCO₂e/m² quoted above.

The great variability in the embodied carbon coefficients (ECCs, which indicate GHG emissions per unit of material for a defined life cycle stage) that might be ascribed to materials has been highlighted by Pomponi and Moncaster (2018). Within the product stage, values for concrete are consistently lower than those for timber and steel in terms of kgCO₂e/kg of material. But an analysis of a real building aimed at understanding the impact of methods on results (Moncaster et al., 2018) returned a different picture, with timber consistently being the option with the lowest embodied carbon out of the systems compared (CLT, RC frame, steel frame, and load-bearing masonry).

It is important to recognize the stresses placed on LCA by methodological variation, data quality, and uncertainty. Emami et al. (2019) investigated the significance of the database selection for the analysis of embodied environmental impacts of a residential building: for this they compared results of analyses using ecoinvent with SimaPro software, and GaBi software database. For some impact categories the differences between the results are stark: more than an order of magnitude for marine eutrophication, for instance, although in the case of climate change the level of consistency is better (±15%). Methodological variation is also important in design: Helal et al. (2020) have found a 22% variation in embodied carbon (stages A1–A5) in tall buildings can result from variations in design methods and structural loads, which highlights the need for clarity and transparency in the design and communication of LCA studies of buildings.

Sources of uncertainty in LCA include the historic data used to derive ECCs (accuracy, completeness, and geographical relevance); uncertainties about future events and (e.g., in-use and end-of-life emissions); and uncertainty in system boundaries and methods of measurement (Gantner et al., 2018). This last point is crucial when coalescing data from a variety of sources with varying methodologies and degrees of translucency. Although international standards such as EN 15978 (BSI, 2011a) support consistency in principle, in some contexts it is not always clear where the boundaries should be drawn.

As it relies on external data sources, this study is not exempt from the challenges of working with data of debatable quality or relevance. Data supporting the analysis is plentiful for the product stage, and straightforward to model for the transport stage. From this point onward, good quality data becomes scarce. Context-relevant data on the processes and primary energy demands associated with construction and demolition are a case in point, and further investigations of this subject would be useful.

There are, therefore, good grounds for employing a systematic treatment of uncertainty, and our approach is detailed in the next section.

2 | METHODS

2.1 | Overview

We investigate the mass and whole-life embodied carbon (WLEC) emissions of building superstructures of three structural systems (steel, reinforced concrete, and engineered timber frames) in the UK context. The 127 structural frame configurations were parametrically generated and designed, and the mass and WLEC are calculated for each of the three structural systems in each configuration: 381 cases in all. The calculation

Building life cycle information														Supplementary info beyond building life cycle
Product stage			Construction process stage		Use stage					End of life stage				
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	
Raw material supply	Transport	Manufacturing	Transport	Construction & installation process	Use	Maintenance	Repair	Refurbishment	Replacement	De-construction / demolition	Transport	Waste processing	Disposal	Reuse, Recovery, Recycling Benefits & loads beyond system boundary
					B6 Operational energy use									
					B7 Operational water use									

FIGURE 1 Life cycle stages classification, as defined in EN 15978 (BSI, 2011a) and used throughout this article. The stages that are assessed in whole or in part in our analysis and therefore included in our system boundary are shaded

of WLEC takes account of uncertainty in the values of the ECCs of materials. The results provide useful guidance on the WLEC associated with different structural systems that designers can apply in different contexts. The analysis is restricted to the superstructure, excluding foundations. Foundation design is highly site specific because of varying ground conditions, and is also project specific because of decisions to include or exclude basements in the project. The cost of this exclusion is that the impact of the structural mass on the WLEC of the foundations is not explored, but the benefit is that the results are more broadly applicable. If basements are included in a building project (as they are in at least half of the projects reviewed for this study), the sensitivity of WLEC to the mass of the superstructure is reduced.

In order to provide answers to questions of interest to the construction industry, LCA methods are often adapted and streamlined for the purpose. First, they often focus entirely on life cycle GHG emissions from buildings with no other impact categories considered, as in this study. Second, buildings typically have a long life, during which a wide range of actors (investors, design teams, contractors, owners, and occupiers, for instance) inherit responsibilities from each other: this encourages transparency on the assessment of each life cycle stage (Figure 1).

Finally, with every building being unique in its combination of form, materials, and context, there is a need to draw general conclusions about categories of buildings from appropriate data sets. The GAMEPAW method (Geometry And Mass ECCs Probability And WLEC) summarized in Figure 2, is designed to meet these needs, and adopted here for the evaluation of structural frame designs suitable for new buildings in contrasting UK cities (London and Edinburgh). It follows these steps:

- Identify design criteria used in the buildings analyzed.
- Parametrically generate a set of structural frame geometries and designs, as detailed in D'Amico and Pomponi (2018), and filter according to the design criteria identified in Edinburgh and London developments, leaving 127 frame configurations, from 2 to 19 stories.
- Calculate mass inventory of every frame configuration in each of the three structural systems (steel, RC, engineered timber).
- Using LCA, determine ECC ranges and probability density functions (PDFs) for each material used in the superstructures, and for each life cycle stage.
- Use the Monte Carlo method in Pomponi et al. (2017) to generate sets of ECC, each set covering the full life cycle.
- For each design, and for each structural system calculate the WLEC distributions for each superstructure and normalize by unit of gross external area (GEA), which is defined as the building footprint multiplied by number of stories.

2.2 | Structural frame design and mass

The tool used to generate the structural designs is the freely available BEETLE² (D'Amico, 2017; D'Amico & Pomponi, 2018, 2020). BEETLE² repeatedly generates a set of input parameters relating to frame geometry and vertical loadings, and produces structural design variants for each set of parameters, consistent with Eurocodes and limit states. Each design is produced in optimized and rationalized form. The optimized version uses a large but finite set of commercially available cross-sections in each material, selected in order to minimize the overall mass. The rationalized version is a result of a trade-off between material cost and construction cost: as such, it is a design that is more likely to be built. In

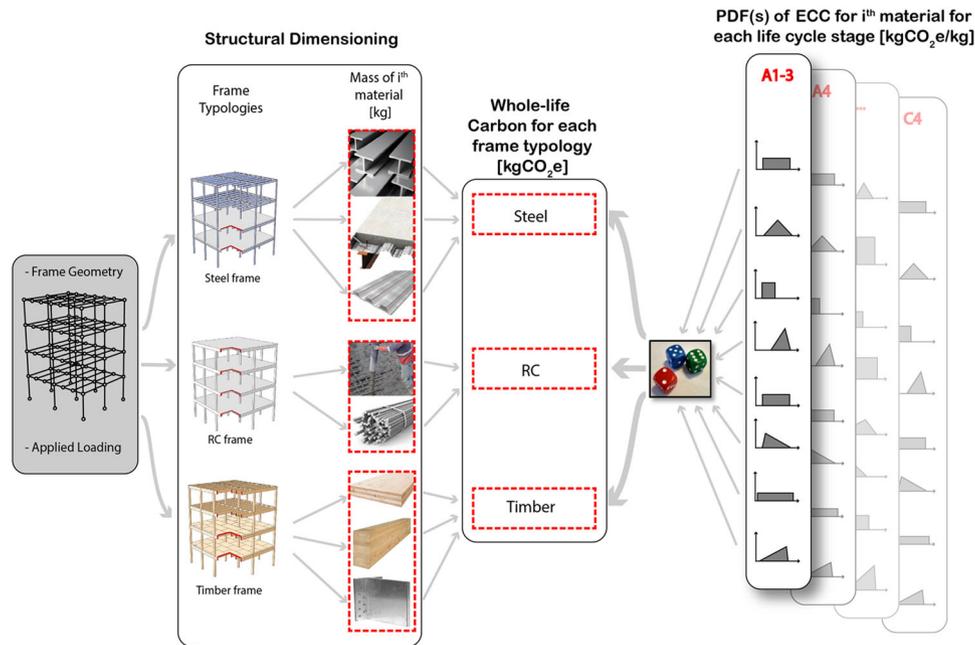


FIGURE 2 GAMEPAW method: Geometry And Mass ECCs Probability And WLEC. Overview of the method for assessing whole-life embodied carbon of structures

Note: ECCs are embodied carbon coefficients, WLEC is whole-life embodied carbon, RC is reinforced concrete, and PDF is probability density function

short, the rationalized designs are heavier, but less complex, and are the designs used in this analysis to reflect realistic approaches to construction. Dunant et al. (2019) discuss the emissions abatement potential of lightweighting construction frame elements, but this is identified as a net financial cost, implying that designers rationalize their structural frames to a point where the cost of the extra material is offset precisely by other benefits.

In order to create archetypes for structural frames in Edinburgh and London, information relating to geometry and loadings in five building projects in each city was analyzed: input parameters used to filter the extended set of frame geometries down to the 127 analyzed here are shown in table S1 of a supplementary data tables file in a repository on Zenodo (<https://doi.org/10.5281/zenodo.4589544>), with loadings based on Eurocode 1 (BS EN 1991-1-1:2002, 2011). Output frame configurations and masses are shown in table S2 in the supplementary data tables file on Zenodo. Those from Edinburgh were low rise (up to five stories), and those from London were higher (7–19 stories), ranges which reflect typical construction activity and the differing land and development pressures in each city. Drewniok et al. (2018) have investigated the various drivers that result in building frames being more massive than they need be, including non-scientific approaches to setting design load values: the purpose of some of the input ranges in table S1 in the supplementary data tables file on Zenodo is to allow for the varying design approaches to the issue.

For each frame configuration, the materials inventories of the three structural systems (steel, RC, and engineered timber) were compiled. The steel superstructures consist of a steel frame with composite floor (steel deck with concrete), representing one of the most commonly used methods of floor construction in UK multistory buildings. The RC superstructures are RC throughout. The engineered timber system is based on a glulam frame with steel connectors and with a CLT floor deck. The glulam frame was preferred to cellular construction with CLT wall panels as it permits a genuine like-for-like comparison at the level of structural geometry. In cellular construction systems employing CLT, the wall panels have additional functions, so valid comparisons with other structural systems (i.e., frames) can only be made at the whole-building level.

2.3 | Whole-life embodied carbon assessment of structural frames

The WLEC of a building structure potentially includes GHG emissions from all life cycle stages from A to D (Figure 1), with the exception of B6 and B7 (operational energy and water). IPCC GWP100 (IPCC, 2013) is the impact category considered, and all modeling assumes a 50-year design life consistent with typical building LCA practice (Saade et al., 2019).

The WLEC of each frame configuration in each of the three structural systems has been calculated through life cycle inventory analysis, from cradle-to-grave. The structural mass components are quantified separately and multiplied by ECCs to obtain the WLEC, which is then normalized by the GEA. Thus the functional unit is 1 m² of GEA of superstructure for its 50-year lifetime. This approach, referred to as process-based analysis, does suffer from truncation errors and can underestimate requirements caused by neglecting upstream layers in the supply chain (Crawford,

2008; Crawford et al., 2018; Lenzen & Treloar, 2002; Lenzen, 2000; Majeau-Bettez et al., 2011). In contrast, input-output analysis is comprehensive but suffers from the aggregation error caused by the lack of granular data (Lenzen, 2011). The higher-quality process data retrieved and used seemed preferable to more complete, yet more aggregate, input-output data. A hybrid approach, which combines the strengths of process-based (granularity) and input-output (comprehensiveness) LCA, would likely produce more accurate results (Pomponi & Lenzen, 2018) but its automated implementation is a very recent development (Stephan et al., 2019). While such novel advancements will make hybrid LCA easier, it is nonetheless still labor intensive and time consuming and as such it would be an interesting avenue for future research to add further depth to the analysis presented in this article.

The WLEC of 1 m² of each superstructure (kgCO₂e/m²) is as follows:

$$\text{WLEC} = \frac{\sum_i M_i \times \text{ECC}_i + \sum_j M_s \times \text{ECC}_j}{A \times h},$$

where M_i is the mass of material i (kg),

ECC_i is the embodied carbon coefficient of material i summed across all life cycle stages except construction (A5) and demolition (C1) (kgCO₂e/kg),

M_s is the total mass of the superstructure (kg),

ECC_j is the embodied carbon coefficient for whole structure process j - (i.e., construction or demolition, kgCO₂e/kg),

A is the footprint of the building (m²),

h is the number of stories, and $A \times h$ is the gross external area (m²).

2.4 | Embodied carbon coefficients

The ECCs used in this study are presented in table S3 in the supplementary data tables file on Zenodo, with details of their derivation and associated references (Section S2 in Supporting Information). Broad information about their scope and derivation is outlined in the rest of this section. For each ECC we define either a uniform or a triangular PDF, as illustrated in Figure 2, and presented in full in table S3 in the supplementary data tables file on Zenodo. The triangular PDFs are based on a middle value, derived from the chosen model in each case (referred to as "default") plus one high and one low alternative from data in relevant literature to represent plausible limits. In some cases there is insufficient evidence to choose a default value, and only the range is presented to define a uniform PDF.

Samples are randomly taken from the ECC ranges using a Monte Carlo method developed for the LCA of buildings (Pomponi et al., 2017). Each Monte Carlo sample consists of a full set of ECCs, and each one operates on a randomly chosen one of the 127 frames in each of its three structural systems. This yields a total sample size of 127,000 for each of the three structural systems. This sample size was checked for robustness by comparing the output's distributions obtained by running the Monte Carlo sampling multiple times, thus comparing the resulting outputs in terms of mean and standard deviation which were shown to be consistent (<1% of error variability). The resulting sample size was therefore calibrated as a trade-off to achieve consistent results without excessive computing resources.

2.4.1 | Product stage

The cradle-to-gate modules A1–A3 have been assessed in aggregate. Ecoinvent 3.5 (Wernet et al., 2016), accessed through SimaPro 9, was the source for the default values. High and low values for the uncertainty analysis were drawn from Pomponi and Moncaster (2018), which identified around 200 construction ECCs from academic literature and Environmental Product Declarations.

2.4.2 | Construction process stage

Freight transport to the construction site (module A4) is modeled using UK Government emission factors for tonne-kilometers (BEIS, 2018a). For each material, a likely range is considered for transport distances, reflecting the possible variations in the end-points of each journey, and so the ECC for each material is reported as a range. Engineered timber is assumed to be imported from central Europe as the UK currently has no manufacturing facility; transport of steel is based on a market mix of steel supplied from Europe, United States, and China; whilst concrete is transported from more local production facilities.

Environmental aspects of the construction process itself (A5) assessed in this study are limited to energy use on site, and the product life cycles of any materials consumed by the process but not incorporated into the final structure (i.e., formwork and site waste). Transportation of equipment and workers to site is out of scope. Emissions associated with construction processes and formwork are derived from literature benchmarks, whilst

the contribution from waste is modeled separately. The Net Waste Tool (WRAP, 2008) suggests that no more than 1% of steel sections ordered are wasted (if delivered out of specification, or damaged on site for instance), and the same for timber frames. Even at these low rates, the life cycle impact of these wasted resources can be a significant proportion of the construction site impact. RC is wasted at a higher rate of up to 5%.

2.4.3 | Use stage

The only use stage emissions considered concern the carbonation of concrete (module B1). Calculations are based on the method and coefficients detailed in Lagerblad (2005) and Pommer and Pade (2005). Modules B2–B5—maintenance, repair, replacement, and refurbishment—are important aspects in a building life cycle, which can involve several iterations of redecoration, renovation, and even extension. In general, such interventions would either be too unpredictable to model, or would not impact significantly on the structural frame, which will have a design life that matches the design life of the building (Helland, 2013) which in this study is assumed to be the same for all systems. Routine maintenance of the structure is the issue that most challenges this approach, with Caruso et al. (2017) drawing attention to the additional maintenance needs of glulam structures. However, maintenance needs are highly dependent on the specification of the glulam itself (timber species and initial treatment), on design details, and on exposure to moisture and ultraviolet light. Accordingly, it is not feasible to identify a generic maintenance regime, and it has been left out of scope, as with other studies that have assessed engineered timber structural systems (Lolli et al., 2019; Robertson et al., 2012).

2.4.4 | End-of-life stage

As with the construction stage, values for emissions associated with deconstruction/demolition (module C1) are derived from literature benchmarks. Again, the scope is limited to on-site activities.

We assume demolition material is transported (module C2) 50 km to landfill or an alternative treatment facility that processes it to an "end of waste" state. Information from regulatory authorities indicates landfill options well within this radius of locations in London and Edinburgh (EA & GLA, 2017), (SEPA, 2018).

The separation of steel into usable scrap is considered in C3, with a negligible impact in C4 attributable to the small fraction that is landfilled with other construction waste. For concrete and engineered timber, the default option is assumed to be landfill, although alternatives are considered for the PDFs. For timber an option is to chip/shred the material to specifications required for energy recovery, and this choice is potentially significant, as landfill results in the emission of methane in landfill gas, albeit at a rate that is open to debate (Krause, 2018). Further carbonation of concrete is considered, allowing for the possibility of an increased surface area following demolition for landfill, or even more if crushed for recycling (Pommer & Pade, 2005), in which case the gains would normally be associated with module D.

2.4.5 | Benefits and loads beyond the system boundary: Module D

Benefits and loads beyond the system are not explicitly included in our assessment, except in sensitivity analysis, with the qualified exception of steel. The consequences of this approach, rather than fully integrating module D into the assessment, are likely to be neutral for steel, negligible for concrete, and unfavorable for timber.

The World Steel Association methodology (WSA, 2017) that underpins theecoinvent data used here takes account of the net production or consumption of scrap over the projected lifetime of the building or component, thereby bringing module D into the system. This tends to have the effect of moderating the cradle-to-gate emissions toward a central value, because processes with lower embodied energy tend to consume scrap (a valuable resource), whilst processes with higher embodied energy tend to produce scrap.

For concrete, the main option available currently is to be recycled as a low-value aggregate: as such the substitution of emissions in the future product system would be very low, and the exclusion of module D for concrete would have negligible consequences for the analysis.

For timber, the main two options at end of life are currently landfill or energy recovery. For landfilled timber there are substitution benefits associated with the use of captured landfill gas. This yields a module D credit to offset part of the atmospheric emissions accounted for in C4. For timber that is used directly for energy recovery, considerably more energy is recovered, giving a substantial module D credit which can exceed the total debits from all other stages, as seen in many Environmental Product Declarations for timber products. This approach was not adopted for this study on a precautionary basis, because the benefits are routinely overstated (Hart & Pomponi, 2020). EN 15978 (BSI, 2011a) indicates that existing technology and context should be assumed for the calculation, but this is not a conservative assumption in this context, relating to activities 50–100 years in the future. Energy supplies are being decarbonized in a way that will probably continue. For example, the emission factor for reporting on grid electricity in the UK has reduced from 0.496 to 0.283 kgCO₂e/kWh in the 10 years to 2018 (BEIS, 2018a), and 50 years from now the substitution benefits associated with landfill gas and waste to energy are likely to be very low.

2.4.6 | Other limitations

The temporal effects of GHG emissions are not directly assessed in this work. Therefore the model assigns the same value to a unit of GHG emitted in the manufacture of products now as it does to the same quantity emitted at end of life. There is a case for taking account of the delayed emissions through dynamic assessment (Levasseur et al., 2013), or through the use of the simpler method outlined in PAS 2050 (BSI, 2011b) which would, in effect, reduce the reported end-of-life GWP100 by around 50%. However, such methods embed further value judgements, and as they are not universally accepted, they have not been adopted. The ECCs for timber also exclude non-anthropogenic fluxes of GHGs, in either direction, associated with forest soils.

The temporary carbon storage function of the wood products is not assessed, and as a consequence any benefits of semi-permanent storage in landfill are only considered in sensitivity analysis. As carbon storage in harvested wood products in buildings is temporary, it is more useful to consider the storage at the building stock level—nationally for instance, or even globally (Johnston & Radeloff, 2019)—rather than at the individual building level. If carbon is added to the building stock faster than it is removed (through demolition for instance) and this is not coupled to a decline in forest carbon, then it may be shown that the carbon storage function of durable wood products has a climate mitigation effect.

3 | RESULTS

3.1 | Building superstructure mass and whole-life embodied carbon

The frequency distribution of masses and WLEC, normalized by GEA, are shown for each of the three structural systems in Figure 3.

The mass distribution shows a clear ranking of the normalized masses of the three types of superstructure, with no overlap between them. The RC superstructure being heavier than the steel—which itself includes a high percentage of concrete—which in turn is much heavier than the timber superstructure. Differences are apparent in the extent of data scattering for the different structural systems.

The broader spread of the WLEC curves (Figure 3b) than the mass curves (Figure 3a) is a result of the uncertainty built into the WLEC analysis, and the input ECC PDFs are responsible for the greater broadening of the steel curve in comparison to the RC curve. The standard deviations of the curves in Figure 3b are higher than those in Figure 3a by the following factors: steel 2.07, RC 1.62, and timber 1.83, meaning that the uncertainties embedded in the ECC PDFs have the greatest impact on the results for the steel superstructure (particularly on account of the product stage ECC for steel), and then the timber superstructure (in this case primarily linked to waste processing and disposal).

3.2 | Relative importance of each life cycle stage

The contribution of each life cycle stage is shown using violin plots (Hintze & Nelson, 1998) in Figure 4. For the steel and RC structural systems, the GHG emissions associated with the product and construction stages (A1–A5) account for at least 93% of the WLEC, based on mean values. The corresponding figures for A1–A3 alone—the product stage—are 75% (steel) and 70% (RC).

By contrast, for the timber structural system, initial emissions are much lower (A1–A5 emissions accounting for 68%, and A1–A3 just 42% of the total on average). This is an advantage for timber, as savings are achieved in the present when the need for GHG emission reduction is greatest and grids are not yet fully decarbonized. In contrast, the end-of-life emissions make a relatively high contribution to the overall WLEC for timber, albeit subject to a high level of uncertainty. This is related to the significant GHG emissions that are expected if the timber is allowed to degrade in landfill.

Whilst values for carbonation of concrete during and after the building lifetime are small relative to the overall WLEC, they are enough to offset a significant proportion of the life cycle GHG emissions that occur following the construction of the building: 48% in the case of the steel superstructure, 55% in the case of RC, and zero for the timber.

4 | DISCUSSION

The median WLEC for each structural system is as follows: timber 119 kgCO₂e/m²; RC 185 kgCO₂e/m²; and steel 228 kgCO₂e/m². These numbers can be compared to those presented in the review in Section 2: in broad terms they are in the vicinity of Nadoushani and Akbarnezhad (2015). On the other hand, the figures quoted from De Wolf et al. (2016) are significantly higher and from Skullestad et al. (2016) significantly lower. In systematically comparing numerous structural configurations across all three typologies, this is the most thorough investigation of the subject to date. The results confirm the widely held assumption that timber structures and buildings are likely to have lower WLEC than their steel and concrete counterparts.

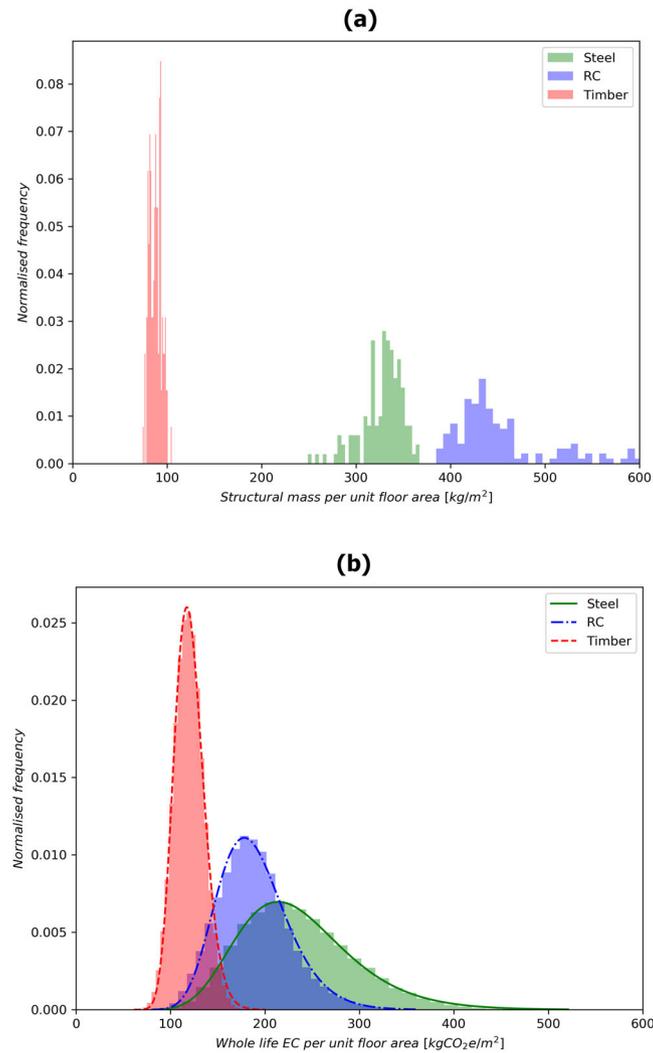


FIGURE 3 (a) Mass distributions of the 127 structural frames (of each type) normalized by gross external area, and (b) whole-life embodied carbon distribution of the same structures, with ECCs sampled using Monte Carlo method, normalized by gross external area; log-normal curve fitted. EC is embodied carbon. Underlying data used to create this figure can be found in a supplementary data tables file in a repository on Zenodo (<https://doi.org/10.5281/zenodo.4589544>)

The advantage for timber, however, is not as great as is often assumed, especially when—as in this study—end of life is included. Based on the averages, the displacement factors for timber superstructures in comparison to RC and steel are 0.51 and 0.85 tC/tC, respectively: these values are low in the context of averages and ranges discussed earlier. As discussed in Section 1.2, this may be a result of general reductions in GHG emissions per unit of output across industry (Arehart et al., 2021); another possibility is that other uses for timber result in better displacement factors, which would be an important consideration if and when a steady supply of sustainable construction timber becomes constrained. A further consideration is that a higher displacement factor is observed for taller buildings. If a subset of the superstructures of eight or more stories is isolated, the differences between timber and the alternatives are enhanced, giving displacement factors with respect to RC and steel of 0.58 and 1.02 tC/tC, respectively. This demonstrates that in cases where sustainable timber supply is constrained, engineered timber offers more substantial normalized benefits in taller buildings and should be prioritized for such use.

The impact of the PDFs on the results is illustrated in Figure 5. There is a considerable range of possibilities for WLEC associated with the variation in normalized mass, but this range is extended further by GAMEPAW. The use of some asymmetric PDFs has also led to small shifts in the distributions, resulting in lower averages in each case. This serves as a reminder that readers should generally be sceptical of data and literature on this subject that does not take account uncertainty and data quality, as we have demonstrated these are absolutely crucial to offering some reliability on the results presented.

Table 1 shows the relative contributions of the uncertainty in each ECC to variation in the overall WLEC. For this analysis, the mean embodied carbon at each stage was calculated for the 127 superstructures in each typology using high and then low ECCs, and the difference between them

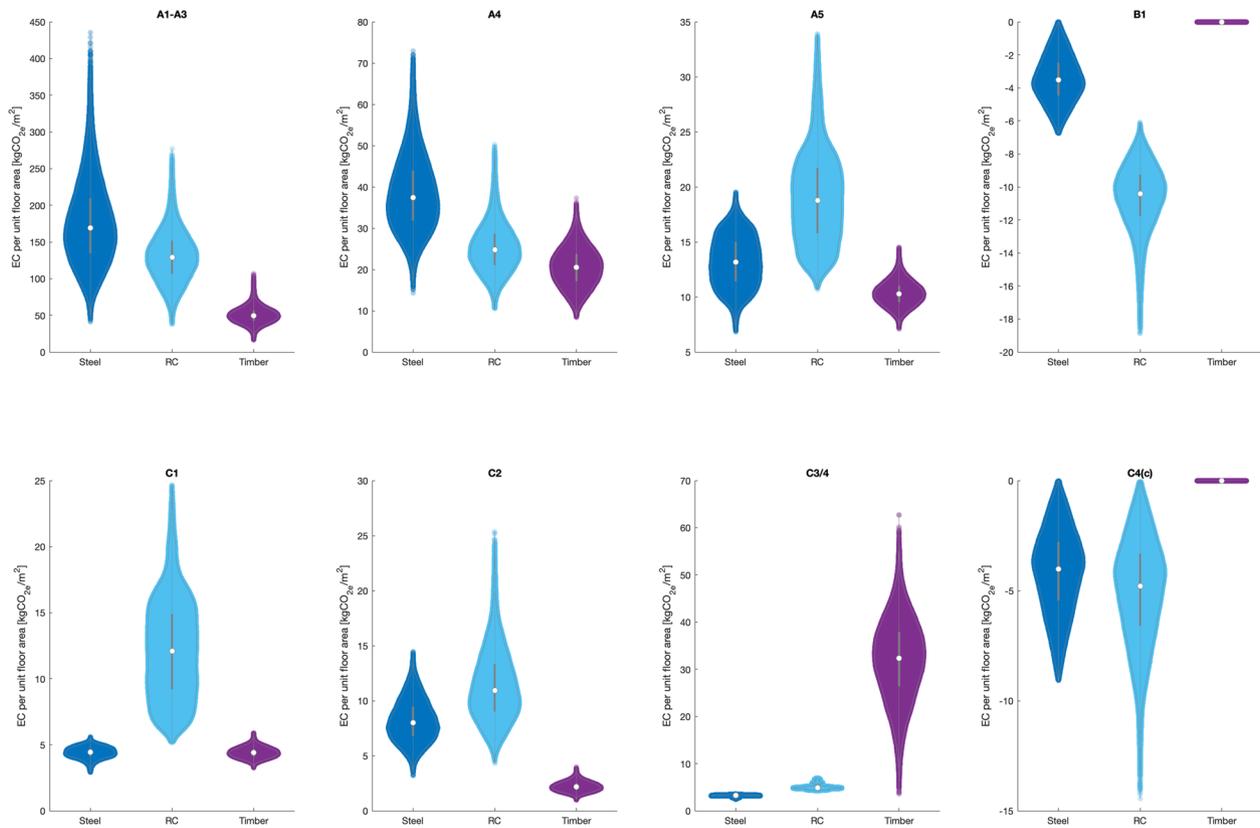


FIGURE 4 Whole-life embodied carbon per unit floor area by life cycle stage—disaggregating the data presented in Figure 3b. Violin plots showing the embodied carbon at each stage for each system. One sub-plot for each stage: Note the variations in scale. Life cycle stage codes are as in Figure 1. B1 and C4(c) relate to carbonation of concrete only and are either on or below the x-axis. C3/4 relates to emissions from C3 and C4 combined, excluding carbonation. Underlying data used to create this figure can be found in a supplementary data tables file in a repository on Zenodo (<https://doi.org/10.5281/zenodo.4589544>)

TABLE 1 Contribution of ECC variability to overall WLEC variability: Coefficient of variability V_i reported as a percentage. The high and low ECC values used for this calculation are the limits of the central 95% (by area) of the ECC PDF in each case

	Product stage A1–A3 (%)	Transport A4 + C2 (%)	Construction and demolition A5 and C1 (%)	Disposal C3/4 (%)	Carbonation B1 and C4 (%)
Steel	81	11	3	0	4
RC	65	16	11	0	7
Timber	46	19	4	32	N/A

is reported as a percentage of the difference between the high and low values for overall WLEC.

$$V_i = \frac{EC_{i,h} - EC_{i,l}}{WLEC_h - WLEC_l},$$

where V_i is the coefficient of variability for life cycle stage (or group of stages) i ; EC_i is the embodied carbon of the same stage or stages; subscripts h and l imply calculation with high and low ECCs, respectively.

For the steel and RC frame buildings, the main source of variation is in the product stage, mostly relating to the steel component—even in the case of the RC frame. This implies that in any LCA of building structures reliant on a single ECC for each material at each stage, the selection and justification of the product stage ECC for steel should be of paramount importance. For the timber frame, the variation in end-of-life embodied carbon is also very important: this is related to the uncertainty around treatment options. In all cases, variation in transport ECCs accounts for over 10% of the overall uncertainty, with the transport to site being the most significant element of this.

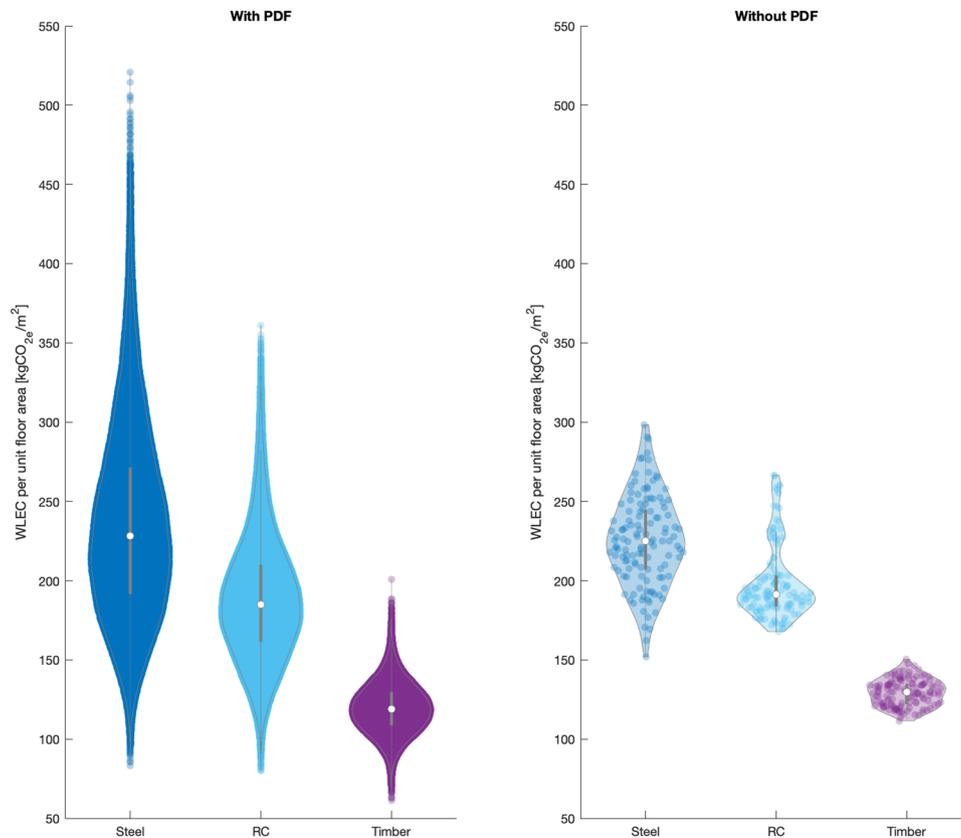


FIGURE 5 Violin plots showing the WLEC for the three systems, with and without the use of the ECC probability density functions. 127 structural frames of each type assessed either with the ECC PDFs (127,000 values per plot) or with the default ECC values (127 values per plot). Underlying data used to create this figure can be found in a supplementary data tables file in a repository on Zenodo (<https://doi.org/10.5281/zenodo.4589544>)

Whilst Figure 5 highlights the importance of variation and uncertainty in data, Figure 6 demonstrates the importance of the later life cycle stages. Figure 6 compares GAMEPAW results (using default ECCs) with results based on a database of cradle-to-gate ECCs popularly used in the construction industry: the inventory of carbon and energy (ICE) (Jones & Hammond, 2019). The ICE results are illustrated as the default option (the full length bars) and an alternative reduced option including module D benefits for steel, and substitution of cement with pulverized fuel ash at a rate of 40%. The alternative option has been designed to introduce a bias against timber, thereby stress testing its superiority in the WLEC results. Figure 6 shows that the ICE results are close to the cradle-to-gate results for GAMEPAW, but that significant impacts are likely to be missed by failing to look beyond the factory gate. Targeting WLEC, as opposed to cradle-to-gate GHG emissions only, also draws attention to construction site waste (including formwork), as a high proportion of the construction site emissions (A5) are associated with the embodied carbon of the materials wasted, even at the low wastage rates implied by NetWaste (WRAP, 2008).

4.1 | WLEC relationship to design criteria

The relationship between WLEC and the inputs to BEETLE² was also assessed. The long tail to the RC mass distribution (Figure 3a) results from a marked discontinuity in the relationship between mass and beam length in the RC structures resulting from a change to floor design triggered by longer (greater than six meters), ribbed floors and therefore more mass-efficient beams (Goodchild et al., 2009). The one input parameter that exhibited a clear and consistent influence on the results across all three typologies was building height, for which moderate positive correlations were observed (Figure S1 in Supporting Information). This is to be expected as taller buildings require heavier columns at the lower levels. The lighter structure means that the gradient of this trend for timber is lower, providing an incentive to use timber when building high. Similarly CLT could replace concrete and steel in the floors of the steel frame buildings, with significant benefits achievable at a global scale (D'Amico, et al., 2020).

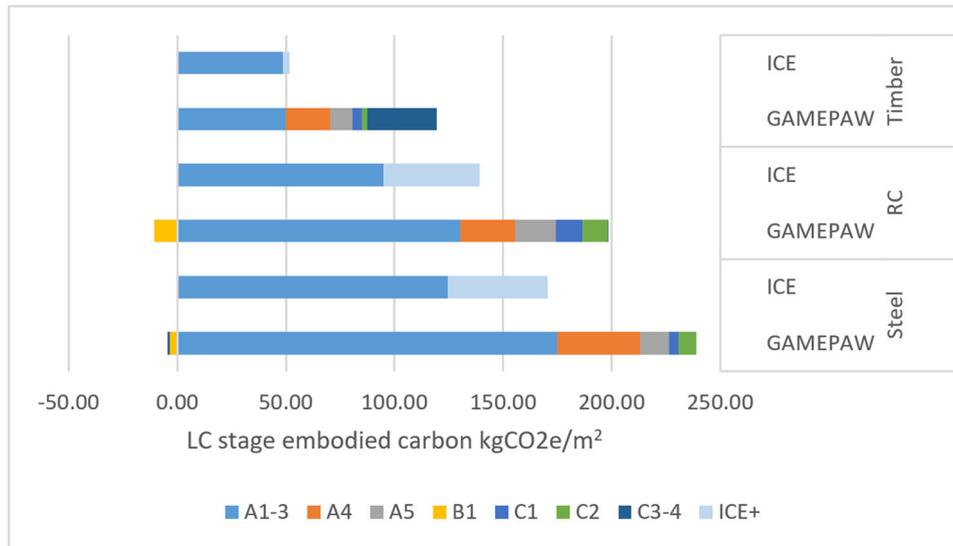


FIGURE 6 Comparison of results using mean values from GAMEPAW, and alternatives using single cradle-to-gate figures, as frequently preferred by industry in the UK, namely the inventory of carbon and energy (Jones & Hammond, 2019). ICE results are represented by two values, the full length of the bar (including ICE+) being the default, and the reduced length benefiting from reductions associated with adjustments made to methodological and material choices. Underlying data used to create this figure can be found in a supplementary data tables file in a repository on Zenodo (<https://doi.org/10.5281/zenodo.4589544>)

The characteristics of the building geometries in the tails of the distributions in Figure 3 also offer insights into the relationships between geometry, mass, and WLEC. Analysis of the 10% of superstructure geometries (i.e., 13) at each end of the WLEC distribution shows (of course) a strong relationship between the mass of each superstructure and the WLEC. In the case of RC, the average mass of material at the high end of the WLEC distribution is 45% higher than the average mass at the low end of the distribution, highlighting the clear synergy between WLEC and material efficiency. More interestingly, whilst several frame geometries appear in more than one of the distribution tails (eight geometries appear in the tails of all three distributions), as many as 34 geometries appear in only one of the tails, suggesting that design features have different effects for the three structural typologies. Aspects of the superstructure geometry that show a clear contrast at either end of the WLEC distribution for each of the three typologies are listed as follows, with further details in table S7 in the supplementary data tables file on Zenodo:

- Structures with the lowest WLEC tend to have somewhat larger footprints, and considerably fewer stories: in the case of RC they are all below five stories, whilst for the timber and steel typologies they are below eight stories.
- Structures with the lowest WLEC have longer beams, especially in the case of RC, for which there is an average difference of 1 m in beam length between the structures at each end of the distribution. The geometries with the very longest beams are, however, absent from the best-performing RC structures, but included in the best-performing timber structures.
- Structures with the lowest WLEC have lower loadings specified for floor and envelope. This effect is most pronounced in the case of timber, and least clear for RC. As the RC typology is already the heaviest, additional loads are proportionately a smaller burden when compared to the lighter timber and steel structures.

There is therefore real potential for reducing WLEC by optimizing design even without material switching. For all three typologies, where site constraints and business imperatives allow, material efficiency and WLEC can usually be improved by optimizing built form for compactness (D'Amico & Pomponi, 2019) and limiting height to around five to seven stories. Beyond that, there are too many variables at play to offer a general prescription, but further savings can be made by minimizing loadings and optimizing spans (beam lengths) for instance: the RC structures with ribbed floors have WLEC 18% lower than those without (and 20% when beam length is limited to 6–7 m).

Additionally, results and analysis are based on the rationalized structures output by BEETLE², but there is also scope for optimizing the designs for material efficiency by, for instance, specifying a continuous reduction of column cross-section at every level rising through the building. The most interesting case is the steel frame, which—in the case of the buildings of seven stories or more—can be reduced in mass by an average of 22%. Whilst this only corresponds to a 5% reduction in the total mass of the superstructure—as nearly 77% of that is in the concrete floor—it does result in a substantial reduction in the WLEC of the superstructure of approximately 14%.

4.2 | Implications for policy, practice, and research

Despite the considerable research efforts into the life cycle impacts of buildings over the years, this work is unique in its approach and systematic coverage of structural frames in steel, concrete, and timber. As such, it provides a valuable contribution to construction stakeholders attempting to minimize environmental impacts both through design and procurement, thereby reducing life cycle GHG emissions and justifying the preferment of materials, specifications, and suppliers that can collectively make the best contribution to this objective.

It is worthwhile to consider the differences in WLEC between building superstructures in the context of construction industry activity and national and global GHG emissions. The difference in the mean WLEC for engineered timber structures and the alternatives averages approximately $90 \text{ kgCO}_2\text{e/m}^2$. For the UK, we estimate that the maximum potential saving in WLEC resulting from a comprehensive switch to engineered timber systems (apartments and commercial buildings) is approximately $1 \text{ MtCO}_2\text{e}$ per annum (Section S3 in Supporting Information). This is approximately 1.5% of the estimated emissions that the construction industry can influence (BEIS, 2010). Although a small proportion, it would represent a valuable contribution to decarbonization efforts at a time when direct GHG emissions from industry are increasing (CCC, 2018), and would also point the way toward further emissions reduction opportunities.

Our results demonstrate the opportunity that exists, if matched by political goodwill, to begin implementing effective measures to decarbonize the built environment. Even if aggressive policies remain lacking, practitioners could build upon our findings and start transitioning to a larger use of timber in construction through a bottom-up process. However, contrarily to what some imply (Churkina et al., 2020), we do not believe that timber represents a one-size-fits-all solution to take the built environment out of the current climate crisis: the unanswered questions are many (Hart & Pomponi, 2020) and issues of global availability and deforestation cast doubt on how much of a solution timber can be to the bigger problem of accommodating an increasing urban population across the world (Pomponi et al., 2020).

Further to the research opportunities mentioned above, the application of GAMEPAW can be extended to other building layers and the additional life cycle stages involved, such as maintenance, repair, and refurbishment. Users should, however, be aware that WLEC using GWP100 is but one measure of environmental performance: numerous others exist, including those which take account of the timing of emissions, prioritizing current GHG emissions over future ones, and many non-climate environmental categories.

4.3 | Sensitivity analysis

As discussed in Section 2.4.5, the choice of system boundaries and end-of-life options is a significant issue in the case of timber in particular. We take the view that no substitution benefits should be associated with combustion of timber or landfill gas in the distant future (e.g., 50 years or more, at a point in time when the energy being substituted will have been decarbonized). However, the gain from the long-term storage of carbon in landfill is a consideration, despite landfill generally being viewed as the least favored option compared to recycling and direct energy recovery. Environmental Product Declarations for CLT typically show that around 88% of the mass of CLT is dry timber, with the remainder being moisture and adhesives, and the carbon content of dry wood is approximately 50% by mass (British Standards Institution, 2014), so we assume engineered timber has carbon content of 44% by mass. The average mass of engineered timber in the timber structural system is 79.9 kg/m^2 which includes 35.2 kg/m^2 of carbon. With up to 91.5% of this carbon potentially still in storage in landfill at the time horizon (Section 3 in Supporting Information), landfill storage represents a GHG sink of up to $118 \text{ kgCO}_2\text{e/m}^2$. This figure is—coincidentally—very close to the median WLEC for timber superstructures ($119 \text{ kgCO}_2\text{e/m}^2$), and although the benefit from carbon storage will be partially offset by increased methane emissions, a case might be made for timber construction followed by landfill being a very low GHG system. However, extending the system boundaries to landfill storage without also expanding the consideration of forestry would be misguided: a global increase in the use of construction timber may simply be a process of moving carbon from the forest to landfill (via buildings), without increasing overall carbon stocks (Pomponi et al., 2020).

In the case of concrete carbonation, sensitivities to end-of-life choices are much lower, and are included in GAMEPAW. If concrete is crushed for recycling instead of landfilled, carbonation is increased by $5.4 \text{ kgCO}_2\text{e/m}^2$ for the concrete floors of the steel superstructure, and $6.7 \text{ kgCO}_2\text{e/m}^2$ for the RC, further reducing WLEC by up to 3.7% compared to the mean values.

It is useful to be aware that sensitivities exist to the many potential design variations outside the scope of this study. The design philosophy and material choices for the floor decks—especially in the case of the steel frame—are a case in point. Justifications for alternative floor specifications can easily be made, leading to different choices, depending on variables such as cost, weight, and constructability. The steel components of both concrete floor systems considered here are significant contributors to the embodied carbon, with even the 1 mm profiled sheet used with the steel frame contributing almost as much to WLEC as the concrete deck above it. In terms of embodied carbon in tall buildings (20–70 stories), Foraboschi et al. (2014) rank RC slabs ahead of any of the lighter systems assessed, including the composite system used in this study. On the other hand, for a four-story school building in the UK, Wang et al. (2018) rank a composite floor system ahead of RC floors, but behind a precast system.

5 | CONCLUSION

There is still an urgent need to reduce GHG emissions from all aspects of building life cycles if societal objectives relating to resource extraction and climate change are to be met. This requires a combination of holistic viewpoints related to industries, cities, and buildings, alongside more focused investigations such as this study of the WLEC associated with the provision of building superstructures in steel, RC, and timber. In this research, we analyzed 381 different frames, satisfying criteria used in selected developments, and mass and WLEC were compared for each geometry in each structural system. PDFs are defined for ECCs for each material at each life cycle stage, permitting the illustration of WLEC results as realistic ranges rather than single points. In terms of WLEC, on average the timber frame system is substantially better than the other two options, although there is some overlap in the results distribution. Timber frames also have, by a wide margin, the lowest mass, and this can also lead to lower mass and WLEC of foundations (Moncaster et al., 2018). Whilst cradle-to-gate emissions are the largest overall, failure to include stages up to and including construction would result in a significant understatement of the true impacts for all systems, and it is also particularly important to consider the end-of-life stages for timber.

The results of this research imply that optimization of frame geometry can be used to increase material efficiency in building structures. Furthermore, choice of frame and floor slab materials can have a significant impact on the WLEC of structural frames, and therefore on the buildings themselves. Whilst timber frames show much lower impacts in the product and construction stages, they can produce higher emissions at the end of life which erodes their overall advantage without however coming close to eliminating it. There are still questions to answer, however, about how to compare LCAs of biogenic and non-biogenic materials. The difference in WLEC between the RC and steel superstructures is not sufficient to dictate the choice between them, and the focus should be on optimizing the design itself to meet relevant criteria.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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