Title

Structural design as a cost competitive and scalable carbon mitigation strategy

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Abstract

The built environment is responsible for a large percentage of the global carbon footprint. Many generations of structural designers have developed material and structural systems for the efficient use of natural resources and low-carbon designs. The accumulated present knowledge we have today around material efficiency would be sufficient to design and build with a much lower carbon footprint, if it weren't for a major constraint: cost. However, current construction economics do not account for the real costs of materials, including their environmental externalities. Considering the actual societal costs associated with embodied carbon emissions could suddenly make material efficiency and low carbon materials more economical. In this paper, we compare the cost of carbon avoidance or storage in the built environment through structural design with other carbon capture technologies. We show how financial incentives for low-carbon design could support carbon reduction targets and provide incentives for design teams to implement them.

Keywords: structural design, carbon storage, carbon capture, design decisions, embodied carbon

1 Introduction

Environmental considerations have been driving research in structural design towards low-carbon solutions for spanning systems. Different strategies exist to lower the embodied carbon of a structure, from material selection, designing components with structurally efficient forms that use less material altogether, or by optimizing the design on a higher level. Perceived economic constraints often hinder the implementation of low carbon design solutions – in engineering practice lowering embodied carbon in buildings is often associated with more costs through more expensive materials, or technologies that are needed for construction [1]. In many legislatures, carbon reductions in the built environment through mandates to decrease embodied carbon of new buildings are part of larger strategies for Greenhouse gas reductions to meet UN climate targets [2]. With billion-dollar investments into carbon reduction and carbon capture technologies [3], we want to investigate how costs for interventions in the built environment to decrease embodied carbon emissions stack up against other carbon mitigation and capture efforts. If low embodied carbon solutions are more expensive to be implemented on a building per tonCO2e, than alternative carbon capture methods along supply chains or the energy grid, outside of the scope of a building, the question needs to be asked, if alternative low-cost, high-carbon solution should be chosen for construction instead. Research has highlighted the complex relationship between costs of construction systems and embodied carbon and it has been shown that through optimization along the pareto front different design solutions can be achieved with similar performance targets [4]. Design frameworks to mitigate both cost and carbon have been proposed to quantify the impact of the different reduction strategies through marginal abatement cost curves (MACC) [5].

After all, costs do not exist in a vacuum, with all strategies for reducing embodied carbon emissions, it is important to keep in mind that outside of an academic context or design research prototypes, additional expenditure for low carbon structural solutions must compete with alternative carbon mitigation and capture technologies for them to make sense to be implemented at scale. Furthermore, this comparison can inform possible research directions towards finding more impactful strategies of lowering carbon emissions through structural design. We want to investigate two specific research questions regarding carbon mitigation in structural systems:

First, how does the cost premium of reducing embodied carbon in a building compare with alternative carbon mitigation strategies outside of the built environment? We want to investigate if carbon mitigation through simple structural design decisions that do not require new technologies, by changing spans or material systems, are orcost-effective. For this, we compare an existing dataset of different structural systems, and the associated cost premium of lowering embodied carbon with market-rate direct air carbon capture technologies.

Secondly, how would the cost premium change if carbon emissions through materials were priced to more accurately reflect their environmental impact? We study this by looking at distributions of cost premiums across different material systems under different carbon tax scenarios. With current supply chains and fabrication methods, many low-carbon structural design solutions have additional costs associated with them. We want to explore how such expenses compare to other carbon mitigation methods, and at what cost of carbon they become economically feasible.

2 Background

The built environment is one of the main drivers of carbon emissions, with almost 40% of global energy related emissions [6]. The construction of buildings is a driver of economic growth, enables higher standards of living, and is a necessity for public health, and access to infrastructure. This makes it crucial to figure out new ways for building new buildings, with reduced emissions, since a decrease of certain building activities would have adverse effects and consequences for both local and global economies. To mitigate carbon emissions across different industries and disciplines, numerous strategies have been proposed: increase of efficiency, replacement of processes, materials, and systems with low or zero carbon alternatives, and offsetting the carbon through alternative processes where reduction strategies are not possible. In many industries, supply chains and manufacturing processes heavily rely on fossil fuels, and are very challenging to decarbonize. In architecture and engineering, perception persists that constructing more sustainably comes with severe negative impacts on the cost of construction and operation, or is outside of the power of stakeholders [1]. If this were indeed the case, a dangerous conclusion could be to abandon building low-carbon buildings altogether, and focus solely on offsetting emissions from buildings with alternative means. This would mean that lowering embodied carbon in construction should only be done, if it was cheaper than offsetting the carbon emissions. In this research, we want to compare lowering carbon emissions through design and engineering with existing methods outside of the discipline, such as direct air capture. One major consideration is that, since there is no silver bullet to mitigate carbon emissions, and there are certain industries where no non-fossil fuel alternatives are available, carbon capture technologies would need to be used in some capacity. Since some more economical carbon offset methods, e.g. forest management, cannot be scaled infinitely, we will not consider them in this analysis, considering them reserved for hard-to-impossible to decarbonize processes. In this research, we compare carbon avoidance through structural design with industrial carbon capture solutions as a benchmark that could theoretically be scaled with enough capital.

2.1 Strategies for designing low carbon structural systems

Different overall strategies, and combinations thereof, have been identified to decarbonize construction processes [7], [8]. Implemented on different levels and at different stages in the design process, they start with changes in overall architectural design, where spatial requirements of a building are highly influential in making low-carbon design possible, through optimizing spans and building floor areas [9].

Design changes can decrease loads on structural elements, (e.g. by decreasing the span of a floor), improving detailing, (e.g. preventing corrosion), or overall building design, (e.g. towards adaptability for future uses), to increase the life span of a building and its structure. Looking at the building as a whole system can reveal opportunities to lower total carbon emissions, for instance, when embodied carbon and operational carbon emissions are directly linked through thermal mass [10].

When the boundary conditions of a structural element are set, different degrees of geometric optimization are possible. Using material only where required by forces can reduce weight and embodied carbon substantially. Dimensions of standard elements can be kept, while material can be removed internally where it is not needed, as demonstrated by filler slabs [11] and bubble deck floor systems [12], [13], [14], [15]. Systems that interface with standard construction systems have been proposed to create ribbed floors [16], [17], waffle slabs, shaped beams [18]. More geometric freedom can further reduce material usage, but can require more complexity and technology for construction, as well as integration into standard architectural typologies [19], [20]. Depending on expenditure on labor, digital fabrication, and technology requirements or specialized materials, they are not currently feasible for implementation in many markets around the world, and come with high associated costs.

Using materials with lower carbon coefficients directly scales to lower emissions. This could include lowering emissions with changes in the supply chain, the use of low-carbon or carbon-negative materials, using materials with carbon sequestration such as timber [21], biomaterials [22], earth [23] or reuse of salvaged materials [24].

2.2 Challenges for measuring impacts and system comparison

A key problem when assessing different low-carbon technologies for structural systems is that the complexity of architectural design makes solutions hard to compare. In theory, we would want to compare structural material quantities (SMQ) and carbon emissions of different systems. Constructed with different requirements in mind, the baseline for comparison shifts for many structural systems. For instance, SMQs will change based on the span and the loads applied to a floor: this can change based on local building code or for creating floors for different building typologies (e.g. warehouse or residential). Secondly, the embodied carbon is hard to compare across geographies. Low-carbon materials are often locally sourced and require the availability of certain material supply chains or technologies that might not exist elsewhere. Furthermore, the embodied carbon emissions of the most common materials can vary substantially, as they depend on the carbon intensity of local electric grids, fabrication, transportation, and manufacturing supply chains.

Additionally, secondary effects must be considered that can fall outside of the scope of an embodied carbon assessment of a single element: Structural solutions can require different types of supports that might mean less material for a floor slab, but more materials for support structures (e.g. lateral supports for vaulted ceilings through steel rods). Additionally, reducing the depth of a floor slab could mean significant savings through lower building heights or have negative effects on building energy performance through reductions in thermal mass. Reductions in weight can have compounding effects such as less loads applied to building foundations, reducing embodied carbon in different parts of the building. This highlights the complexities where weight and not the embodied carbon of a floor slab could lead to reductions in embodied carbon and warrants further investigations. Interactions between thermal mass and structural design have implications for operational carbon emissions and have been highlighted by Gascon et al. [10]. Other system selection criteria, such as fire ratings and acoustic properties [25] have to be considered as well.

2.3 Costing carbon capture and mitigation outside of the built environment

When comparing carbon mitigation strategies in structural design, it is important to keep in mind the different carbon dioxide removal (CDR) technologies and ways in which carbon emissions are mitigated outside of the built environment. Three main methods are used to mitigate emissions: 1. Avoid emissions through more efficient or alternative processes 2. Extracting carbon from the atmosphere through natural or technical processes 3. Adding new capacity of renewables that replace fossil fuels [26]. With investments into photovoltaics and heat pumps lowering prices substantially over the last decades, it is expected that technical CDR technologies, such as direct air capture (DAC), will become cheaper. We use a projected range of ~170£/tCO2 to 625£/tCO2 and 2500£/tCO2 (current rate) for comparisons [27]. The costs come with a high degree of uncertainty and large upfront investments, while the strategies we deploy in the built environment (from a design side) can be implemented today with current technology.

3 Methods

3.1 General methodology

We start with a simple comparison of three beam sections, assumed to be designed for similar loading conditions and structural requirements.

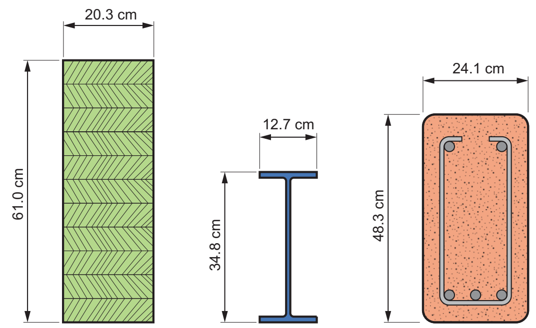

Figure 1: Three beam sections of a structure in timber (glulam) (green), steel (blue), and reinforced concrete (RC)(orange) (from left to right), designed for the same load conditions and performance requirements.

For these three beams, we can estimate their mass, their embodied carbon, and their cost. The value in the table represents a fictional case with realistic estimates, only for the sake of the demonstration of the methodology.

Table 1: Estimate of Mass [kg/m], Embodied Carbon [kgCO2e], and Cost [£] for the three beam cross-sections.

Material	Timber	Steel	Concrete
Mass [kg/m]	58	57	305
Embodied Carbon [kgCO2e]	179	397	249
Cost estimate [£]	840	780	760

In this example, we find that the timber section has the lowest embodied carbon, and the concrete section has the lowest price. We define the *baseline cost* = 760 [£/m], and *baseline carbon footprint* = 249 [kgCO2e/m] as the concrete solution, the design solution with the lowest cost. From this, we can calculate the Abatement *Cost of Carbon Avoidance* for other design solutions, according to the following equation:

$$CC_{struc} = \frac{cost\ of\ structure - baseline\ cost}{carbon\ footprint\ of\ structure - baseline\ carbon}$$

For the three beam sections above, when compared to the baseline concrete solution, we have:

$$CC_{steel} = \frac{780 - 760}{397 - 249} = \frac{20\ [£]}{148\ [kgCO2e]} = +\ 135\ [\frac{£}{tCO2e}]$$

$$CC_{timber} = \frac{840-760}{179-249} = \frac{80[£]}{-70\ [kgCO2e]} = -1143\ [\frac{£}{tCO2e}]$$

In this case, a positive CC_{struc} value indicates that a switch to the material results in a cost to emit more carbon. A negative CC_{struc} value indicates that a switch to the new design results in a cost to reduce carbon. Here, switching from a concrete design to a timber design captures carbon at the rate of 1143 £/tCO2e. Thus, we have:

$$CC_{struc} \begin{cases} \geq 0, & cost\ £\ to\ emit\ carbon \\ \leq 0, & cost\ £\ to\ reduce\ carbon \\ = 0, & no\ change \end{cases}$$

3.2 Dataset

We expand and build our analysis on a dataset with cost and carbon of different structural systems by Gauch et al. [28], where, based on UK cost data, different structural solutions for a multi-story building are parametrically generated, dimensioned, and analyzed. The analysis reveals a dataset of 229185 unique buildings with different material systems for decking and frame (Steel, Reinforced Concrete (RC), and mass timber structures), and spans for frames, floors, columns, and foundations. The structural systems have an embodied carbon coefficient of 77.2 kgCO2e/m2 to 349.5 kgCO2e/m2 with LCA scope "cradle-to-completion" (A1-A5). Please note that the actual embodied carbon emissions of a building will be substantially higher, as it would include additional elements, such as facades, interiors, and MEP systems [29]. For this analysis, we only consider the structural systems portion of the dataset.

4 Results

Figure 2 shows the cost and carbon data of the dataset, colored by material systems. The material systems are colored based on the main material of the floor and frame systems: steel frame with a steel deck, reinforced concrete frame with a reinforced concrete deck, steel frame with a reinforced concrete deck, timber frame with a timber deck, and partial timber frame or deck (consisting of a steel superstructure with CLT decking or glulam structure with steel decking).

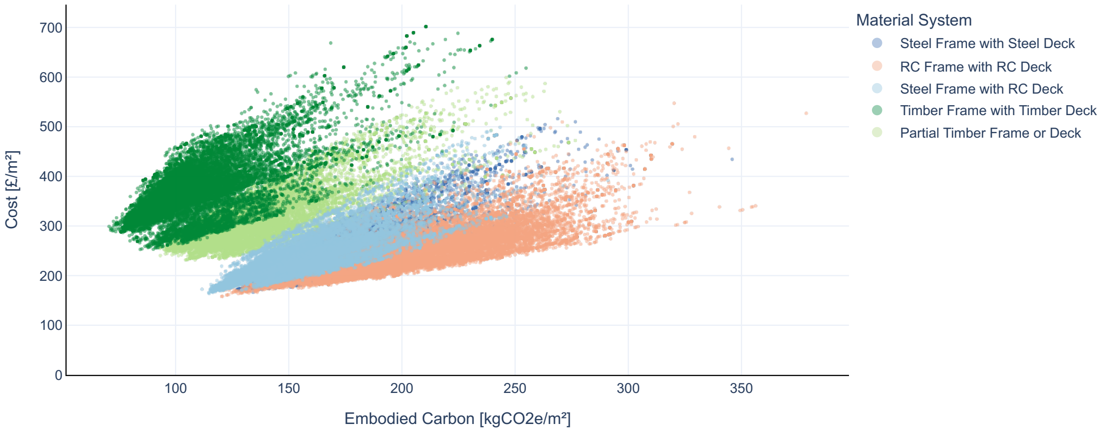

Figure 2: Cost premium and embodied carbon per square meter of all buildings in the dataset.

4.1 Carbon avoidance and storage potential in building structures

4.1.1 Dataset: cost and carbon comparison to a baseline

We create a baseline for the building structure of 300 £/m2, and 250 kgCO2e/m2, to which we compare all buildings in the database. In Figure 3, we assess the total cost and carbon savings compared to the baseline. We show the cost premium to the baseline and the overall embodied carbon premium of each building in the dataset. A positive carbon premium means that the building structure emits more carbon than the baseline structure. A negative cost premium means that the building structure costs less than the baseline scenario.

The baseline organizes the data in four categories: structures with lower carbon footprint, structures with higher carbon footprint, structures with higher cost, and structures with lower cost. The top right quadrant of the diagram, for example, shows the structural system that displays a higher cost and higher carbon footprint than the baseline structure. The lower left quadrant shows structural systems that have a lower cost and lower carbon footprint than the baseline structure.

We can see that different frame materials of the superstructure differentiate the data into different clusters. Full timber structures have an average cost premium of 71 £/m2 with an average EC saving of 140 kgCO2e/m2, while RC structures are 41 £/m2 cheaper and save 4 kgCO2e/m2 compared to the baseline. Steel structures with RC and steel deck fall in between, being 61 £/m2 cheaper and saving 9 kgCO2e/m2 carbon. Partial timber frame and deck have an average cost premium of 9 £/m2 with an average EC saving of 120 kgCO2e/m2.

Many structures with significant carbon savings do not have a cost premium, but are in fact cheaper, especially for steel and concrete structures. Cost scales with material use, and lower material use means lower cost. In timber, however, more carbon savings can be associated with a higher cost. Most timber frame structures are in the upper left quadrant of the graph, displaying a lower carbon footprint and higher cost than the baseline structure. The structures with the highest carbon-saving potential are timber and partial timber structures. The structures with the lowest costs are RC frame and steel frames.

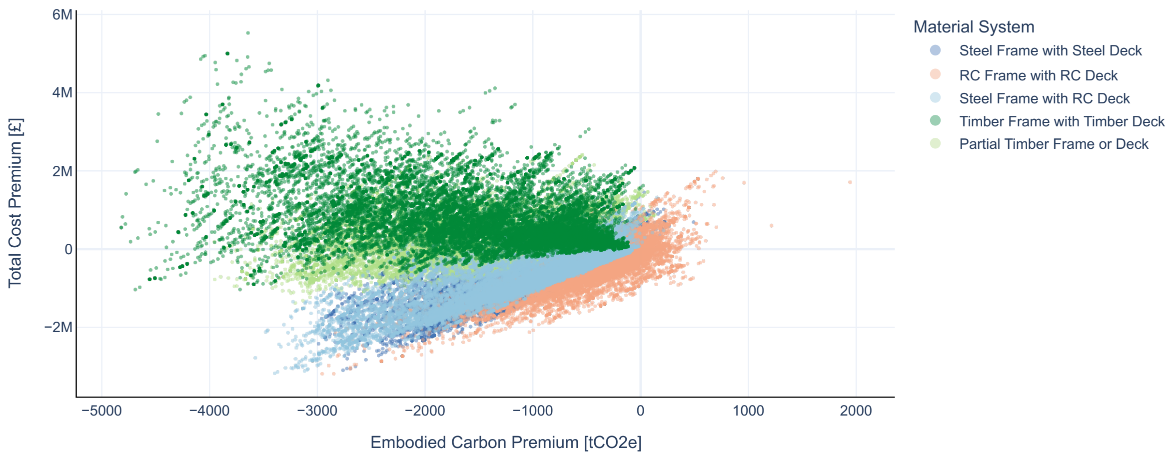

Figure 3: Total premium and total embodied carbon savings of each structure when compared to a baseline building with 300£/m2 and 250 kgCO2e/m2.

All the structural systems in the lower left quadrant have the potential for direct carbon mitigation through avoiding emissions and biogenic carbon storage avoidance, without any financial incentives. They represent structural systems with a lower carbon footprint and a lower cost than a defined baseline structural system. Design teams selecting these designs are effectively reducing the carbon footprint of the build environment when compared to a baseline scenario.

The dataset shows a large variety of building designs across different loading conditions, spans, and material systems. While the data suggests that some designs are much better than others according to these metrics, they are not entirely equivalent designs. Nevertheless, the fact is that among all design options available to a design team, lower-cost and lower-carbon alternatives exist.

4.1.2 Cost of carbon avoidance in building structures

In Figure 4, we assess the cost of avoiding carbon and the carbon savings per square meter, compared to the baseline scenario of 300 £/m2 and 250 kgCO2e/m2, using the equation for the *Cost of Carbon* CC_{struc} defined in section 3.1. The scatter plot shows how many solutions in steel and timber achieve carbon savings while staying well below the costs of traditional CDR technologies [27]. Carbon savings are the highest for structures that combine a superstructure and decking in timber, followed by structures that combine steel with timber and concrete. The addition of the biogenic carbon, assuming carbon storage for timber of 1.43 kgCO2e/kg, in the cost of carbon equation has an important impact on the cost of carbon, as it can be seen with the shift to the bottom left of the timber frame and partial timber frame data points. the full timber structures (dark green in Figure 4,) increase their carbon savings significantly by 150 [kgCO2e/m2] on average and decrease the cost of carbon (CC Cost) saving per ton CO2e by 372 [£/tCO2e] on average. In both cases, the timber frame structure displays the lowest cost to mitigate carbon in the built environment, below the cost range of current CDR technology.

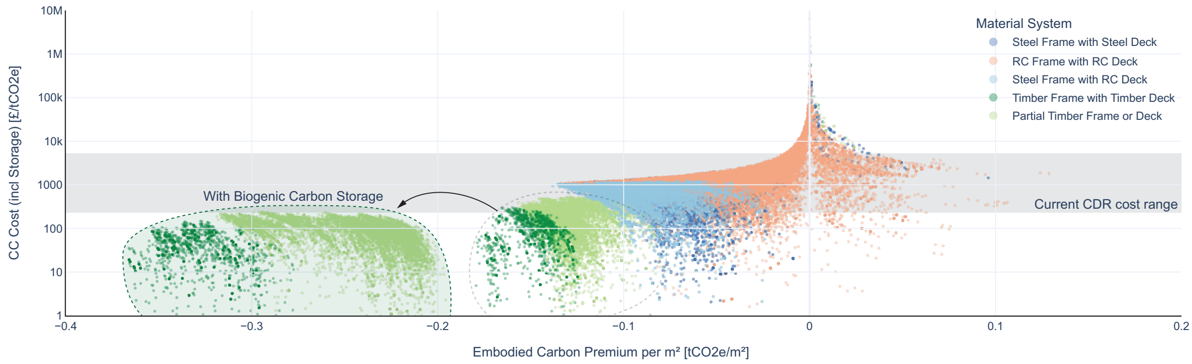

Figure 4: Cost of Carbon in buildings and embodied carbon savings of each structure when compared to a baseline building of 300£/m2 and 250 kgCO2e/m2. Industry-scale carbon dioxide removal (CDR) rates and targets are compared with interventions in buildings with (bottom) and without (top) biogenic carbon storage included in the calculation.

4.2 Carbon tax discount scenario

To compare the performance and distribution of different material systems in terms of embodied carbon and cost premium we utilize kernel density estimation (KDE) plots. The lines represent a smoothed probability density of the cost premium of each material system. The KDE plot allows us to visualize where the simulated projects in the dataset are clustered. In Figure 5 we show the distribution of embodied carbon emissions per square meter across material systems. In Figure 6 we show how the cost premium changes with add scenarios for different theoretical carbon tax discounts of 100, 250, and 500 £/tCO2e (carbon savings compared to a baseline scenario get subsidized for the amount of carbon they save). We assume the same categorization of structural systems and differentiate the timber frame options with or without biogenic carbon storage. While 100 and 250 £/tCO2e represent aspirational carbon tax scenarios, ~500 £/tCO2e would be more in the range of the true social cost of carbon when considering health impacts and climate damage [30].

A high distribution value for a given premium means that for the selected category, a large portion of data points have the same cost premium. For example, in the no carbon tax graph, in the upper left corner of Figure 6, the timber frame with timber deck has the most building design with higher cost premium than the baseline scenario, at around 70.9 £/m^2. In this example, only 6.8 % of all design have a lower cost premium than the baseline scenario, as indicated in the legend of the graph. With the addition of increasingly higher carbon taxes, we can observe the shift of design solutions towards the left of the graph. Here, the cost premium of the timber solution in the 500 £/tCO2e scenario disappears with 0.9 £/m^2. At the same time, the distributions are getting generally wider, signaling that the tax is pushing apart solutions of the same material systems on either side of the baseline. The larger distribution shift happens with solutions with lower carbon footprints, as they get larger tax discounts for the carbon savings compared to the baseline carbon amount. The timber frame with timber deck and biogenic storage changes from 13.7 % of solutions below the baseline cost to 90 % of solutions below the baseline cost with a carbon tax of 500 £/tCO2e.

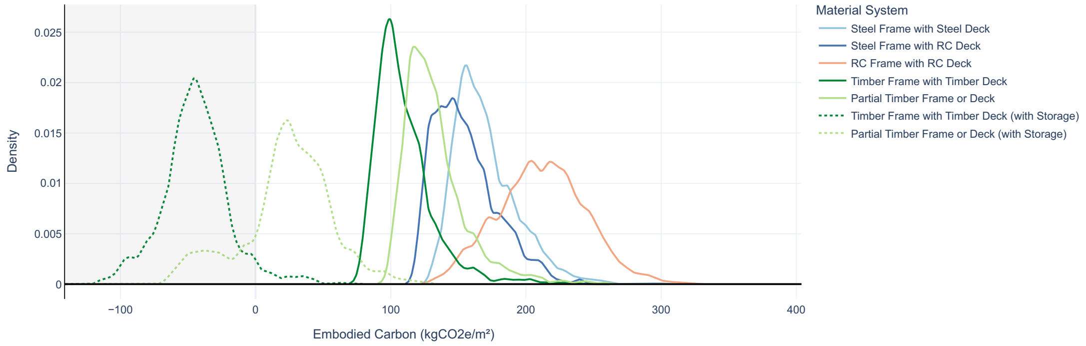

Figure 5: Kernel Density Estimation (KDE) plot of Embodied Carbon per square meter of different material systems, with and without biogenic carbon storage.

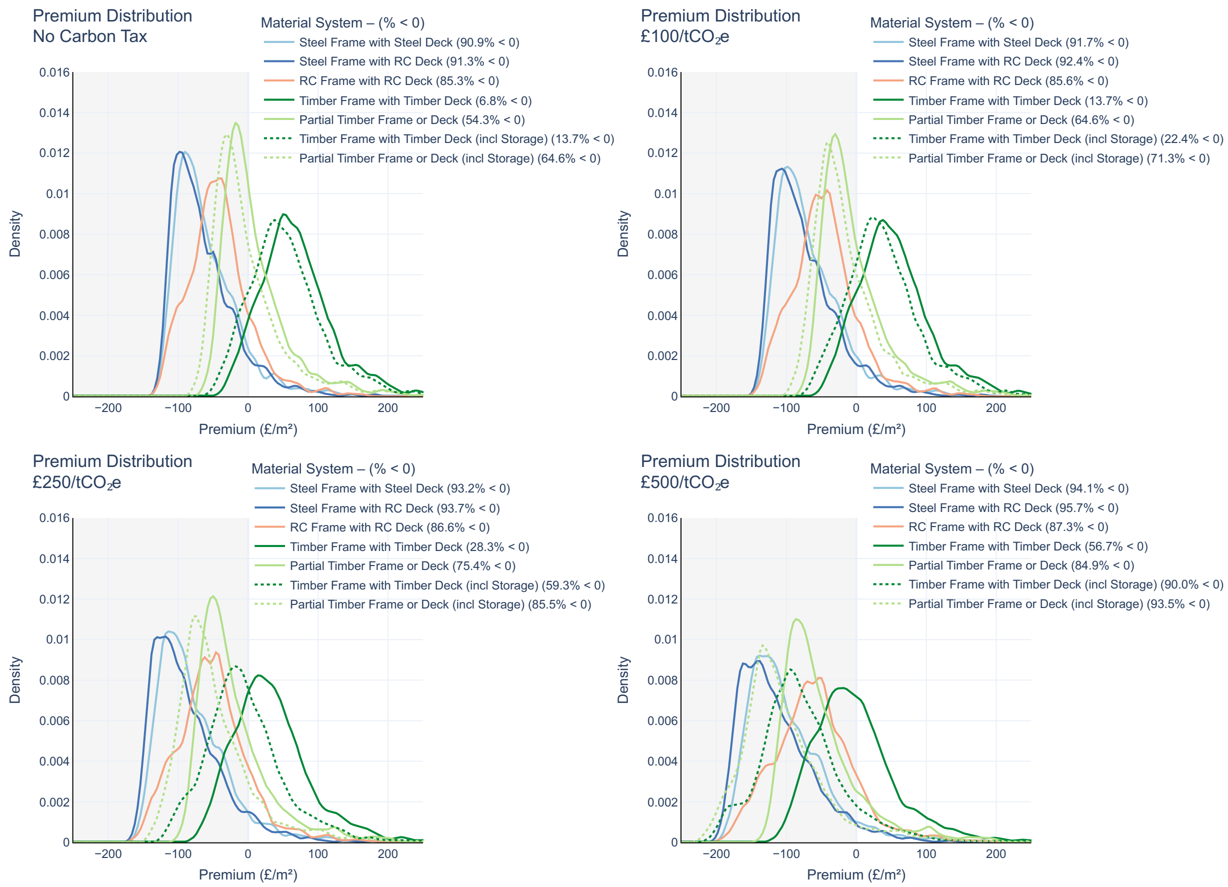

Figure 6: KDE distribution of the cost premium of different material systems when adjusted with a carbon tax discount scenario of £100, £250, and £500/tCO2. The baseline scenario of 300 £/m2 and 250 kgCO2e/m2 stays the same for all carbon tax discount scenarios. Each graph shows the density distribution of each building design when compared to the baseline scenario. The number of building solutions in percentage (%) of the total number of solutions for this category is shown in the legend.

5 Conclusion and discussion

The paper presents an approach to quantify the carbon impact of structural design decisions, and comparing it to industry standard carbon capture solutions, as a pathway to carbon accounting in the Architecture, Engineering, and Construction (AEC) sector. By considering the cost of design changes for lower-carbon building design solutions, we compute the cost of carbon avoidance of low-carbon building solutions.

Large-scale construction decisions are often governed by cost among design alternatives. While low-carbon design decisions (often at a premium) are not recognized or easy to enforce at scale, the paper presents an approach that puts a monetary value on sustainable designs through carbon capture. The cost of low-carbon design decisions is compared to current and target carbon capture costs. The analysis from a large data set of simulated buildings shows that the AEC sector offers on par or better carbon mitigation potential through avoiding and storing carbon, when compared to carbon capture technology, assuming that buildings are built anyway.

Because of the uncertainty around the permanence and end-of-life scenarios of timber buildings, we present the results both with and without considering biogenic carbon storage when accounting for the emissions. Importantly, even excluding biogenic carbon storage, the data shows, the potential for avoiding carbon in the built environment through structural changes – a strategy that can be deployed right away by design teams building lower-carbon buildings. Meanwhile, carbon capture options, such as direct air capture, typically require large upfront investments, and have much higher associated costs than avoiding carbon in the first place.

5.1 Potential implementation

The definition of baseline carbon and cost is an important parameter in our approach. In the current results, we pick a realistic baseline for contemporary construction as an example. However, the selection of the baseline scenario, if carbon credits were associated with the built environment, should be made carefully. It would require high quality data sets and consistent standards for calculating emissions from the materials used in the construction of a building. A high baseline scenario will amplify the carbon storage capability of the built environment. A low baseline scenario can make the appeal of carbon storage in the built environment challenging to activate.

The implementation of carbon capture is likely to be regionally defined by local governmental organizations. For example, the city of San Francisco could decide to publish a roadmap of its baseline values for the next 20 years, in the same way governments are pledging to reduce carbon emissions in climate agreements. The baseline carbon and cost would be decided scientifically, based on the knowledge of local construction practices and costs, for different building categories. The design team would then have a target cost and an embodied carbon value to design against, to claim carbon capture credits in their designs. Based on the reduction of embodied and operational carbon predicted at the design phase, an incentive could be distributed to the design and construction team. Upon completion of the building, an analysis of the as-built condition would provide a better estimate of the embodied carbon of the construction. Yearly, an organization would determine the carbon emissions reduction for both spent operational energy and embodied carbon, in the case of renovations or upgrades. An ambitious roadmap would have a steep reduction of the baseline design over a short amount of time, incentivizing material manufacturers, developers, design teams, and construction companies to implement new low-carbon design solutions rapidly.

Such programs are already in place for other industries and are effective. The California Cap-and-Trade Program launched in 2013, for example, has supported carbon emissions reductions successfully. Embodied carbon in buildings, however, is not considered. Voluntary embodied carbon reduction pledges, like the Structural Engineering 2050 Commitment Program, give merit-based incentives to design firms to reduce the carbon footprint of their projects. A list of design firms and their reduction pledges is available online, showing that companies are already willing to work on embodied carbon reduction and publish their carbon emissions reduction data for some projects. The program, however, has no financial incentives associated with carbon reductions.

We argue that compensating the design team's effort to low-carbon design will have important effects on the sustainability of the built environment. These incentives would provide a boost in the development and deployment of new low-carbon ideas and technology in the construction sector. The field of structural design is moving towards low-carbon solutions for the built environment through different techniques, such as structural optimization and the use of low-carbon materials. These solutions display important carbon reductions but currently have a slow adoption rate due to the associated potential increased cost and adoption risk.

5.2 Outlook

The research shows the potential of avoiding and storing carbon as a design driver for structural design. New regulatory and incentive frameworks could be proposed to incentivize both research and implementation of low-carbon building designs. The current cost of avoiding carbon in building structures can be cheaper than the current CDR technology costs. We have the legislative and financial framework in place for trading carbon in the voluntary carbon markets. We have tools to assess the carbon footprints of different design options. We also have a design approach and material systems to reduce the carbon footprint of the construction systems, winning in the marketplace.

Discussions around the quality of carbon capture projects, and double counting of carbon credits along the supply chain of materials should be carefully considered for this application. In current carbon offset projects, studies have shown that some certification agencies for carbon projects can underdeliver the carbon benefits or be classified as low-quality carbon offsets [32]. Especially with long-term carbon offset projects, such as reforestation, the carbon benefits are distributed over a long period of time. The actual carbon reduction benefits could take decades to be measured, while the credits are being allocated at the start of the project. Considering this for embodied and operational carbon of buildings, carbon accounting should only consider direct carbon savings for higher-quality carbon credits. However, the stored carbon could benefit future generations and incentivize them to recirculate structural materials in the future for carbon credits. For operational energy savings, the carbon credits should only be given after measurements of the actual energy use of the building. Not only would this provide incentives for a continual improvement of the building performance, with incentives for building upgrades, but also incentives for building occupants to tune their behaviors towards low operational energy usage.

Carbon credits are emerging financial leverages to incentivize the reduction of carbon emissions. There is no doubt that low-carbon design in the built environment has an important role to play in climate change mitigation strategies. Given the results of this study, it is only a matter of time until our community receives credit for the ongoing contributions of carbon emissions reduction. The study showed the impact of design decisions if a financial incentive was attached to low-carbon design decisions. These incentives would support low-carbon decision making, support the development and deployment of new low-carbon structural design strategies, and incentivize low-carbon design education.

The success of shell designers and builders like Heinz Isler was in part linked to the commercial success of his design, supported by low material use and ingenious construction methods. At a time when material costs might have severely impacted implementation decisions of such designs, material-efficient designs were successful and competitive in the marketplace. Considering the environmental externalities of building design could trigger an important shift in design practices.

6 Acknowledgements

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