Barriers to the use of computational tools for embodied carbon reduction in structural engineering practice

By

Margaret Smith

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Authored by: Margaret Smith
Department of Civil and Environmental Engineering
May 12, 2023

Certified by: Josephine Carstensen
Department of Civil and Environmental Engineering
Thesis supervisor

Accepted by: Colette L. Heald
Professor of Civil and Environmental Engineering
Chair, Graduate Program Committee

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Abstract

There is an immediate need to decrease carbon emissions to minimize the impacts of climate change, and building materials, which in 2019 accounted for 10% of global carbon emissions, have an important role to play in this reduction. As key stakeholders in the building design process, structural engineers must implement strategies to reduce embodied carbon. One strategy is using less material, and in academia, many methods and tools have been proposed to reduce embodied carbon through material efficiency. This includes parametric models that demonstrate how structural parameters impact embodied carbon and shape or topology optimized components which save considerable amounts of material compared to conventional alternatives. However, these tools are not used often in industry. To better understand why, a survey was distributed to practicing structural engineers in the northeast US which probed their views on embodied carbon and computational tools to reduce it. Case studies on parametric design, shape optimization, and topology optimization were presented, and participants were asked if they would use each tool and why or why not.

A total of 38 structural engineers, representing 26 different employers, responded to the survey. Most respondents could name a strategy to reduce embodied carbon, however, low-carbon materials were mentioned far more than using less material, indicating that there is a need for increased education on the power of material efficiency to impact embodied carbon. As expected, respondents were most willing to use parametric design, followed by shape optimization, then topology optimization. For all case studies, time and/or cost increase was identified as the strongest barriers to their use. For parametric design, lack of power during the design process was also a strong barrier, as structural engineers often do not have complete control over all structural parameters. For shape and topology optimization, constructability and the robustness of optimized designs were key concerns. By formalizing the barriers to their use, this work enables researchers to create computational tools that are more likely to be adopted in industry. These tools have great potential to decrease embodied carbon emissions, and for this to be realized, they must be put into practice.

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1. Introduction

The negative impacts of human-induced climate change on ecosystems and people are already seen today. As such, significant reductions in greenhouse gas emissions are urgently needed to limit global average temperature increase to the 1.5ºC target set by the IPCC and Paris Agreement (*The Paris Agreement*, n.d.). The building sector has an important role in this reduction, as in 2019, it accounted for approximately 37% of global CO2 emissions (IEA, 2020). This includes emissions from the building's use (also known as *operational carbon*) and from the building's materials (also known as *embodied carbon*). Embodied carbon includes emissions associated with the production, transportation, installation, maintenance, and disposal of building materials (*Embodied Carbon 101*, n.d.).

In recent years, the operational carbon of buildings in the US has decreased due to increased awareness and energy performance standards, however, embodied carbon has not seen the same reduction (De Wolf et al., 2016). In 2019, building materials accounted for 10% of global carbon emissions (IEA, 2020), and therefore a decrease in emissions associated with these materials could significantly impact global carbon emissions. The building design process needs to change drastically to realize this.

As key stakeholders in the design process, structural engineers can impact embodied carbon through their design decisions. The equation for calculating embodied carbon (Equation 1) reveals the two main ways to do so: through material choice (reducing $ECC_i)$ and material efficiency (reducing Q_i). Material choice refers to choosing low-carbon materials in design, such as timber or more sustainable concrete mixes. Material efficiency, which is the focus of this paper, means using less material and creating structures that are more efficient.

$$Embodied\ carbon = \sum_i Q_i \times ECC_i \quad \textit{(Equation 1)}$$

where i = a given structural material
Q_i = the quantity of material i (volume or weight)
ECC_i = the embodied carbon coefficient of material i, often in
units ofCO_2e (CO_2 equivalent) per unit volume or weight

Researchers have proposed a variety of methods to decrease the embodied carbon of structures through material efficiency, many of which involve the use of computational tools. For example, parametric models can be used to understand the impact of building parameters, like column spacing, on embodied carbon; or optimization can be used to find the most materially efficient solution that meets structural and project constraints. Several publications have identified the need to implement these tools to reduce the embodied carbon of structures, including a 2020 report by the SEI Sustainability Committee (Webster et al., 2020). However, it has proven difficult to implement these solutions in practice, partly because designers tend to stick with conventional methods and materials. Additionally, researchers that develop solutions to reduce embodied carbon may not be aware of all the factors and stakeholders involved in design, for example, construction feasibility or minimum column spacings required by the client. Practitioners may also lack the training or software required to implement these solutions.

Some studies have used surveys to understand why strategies to reduce embodied carbon, or increase material efficiency, are not implemented regularly in practice. Giesekam et al. (2016) examined construction practitioners' views on low carbon materials, and Orr et al. (2019) aimed to understand material efficiency in design and sources of inefficiency in current structural engineering practice.

However, to the author's knowledge, none of these surveys have focused on structural engineers in the United States, and none focused on the use of computational tools to increase material efficiency.

This study aims to address this gap through a survey of practicing structural engineers in the northeast United States, which has the following objectives:

1. Survey current structural engineering practice: To what extent do structural engineers consider embodied carbon during building design? How are computational tools, such as parametric design and optimization, currently used in practice?
2. Identify barriers to the use of computational tools which reduce embodied carbon through material efficiency.

This information will enable researchers and practitioners alike to better understand what needs to be done to encourage the adoption of such technologies. It is not enough that these technologies exist – to have an impact on the embodied carbon of the built environment, which is urgently needed, they must be put into practice.

2. Literature Review

2.1 Computational tools to reduce embodied carbon through material efficiency

An abundance of structural solutions and tools have been developed to decrease embodied carbon through smarter use of material. Although these studies often only include the embodied carbon associated with material production and transportation (called the cradle-to-gate phase), it has been shown that this phase accounts for 70-90% of the life cycle embodied carbon (Monahan & Powell, 2011; Li et al., 2013; Nadoushani & Akbarnezhad, 2015; Meneghelli, 2018; Moncaster et al., 2018 ctd. in Jayasinghe, 2022). The following section summarizes previous work in this field, including parametric models and alternative structural components that are more materially efficient, as well as surveys of construction practitioners on relevant topics.

The first category of studies discussed here are whole-building parametric models used to understand the impact of building parameters on material quantities and/or embodied carbon. A study by Trinh et al. (2021) on the embodied carbon in the superstructure of flat plate reinforced concrete buildings found that column spacing and post-tensioning can have significant impacts on cradle-to-site embodied carbon because both decrease the slab thickness, with reductions of 26-34% due to post-tensioning. When the column spacing was doubled from 6.67 to 13.33 meters, the embodied carbon increased by 117-129%. Many other parametric studies have demonstrated that as column spacing increases, so does embodied carbon (De Wolf et al., 2016; Eleftheriadis et al., 2018; Ferreiro-Cabello et al., 2016; Miller et al., 2015). As members primarily in bending, floor slabs are inherently inefficient, and an increase in the distance they span has a large impact on slab thickness and therefore embodied carbon. However, in practice, structural spans are often determined by the building use. Therefore, it may be more feasible to use different slab types instead to decrease material usage. Jayasinghe et al. (2022) compared several concrete floor systems in a concrete frame office building and found that two-way slabs on beams or hollow-core slabs can reduce cradle-to-gate embodied carbon by up to 36%, while a novel thin-shell floor can reduce it by up to 65% compared to a flat slab. While such findings are valuable in understanding the relative importance of design parameters in terms of embodied carbon reduction, the tools used are just as valuable, as findings can differ depending on the building being studied. In practice, a parametric model of a proposed building gives engineers powerful insights into how parameters impact design goals, such as embodied carbon reduction, so that they can make informed design decisions.

Computational tools can also be used on a smaller scale to decrease the embodied carbon of structural components. Ismail and Mueller (2021) developed, constructed, and tested shape-optimized ribbed slabs with varying cross-sections that meet structural requirements while minimizing the slab's embodied energy. The optimized designs reduced embodied energy by 48-64% compared to the equivalent one-way flat slab, and a slab prototype performed well in the load test, exceeding the serviceability deflection criteria. Mata Falcón et al. (2022) summarized several digitally fabricated floor slab designs, including the Smart Takes from the Strong project. In this project, two slabs with stay-in-place formwork were designed using topology optimization. In topology optimization, the user defines a design domain (a geometric region where the structure is allowed to exist), applied loads, and support conditions. An objective is also defined, which often is to maximize the stiffness of the structure with a constraint on material volume. The optimizer then figures out where to "place" material such that the stiffness is maximized. In other words, it generates a structure that has the highest stiffness for a given amount of material. This method can dramatically decrease material usage. For example, Galjaard et al. (2015) used topology optimization to design a steel connection and achieved a 75% reduction in weight compared to the original, conventional design. However, this decrease comes with a cost: these designs are often very complex and difficult to manufacture. One way to overcome this is to implement pattern gradation and repetition, which was done in Stromberg et al. (2011) to design lateral systems for high-rises. There are many other proposed ways to increase manufacturability of topology optimized designs, such as reducing the number of unique members in truss designs (Lu & Xie, 2023) and minimizing the use of support material by implementing overhang constraints (Gaynor & Guest, 2016).

The research summarized here shows that there are many different strategies to reduce embodied carbon through material efficiency, all with different levels of complexity. In general, increased complexity leads to more material and embodied carbon savings, however, more complex solutions are more difficult to implement.

2.2 Surveys of construction practitioners

Several studies examine the feasibility of strategies to reduce embodied carbon through surveys of construction industry practitioners. Orr et al. (2019) surveyed engineering practitioners on material efficiency in structural design, receiving 129 full responses. Studies have shown that utilization ratios of members in real buildings are low (Dunant et al., 2021; Moynihan & Allwood, 2014) and design loads used in practice are often higher than they need to be (Orr et al., 2019), both of which lead to material inefficiency. In this survey, when respondents were asked to choose the load capacity of a beam with an applied load, the average response had a utilization ratio of 89%, reflecting a culture in which overdesign is standard practice. In addition, they found that member standardization, which is done to simplify construction, as well as uncertainty about how serviceability loads impact the structure, lead to increased conservatism.

A 2016 study by Giesekam et al. focuses on material choice, rather than material efficiency, as a strategy to reduce embodied carbon. They surveyed 47 construction professionals on the adoption of low carbon materials and found that lack of knowledge or training was the primary barrier to use of such materials. Industry culture also seems to play an important role – as one interviewee put it, "existing practice becomes entrenched under the mantra of 'it's the way we've always done things'". Other key barriers include a perception of higher costs, concerns about durability, a lack of standards, low material availability, and the conservative nature of clients. In addition, they found the use of such materials is often driven by individual moral obligations, as there is a lack of strong economic or regulatory drivers to reduce embodied carbon.

These studies show that while some barriers to sustainable design practices are practical, such as construction feasibility and material availability, some are rooted in an industry culture of conservatism.

2.3 Hypothesized barriers to the use of computational tools to reduce embodied carbon

Based on this literature, as well as the author's personal experiences and conversations with practitioners, the following barriers to the use of computational tools to reduce embodied carbon were hypothesized:

- Lack of awareness of embodied carbon or strategies to reduce it (such as alternative materials, parametric design, or optimization methods)
- Lack of incentives to reduce embodied carbon
- Lack of skills or software to use these computational tools
- The engineer or their firm does not have the resources to devote people and time to learning a new tool or adding more steps to their workflows
- Concerns about the safety, feasibility, or robustness of the proposed technology
- Concerns about cost
- The power to make decisions that impact embodied carbon lies with another stakeholder, such as the client or architect, not the structural engineer (or structural engineers *believe* they do not have the power to impact the embodied carbon of the structure)

In order to encourage the adoption of computational tools such as the ones summarized in this literature review, these hypothesized barriers must be formalized. However, few, if any, studies have investigated structural engineers' views on these tools. In addition, of the studies that survey structural engineers on topics related to sustainability in design, few are primarily based in the United States.

3. Methods

To achieve the goals previously outlined, an online survey was created to understand structural engineers' views on strategies to reduce embodied carbon using computational tools. The survey design process was primarily informed by two books on social science research: *Handbook of Survey Methodology for the Social Sciences* (Gideon, 2012) and *Research with People: Theory, Plans, and Practicals* (Holt & Walker, 2009). The hypothesized barriers were used to guide question creation such that each barrier was addressed by at least one question and all questions were relevant to the study objectives.

Most questions used a Likert scale format (see Figure 1), which is commonly used to survey opinions and attitudes. Efforts were made to use only a few different scaling systems to make it easier for respondents. The scaling systems included Never/Always, Definitely not/Definitely yes, Not familiar at all/Extremely familiar, and Not at all aware/Extremely aware. The popular Strongly Disagree/Strongly Agree scale was not used, as studies have shown that respondents tend to want to be agreeable and answer accordingly ("Writing Survey Questions," n.d.). A seven-point Likert scale was used, and so respondents were able to select a neutral response. Other question types included multiple choice and free text. For multiple choice questions, response choices were randomized to minimize order bias, unless there was a logical order of choices.

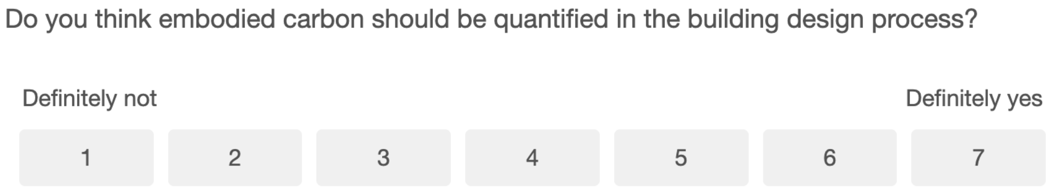
Do you think embodied carbon should be quantified in the building design process?

Figure 1. An example of one of the Likert scale questions in the survey.

The survey design guidelines set forth in Gideon (2012) were used to minimize survey error. This includes, but is not limited to, using clear and simple language with a neutral tone and being mindful about whether a question closed- or open-ended. It is also important to consider framing effects, which, as described Gideon (2012), occur when survey text or questions influence how respondents interpret information and form opinions. This was carefully considered in the survey introduction sent to potential participants in order to increase participation rates while not impacting how respondents view and respond to the survey. For example, it was not explicitly stated that their participation would help identify ways to increase the adoption of strategies to decrease embodied carbon. This could bias respondents' answers if they think we want them to respond more favorably to strategies to reduce embodied carbon.

All questions were optional to increase participation. Respondents were not allowed to return to a page once it was completed to prevent them from changing their answers after new information was presented. The following sections describe the contents of each survey section. The full list of questions as well as the accompanying text can be found in Appendix 1.

3.1 Survey organization

The survey consisted of nine sections, which are summarized in Table 1. Respondents first answered questions on the building design process, including how embodied carbon is considered (if at all) during design, and their awareness of and opinions on embodied carbon. The rest of the survey was dedicated to understanding the use of computational tools in practice and respondents' views on such tools. This involved three case studies: one on parametric design, one on shape optimization, and one on topology optimization. After briefly presenting each case study, follow-up questions probe whether the participant would use such technologies in their practice, and why or why not.

Table 1. Survey sections and guiding questions.

Section	**Number of questions**	**Guiding Questions**
1. Design Process	11	How are early-stage design decisions made? What stakeholders have power in the design process?
2. Embodied Carbon	17	What is the respondent's level of familiarity with embodied carbon quantification and benchmarks? To what extent is embodied carbon currently considered in the design process? Do respondents think embodied carbon should be quantified more often in design?
3. Computational Tools	3	Do respondents think that computational tools should be used more often by structural engineers?
4. Case Study 1: Parametric Design	10	How familiar are respondents with parametric models? Are parametric models used in practice, and for what purpose? Would respondents use a parametric model in early-stage design? Why or why not?
5. Structural Optimization	3	How often do respondents use structural optimization tools?
6. Case Study 2: Shape Optimization	8	How familiar are respondents with shape optimization? Would respondents use shape optimization to design components? Why or why not?
7. Case Study 3: Topology Optimization	8	*Same as above, but with topology optimization.*
8. Final Thoughts	3	Did the survey and case studies change respondents' opinions on embodied carbon or the use of computational tools?
9. Population Questions	5	
TOTAL # QUESTIONS	68	

3.1.1 Survey section 1: The building design process

The first section of the survey aimed to understand the typical structural design process and to what extent sustainability is considered. First, information on the types of projects the respondent usually works on was collected to provide context for their responses. They were then asked about the decision-making process in early-stage design, as this is when designers can have the greatest impact on the embodied carbon of the structure (Häkkinen et al., 2015). However, even if structural engineers wish to consider sustainability during design, there are some structural parameters that are determined by other stakeholders. For example, the architect or client may set minimum spans or floor to ceiling heights, or they may specify the structural material. Therefore, a lack of power in the design process can be a barrier to more sustainable design practices. Respondents were asked what parameters are determined by other stakeholders to better understand this barrier.

This study focuses on the use of computational tools to increase material efficiency and decrease embodied carbon, however, computational tools are not necessary to increase material efficiency. The simplest way to do so is to increase utilization ratios. As described in Orr et al. (2019), there are many inefficiencies in structural design, for example, the use of very conservative utilization ratios. Therefore, respondents were asked how often they consider material efficiency in design. It is expected that most respondents will consider material efficiency quite frequently, as it is an essential part of structural design. If they do not consider it frequently, that indicates that there is a fundamental barrier to the use of the proposed tools, which is that engineers do not feel the need to increase material efficiency.

Finally, respondents were asked how often they consider environmental impacts during design, which was asked here, before the embodied carbon section, so that reading the embodied carbon section would not influence their answer.

3.1.2 Survey section 2: Embodied carbon

The next section focused on embodied carbon. It first gauged participants' awareness of embodied carbon and embodied carbon benchmarks as well as whether any incentives (such as client's design goals) have motivated embodied carbon reduction in past projects. Structural engineers may be aware of embodied carbon; however, they may not know how they can reduce it. Therefore, they were asked to list any strategies that they know of to reduce embodied carbon, whether they have tried to implement these strategies in a project, and whether this was successful. Participants were also asked how often their team quantifies embodied carbon and what this data is used for. The data may just be added to a database, which, although useful to identify embodied carbon benchmarks, does not actively reduce the embodied carbon of the project. It is important to differentiate between these uses. Finally, we returned to the idea of power in the design process by asking participants whether they think structural engineers have the power to influence the embodied carbon of a building, and whether they as individuals feel they have this power. At the end of the survey, they were asked again whether they think structural engineers have this power, to understand if the survey and case studies influenced their response.

3.1.3 Survey sections 3 and 5: Use of computational tools and optimization in design

The rest of the survey was dedicated to questions about the use of computational tools and the case studies. Participants were asked if they think computational tools should be used more often during the design process before the case studies were presented, as the studies could bias their response. In two follow-up free text questions, participants were asked why they would use computational tools during design and why they would not. After the parametric design case study, they were also asked how often they use optimization tools. It was expected that optimization tools for automatic member sizing are commonly used, as these are built into most design software, however, other forms of optimization may be used less. Therefore, participants were asked specifically how often they use optimization for automatic member sizing, and in a separate question, how often they use optimization for any other purpose. In a free text follow-up, they were asked to give the name of the tool and what it is used for.

3.1.4 Survey section 4: Case studies

The case studies represented a range of techniques with varying expected levels of feasibility: parametric models to reduce embodied carbon, which are already used in some offices; shape optimization; and topology optimization, which has only been used in a few specialized building projects. For each study, only the methods were presented, not the results, such as the amount of embodied carbon saved. This was done so that respondents would focus on the technologies themselves, not their potential savings. If the amount of weight, embodied carbon, or cost savings was listed, this may cause them to respond more positively. Additionally, the amount of savings is dependent on a number of factors, such as the embodied carbon coefficients used. Presenting cost savings could be particularly misleading, as costs vary widely from region to region and are highly dependent on the local market.

A similar set of questions was posed for each case study to reduce complexity, making it easier and faster for respondents. This also allowed for a more direct comparison of responses to different studies. These questions are shown in Table 2. Because it was expected that parametric design is already used at some firms, this section included an extra set of questions after the case study was presented asking how often parametric models are used in early-stage design (Q4.2), what these models are used for (Q4.3), and what tools are used to create these models (Q4.4). In the last question in each section, the barriers of lack of power, time, and cost were removed, which was done to understand the importance of these barriers. The following sections will describe each case study section in more detail.

Table 2. Questions posed in case study sections.

<table>
<tr><th></th><th>PARAMETRIC DESIGN</th><th>SHAPE OPTIMIZATION</th><th>TOPOLOGY OPTIMIZATION</th></tr>
<tr><td><i>HOW FAMILIAR ARE YOU WITH...</i>
<i>Not familiar at all – Extremely familiar</i></td><td>...the term “parametric design”?
Q4.1</td><td>...the term “shape optimization”?
Q6.1</td><td>...the term “topology optimization”?
...Arup’s topology optimized connection?
Q7.1/7.2</td></tr>
<tr><td colspan="4"><i>CASE STUDY DESCRIPTIONS</i></td></tr>
<tr><td><i>DO YOU FEEL YOU HAVE THE SKILLS AND TOOLS TO...</i>
<i>Definitely not – Definitely yes</i></td><td>…create a parametric model to understand how building parameters impact a performance metric?
Q4.5</td><td>…use shape optimization to increase the material efficiency of a structural component, such as a slab, beam, or column?
Q6.2</td><td>…use topology optimization to increase the material efficiency of a structural component (such as a beam, column, slab, or connection)?
Q7.3</td></tr>
<tr><td rowspan="3"><i>WOULD YOU... IF YOU HAD THE SKILLS AND TOOLS TO DO SO?</i>
<i>Definitely not – Definitely yes</i></td><td rowspan="3">…create a parametric model in early-stage design for a future project…
Q4.6</td><td>…use shape optimization to design a floor slab in a future project… Q6.3</td><td rowspan="3">…use topology optimization to design structural components in a future project…
Q7.4</td></tr>
<tr><td><i>LOAD TEST INFO</i></td></tr>
<tr><td>Given this new information, would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so?
Q6.4</td></tr>
<tr><td><i>WHAT ARE THE MAIN REASONS, IF ANY, THAT YOU WOULD/ WOULD NOT...</i>
<i>Free text</i></td><td>…create a parametric model in early-stage design?
Q4.7/4.8</td><td>…use shape optimization to design a floor slab?
Q6.5/6.6</td><td>…use topology optimization to design structural components?
Q7.5/7.6</td></tr>
<tr><td><i>IF YOU HAD COMPLETE CONTROL OVER THE BUILDING DESIGN AND UNLIMITED TIME AND BUDGET, WOULD YOU USE...</i>
<i>Definitely not – Definitely yes</i></td><td>…a parametric model in early-stage design to explore high-performing designs?
Q4.9</td><td>…shape optimization to design structural components?
Q6.7</td><td>…topology optimization to design structural components?
Q7.7</td></tr>
</table>

In the parametric design section, respondents were first asked about their familiarity with parametric design. Then, parametric design was briefly explained with an example of a steel frame with varying column spacings. It was also explained that although parametric design can be used for member sizing, the focus of this section is its use in early-stage design of whole building systems.

The study by Trinh et al. (2021) was then presented. This study focused on the embodied carbon of flat plate reinforced concrete buildings. It examined a 10-story building with a square grid of columns and constant dimensions in plan of 133 by 133 ft, however, the spacing of the columns was varied. Lateral loads were ignored, as it was assumed that a central core provided adequate resistance. The concrete could either be reinforced or prestressed, and the concrete strength of the slabs and the columns was varied. Additionally, columns could either have the minimum allowable amount of longitudinal reinforcement or the maximum amount. The columns and slabs were designed in Excel according to Australian standards using different combinations of these parameters. This study was chosen because it considered conventional building methods, and the use of Excel, rather than say, Grasshopper and Karamba3D, is likely more accessible and appealing to practicing structural engineers.

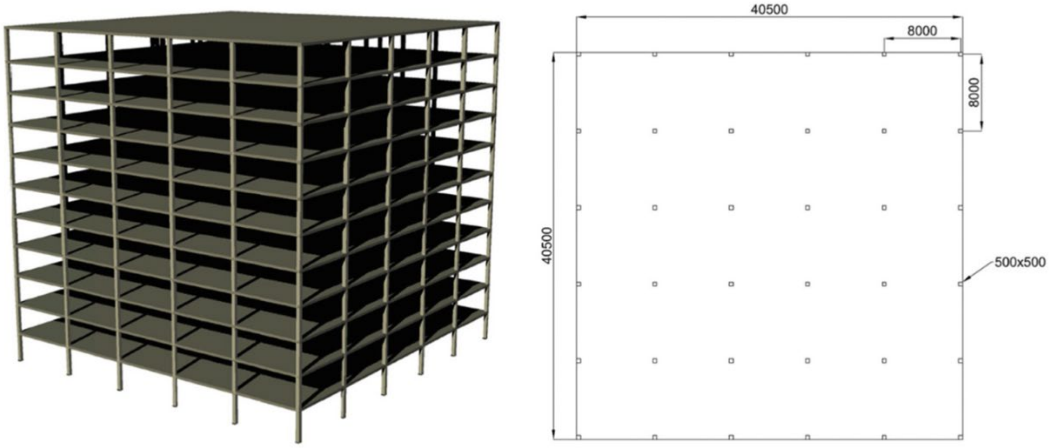

Figure 2. The building used in Trinh et al. (2021), which was adapted from Miller et al. (2015). This image was shown to survey participants.

For the shape optimization section, the study on shape optimized ribbed slabs by Ismail and Mueller (2021) was chosen. In this study, ribbed slab cross-sections were also designed according to code (in this case, ACI 318 and the National Building Code of India). The slab was modeled as a simply supported beam with a uniformly distributed load of 42 psf. The geometry was created by defining up to five cross-sections along its length which were continuously interpolated to create one volume. The optimization algorithm then used the control points of the cross-sections to create different designs, checking each cross-section for flexural and shear capacity, ductility, minimum flange width and thickness, and clear cover. It would then find a solution that meets these structural requirements while minimizing embodied energy[1]. The final design was compared to the equivalent one-way flat slab designed for the same loads and span using the NBC in India to understand how much embodied energy was saved. Note that for reasons previously described, the embodied energy savings was not disclosed to participants.

After asking Q6.2 and Q6.3, respondents were given additional information about the construction and load testing of a slab prototype, as well as the images in Figure 4. It was constructed using a sheet metal mold of laser-cut steel. The beam exhibited a ductile failure mode and reached the service load (1.8 kips) and ultimate design load (2.6 kips) without deflecting beyond the L/250 deflection limit, and at the ultimate design load, it had deflected approximately 0.5 inches. Additionally, experimental results aligned with the predicted performance. After presenting these questions, Q6.3 was repeated to understand how load test information impacts structural engineers' willingness to use a new structural system. After seeing the new information, respondents were not able to go back to change their

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[1] Here, embodied energy was defined, as only embodied carbon had been defined previously in the survey. It was noted that for widely available materials, embodied energy is typically proportional to embodied carbon.

response to the previous question. The embodied energy savings, as well as the cost of the slab prototype, were not provided.

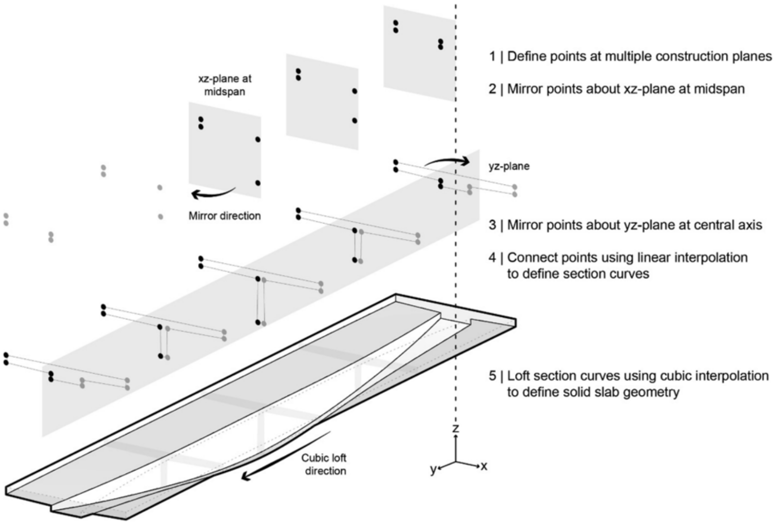

Figure 3. Definition of shape optimized ribbed slabs developed in Ismail & Mueller (2021). This image was presented to survey participants.

Figure 4. Formwork (top) and load testing setup (bottom) of the prototype shaped ribbed slab (Ismail & Mueller, 2021). Both images were shown to survey participants.

For the topology optimization section, topology optimization was briefly explained after asking about participants' familiarity with the term. An example of a 2D simply supported beam with a central point load was shown, using continuum elements and optimizing for maximized stiffness.

It was important the chosen study had manufactured the design, as manufacturability in topology optimization tends to be a significant concern. One area of research in topology optimization is the design of lateral systems for high-rises, which has been implemented in building designs, one of which, 100 Mount St, was constructed (Beghini et al., 2014). However, this solution with offset diagonal bracing does not represent the complexity and detail of most topology optimized solutions. The two remaining studies under consideration were a topology optimized reinforced concrete beam (Jewett & Carstensen, 2019), and Arup's topology optimized steel connection (Galjaard et al., 2015). Arup's connection was chosen because those in industry may be more familiar with it, and the fact that it was designed by practicing structural engineers may make it more appealing. Choosing a study that would appeal more to practitioners was important because it enables us to see what criticisms there still are even for technologies that are more accepted by those in industry. Because it was expected that some may know about this study, respondents were asked about their familiarity with it before it was described.

Arup's connection was designed for a tensegrity structure in which many cables connect to one node. The authors chose to explore the use of topology optimization to minimize weight, as the weight of the connections in this structure could significantly impact the size and weight of the members. They used Altair Optistruct with stress limits and the material properties of stainless steel. The optimizer accounted for some manufacturability constraints, and two versions of the node were produced by direct metal laser sintering of stainless steel. Again, the final material reduction achieved was not stated, and only the image in Figure 5 was shown.

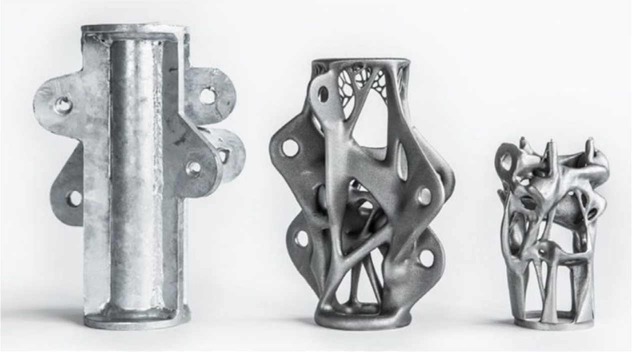

Figure 5. Arup's topology optimized node, which was used for the third case study in the survey (Galjaard et al., 2015). This image was shown to survey participants.

All the case studies demonstrate the benefits of using computational tools to reduce embodied carbon, and therefore these sections are inherently leading. However, because this is an exploratory study with the aim of understanding reasons why practitioners would not use these tools, this was considered acceptable. If potential downsides to these technologies were presented, this would influence their response. For example, someone who maybe would not think of the issue of construction complexity on their own would likely agree that it is a barrier if it was presented to them. Therefore, it was preferred to have respondents think on their own of the downsides of these tools to understand what first comes to mind, as this tells us what is considered to be the most important. To account for the leading nature of these sections, the question asked before the case studies (Q3.1, "Do you think that computational tools, such as parametric design and optimization, should be used more often by structural engineers in building design?") was repeated after the case studies. This was done to understand the impact that reading the case studies had on their views on computational tools. If participants feel more strongly that these tools should be used, this indicates that education is an important way to increase the adoption of computational tools in industry.

3.1.5 Miscellaneous questions

In addition to the sections described above, several questions throughout the survey focus on the barriers of lack of awareness and lack of software or training to use these computational tools. It is likely that engineers would be more willing to use new tools if they were integrated into software that they are most familiar with. Therefore, participants are asked what software they typically use for structural analysis and design, as well as for parametric models. They are also asked how often they hear about research related to either structural optimization or embodied carbon and how they hear about such research. This could be used to determine the current level of awareness of these research topics in industry, as well as the best ways to increase awareness.

3.3 Pilot studies and distribution

To refine the questionnaire, two pilot studies were conducted: one with civil engineering master's and PhD students and one with practicing structural engineers located outside the region of interest, the northeast US. Survey distribution was limited to the northeast US because structural design practices are highly dependent on local climate and supply chains. Advertising messages asked for structural engineers with experience in building design, as buildings are the focus of the case studies. The survey was distributed through state structural engineering associations in the northeast US who advertised it to their members via email, LinkedIn, and/or announcements during meetings. This was effective in facilitating responses from smaller firms; however, it was not as successful in reaching larger ones. Therefore, the survey was also distributed to personal contacts at under-represented firms. It is important to note that these contacts are likely to be more familiar with embodied carbon and/or computational tools. Additionally, those who are more interested in sustainability or computational tools are more likely to participate in the survey, which introduces additional bias in the sample. In total, the survey was open to responses for six weeks in early 2023.

3.4 Data Analysis

The sampling method used in this study is nonrandom, which means that this sample is not necessarily representative of the entire population of structural engineers in the northeast US (Gideon, 2012). Therefore, it cannot be assumed that the results found in this study are true of this population. Furthermore, parametric tests cannot be used to analyze the data, as these tests often require larger sample sizes and cannot be used with categorical or ordinal data. Non-parametric tests, on the other hand, allow for smaller sample sizes and the use of categorical and ordinal data, and they can be used on populations with non-normal distributions (Pett, 2016).

Data was compiled in Excel and imported into either Python or IBM SPSS Statistics (IBM Corp, 2022) for analysis. The following sections describe the methods of analysis for each question type. A glossary of statistical terms used can be found in Appendix 2.

3.3.1 Likert scale questions

In this section, the term *agreeable response* refers to responses of five through seven on the Likert scale, and *disagreeable responses* refers to responses of one through three, even though the Agree/Disagree scale was not used in this study. A response of four fits in neither of these categories and is termed the *neutral response*.

When analyzing Likert scale data, there are several questions of interest:

Q1. For a given question, do respondents tend to respond agreeably (with a score greater than 4) or disagreeably (with a score less than 4)?

Q2. Given two independent groups (for example, respondents from SE 2050 signatory firms and those who are not) is there a difference in how the two groups respond to a question?

Q3a. When a question is asked once at the beginning of the survey and once at the end, do respondents change their answers? Do they tend to respond more agreeably, or more disagreeably?

Q3b. For two questions using the same rating scale (ex. Not familiar at all to Extremely familiar), do respondents change their answers from one question to the next? Do they tend to respond more agreeably, or more disagreeably?

Q4. Are the responses to two questions correlated? For example, are respondents who calculated embodied carbon more often also more familiar with embodied carbon?

Although one may infer the answers to these questions by simply visualizing the data, statistical tests must be used to understand if observed differences are statistically significant. For example, if a coin is tossed ten times, it may land on heads six times and tails four times, however, this does not mean that it is biased to land on heads. The difference in the number it lands on heads and tails is due to randomness. Significance tests aim to understand whether such a difference is due to randomness or due to an underlying effect.

For Q1, this was determined using the chi-squared test, which is a commonly used nonparametric significance test (Pett, 2016). In a Python script, the Likert scale data was sorted into two categories for each question: agreeable responses (five through 7) and disagreeable responses (one through three). The chi-squared test was then used to determine whether the difference between the number of agreeable and disagreeable responses was significant. First, the expected number of disagreeable and agreeable responses was calculated by dividing the total number of responses by two. The chi-squared (X2) value was then calculated using the equation

$$X_c^2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad \textit{(Equation 1)}$$

where O_i is the observed number of responses and E_i is the expected number of responses for agreeable responses (i = 1) or disagreeable responses (i = 0). If the chi-squared value is greater than the chosen critical value, there is a significant difference between the number of positive and negative responses. The critical value is determined with a chi-square distribution table using the degrees of freedom (here, *dof* = 1) and the desired level of confidence. For example, for a 95% confidence level (*alpha* = 0.05), the critical value is 3.841. For a confidence level of 99.9% (*alpha* = 0.001), the critical value increases to 10.828. A confidence level of 95% is often used as the minimum confidence level to prove significance and will be used here as such. In figures displaying Likert scale results, questions with an asterisk next to them are ones where the difference between positive and negative responses was found to be significant with at least 95% confidence.

To understand how two independent groups respond to the same question (Q2) the chi-squared test can also be used, as described in Pett (2016). The data was again modified so responses are either agreeable or disagreeable[2], however, the test is now considering two independent groups. Thus, the equation for the chi-squared statistic becomes

$$X_c^2 = \sum_{i=1}^{r} \sum_{j=1}^{c} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \quad \textit{(Equation 2)}$$

where O_{ij} is the observed number of responses and E_{ij} is the expected number of responses for agreeable responses (i = 1) or disagreeable responses (i = 0) and responses from group one (j = 0) or group two (j = 1) (Pett, 2016). Again, the chi-squared value must be greater than the critical value of 3.841 to show that the two groups responded differently to the question with a confidence level of 95%. IBM SPSS Statistics was used for this calculation, which provides both the chi-squared statistic and the exact confidence level that it correlates to.

To understand differences in responses between two questions (Q3), the Wilcoxon signed-rank test was performed using IBM SPSS Statistics. This test is used to understand how much respondents' answers change between two questions and is especially effective for small sample sizes and non-normally distributed data (Pett, 2016). It is often used to compare responses to the same question that is repeated after a period of time. In this survey, there were two questions asked near the beginning and the end of the survey. The Wilcoxon signed-rank test can be used to understand how participants change their answers between the two. Additionally, it can be used to compare two separate questions which operate on the same rating scale, for example, two Likert questions which both use the "Definitely not" to "Definitely yes" scale. One key assumption of this test is that the distribution of the differences between responses to two questions is symmetrical (Pett, 2016). This was determined by plotting a histogram of the differences between responses and seeing whether it is badly skewed.

Finally, the Spearman rank-order coefficient was used to understand if responses to two questions are correlated (Q4). It can range from -1 to +1, where +1 indicates a perfect positive relationship, -1

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[2] The chi-squared test could be performed using the original set of Likert scale data, with seven categories (i = 0, 1, 2, 3, 4, 5, 6), however, as discussed in Pett (2015) chapter _, it is recommended that no more than 20% of the expected frequencies are less than 5. With the small sample size of this study, this is not possible. Therefore, the data was broken into two groups of agreeable and disagreeable responses.

indicates a perfect negative relationship, and 0 indicates no relationship. For example, if respondents that respond agreeably to Question A also respond agreeably to Question B, there is a positive relationship between the two question responses. It is important to note that even if there is a *correlation* between two questions, that does not indicate *causation*.

The Spearman rank-order coefficient was calculated in IBM SPSS Statistics using a two-sided test. The associated confidence level is outputted for each pair of questions, which is what will be provided here to indicate the strength of the relationship between two questions. For further information on the Wilcoxon signed-rank test and the Spearman rank-order coefficient, see Pett (2016).

3.3.2 Free text questions

Free text coding was used to extract quantitative results from free text responses. The book *The Coding Manual for Qualitative Researchers* (Saldaña, 2009) informed the coding process. A code is defined as “a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language-based or visual data” (Saldaña, 2009). The author and Demi Fang, a PhD student in MIT’s Department of Architecture, first reviewed the free text responses and developed a set of codes for each question to capture information of interest. Then, codes were assigned to responses individually, after which the assignments of the two researchers were compared, and differences were resolved. A code was only assigned to a response if both researchers agreed that the response was clear and explicit enough to justify assigning the code. Additionally, at the end of each case study section, a final free-text question asked if respondents had any other comments on the study. Some of the responses answered a previous question in the section, and during free text coding, the response was moved to the appropriate question. This was also done for another response in the embodied carbon section where it was clear the respondent was answering a different question.

4. Results

The following sections describe the results of the survey. A total of 38 responses were collected, representing 26 different employers. However, because all questions were optional, not all received 38 responses. Therefore, the number of responses for each question will be provided.

4.1 Population Details

It is important to first understand the survey sample, which includes participants' office location, size of employer, years of experience as a structural engineer, and design experience. Out of the 29 respondents who disclosed their office location, 65% were in either New York or Massachusetts (Figure 6). These two locations were the primary focus of distribution efforts. Three respondents were located in other parts of the US outside of the northeast region. All 38 participants disclosed their years of experience as a structural engineer (Figure 7). The median was 11-15 years. The company names given in the consent form responses were used to determine company sizes using LinkedIn, and it was found that the median was 501-1,000 employees (Figure 8). Details about participants' design experience were also collected. Most typically worked on new construction, closely followed by retrofit projects (Figure 9), and most worked on low- to mid-rises (Figure 11). Figure 10 shows that there were a variety of use types represented, with residential construction being the most common. Two respondents were bridge engineers. Finally, when asked what structural materials they work with most often, concrete and steel were the most commonly used, with timber and masonry used less, as shown in Figure 12.

Company names were also used to determine how many respondents were from SE2050 signatory firms. SE2050, which stands for the Structural Engineers 2050 Commitment Program, was created with the goal that "All structural engineers shall understand, reduce, and ultimately eliminate embodied carbon in their projects by 2050" (*What Is SE 2050 Overview?*, n.d.). Firms that sign the commitment must create an Embodied Carbon Action Plan (ECAP) detailing how they will educate employees about embodied carbon. They must also set goals to reduce the embodied carbon of their projects and share embodied carbon data for a minimum of two projects per US office to the SE2050 database[3].

Comparing responses from signatory and non-signatory firms will aid in understanding the success of the SE2050 program thus far. It is expected that respondents from signatory firms will have a greater awareness of embodied carbon. It should be noted that the program is quite recent, with the first signatory firms joining in 2020, and therefore firms are likely still in the process of educating employees on embodied carbon and increasing the amount of sustainable design strategies used in their projects.

The SE2050 website was used to determine which firms have signed the commitment (*Signatory Firms – SE2050*, n.d.). It was found that 55% of respondents worked at a signatory firm. It is important to note that there may be other variables, such as office location or firm size, that caused differences in responses from signatory and non-signatory firms. As shown in Figure 8, signatory firms represented in this survey tended to be much larger, with a median of 1,001-5,000 employees compared to 11-50 for non-signatory firms, likely because smaller firms are less likely to have the resources to commit to SE2050. Those from signatory firms were also primarily located in Massachusetts or New York (82%) with none from CT, NH, NJ, or RI. Furthermore, more respondents from signatory firms indicated that they work on high-rises (Figure 11). For years of experience, the results for respondents from signatory

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[3] If a firm has multiple offices, no more than five projects need to be submitted across the whole firm.

and non-signatory firms were more similar, with medians of 6-10 and 11-15 years, respectively. Results for project type (new construction, retrofit, and historic preservation) were also similar.

As explained previously, because random sampling was not used, the results of this survey may not be representative of all structural engineers in the northeast US. However, the results of the population questions give more confidence that there is a good distribution of office locations, years of experience, employer size, and project types. Therefore, although the results presented in the subsequent sections are not entirely representative of structural engineers, they are not entirely unrepresentative, and can still be useful in understanding this population and ways to encourage the use of computational tools to reduce embodied carbon.

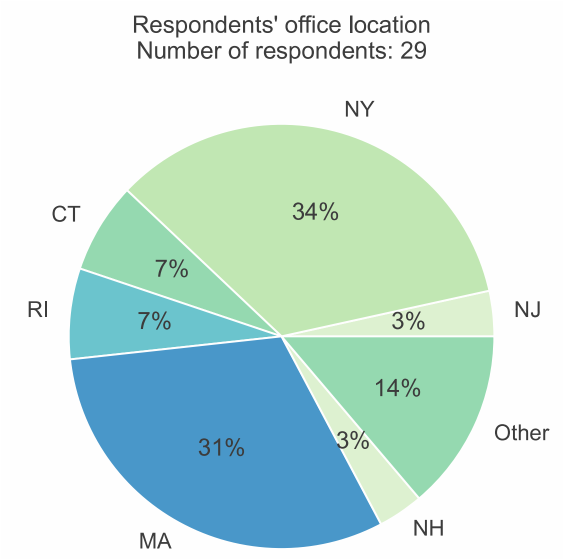

Figure 6. Office locations of the respondents. Note that this question received only 29 responses out of the total of 39 survey participants.

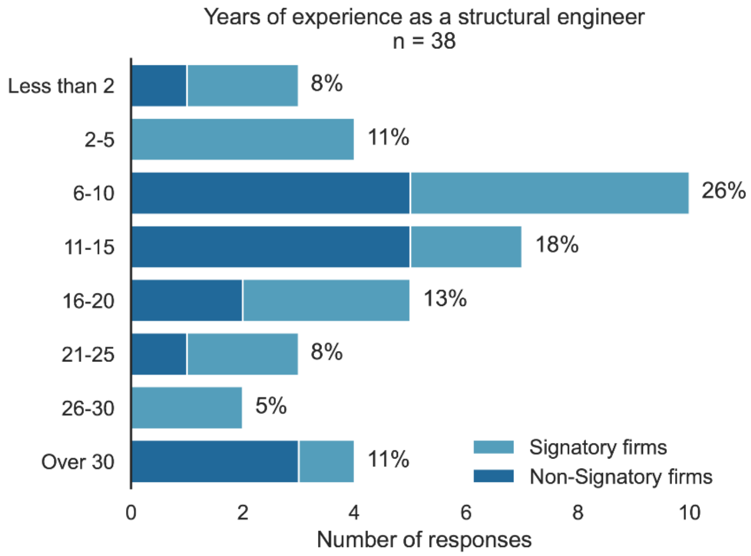

Figure 7. Participants' years of experience as a structural engineer broken down by participants at SE2050 signatory firms and those not at a signatory firm. The median was 11-15 years. The median of those from signatory firms was 6-10 years, while for those not from a signatory firm, it was 11-15 years.

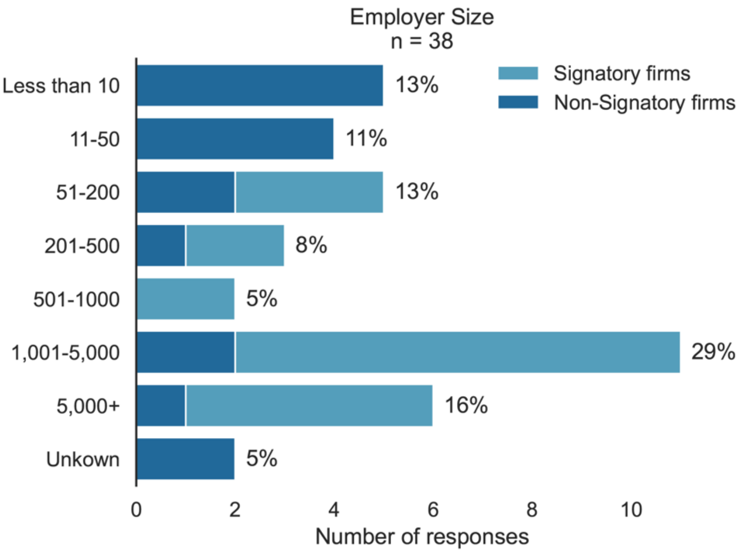

Figure 8. Size of employer of survey participants broken down by participants at SE2050 signatory firms and those not at a signatory firm. Employer size was determined using LinkedIn and company websites. The overall median was 501-1,000 employees. The median for those from signatory firms was 1,001-5,000 employees, and for those not from signatory firms it was 11-50 employees.

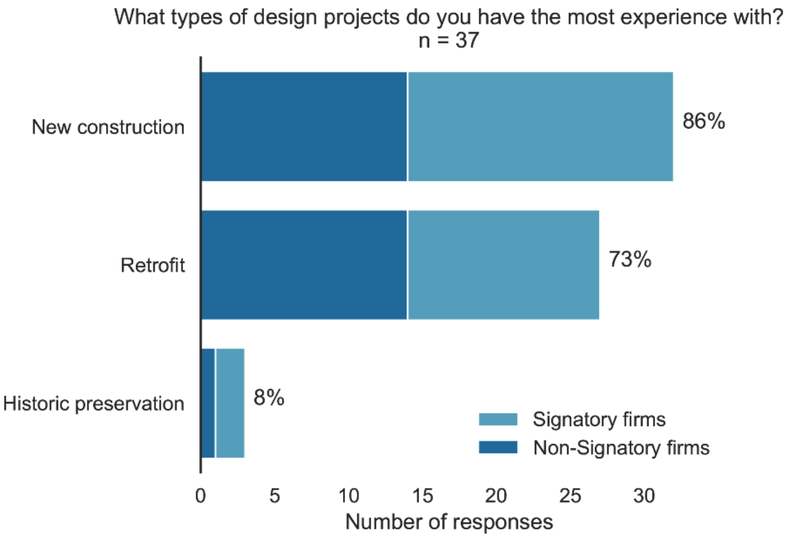

Figure 9. Results for Q1.1 ("What types of design projects do you have the most experience in? (Select all that apply)") and breakdown of responses between respondents from SE2050 signatory firms and those not from a signatory firm.

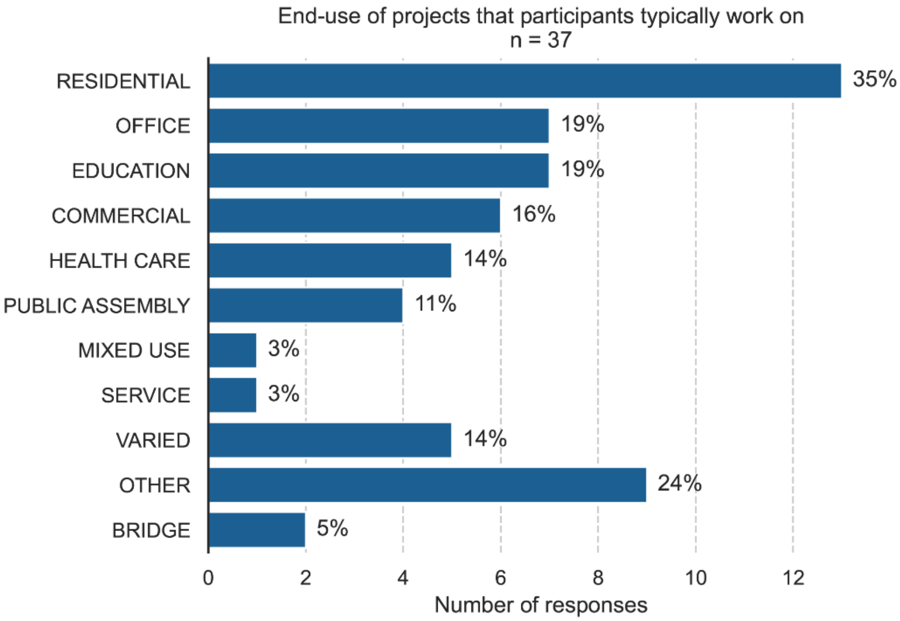

Figure 10. Coding results for free text question Q1.2 ("In most of your projects, what is the end-use of the building (ex. education, office, health care, residential)?"). "Varied" means that the respondent said they work on multiple types but did not specify which ones. "Other" includes transportation, research, industrial, aviation, and pharmaceutical.

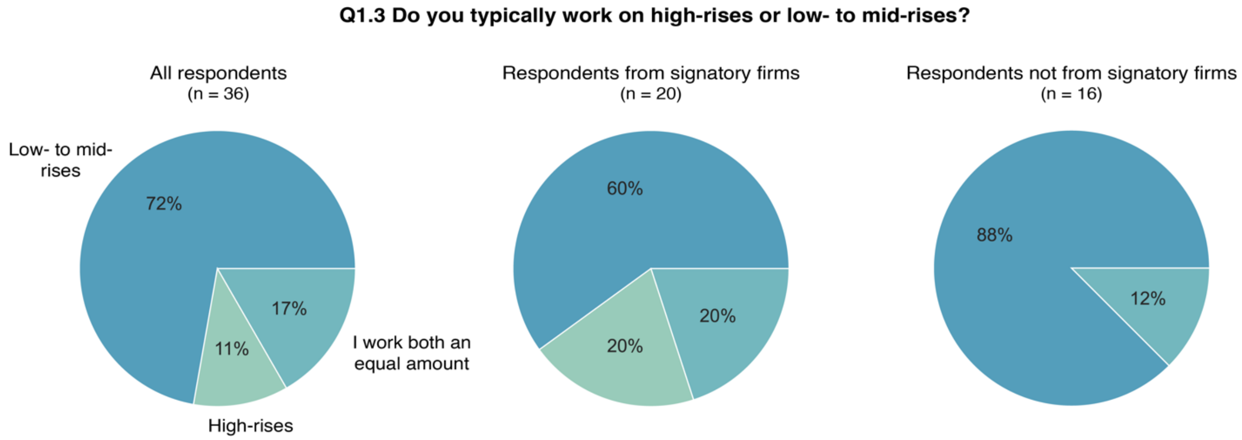

Figure 11. Results for Q1.3 ("Do you typically work on high-rises or low- to mid-rises?") and breakdown of responses between respondents from SE2050 signatory firms and those not from a signatory firm.

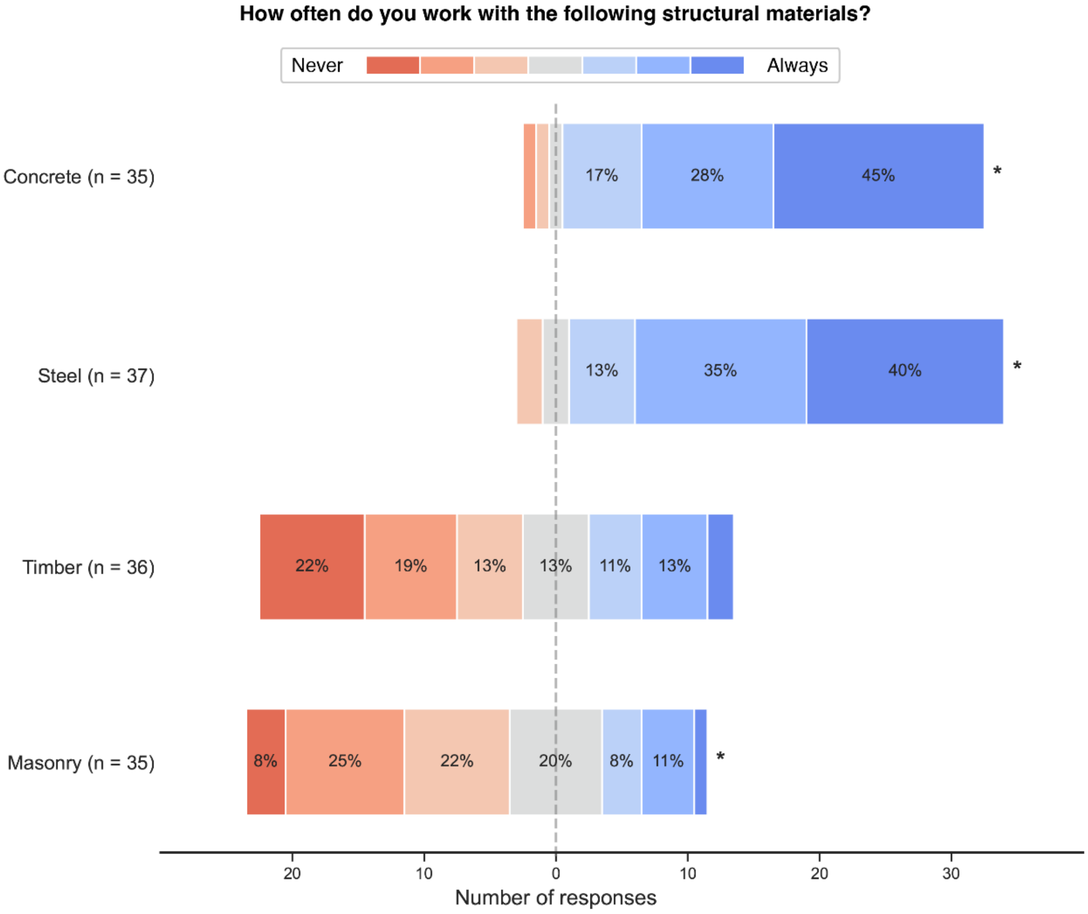

Figure 12. Results for Q1.4 ("How often do you work with the following structural materials?"). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

4.2 Design Process

The first section of the survey aimed to understand the typical structural design process and to what extent sustainability is considered. Participants were asked about the decision-making process in early-stage design (Q1.7), as this is when designers can have the greatest impact on the embodied carbon of the structure. The results are shown in Figure 13. Respondents mentioned several factors that are used to choose between design schemes, including cost (32% of 25 respondents), constructability (24%), and sustainability (20%). Structural efficiency was only mentioned by three respondents (12%). When asked how structural materials are chosen (Q1.8), a similar pattern emerged (see Figure 14). Cost was most common (44% of 27 responses), followed by constructability (26%), sustainability (19%), and structural efficiency (15%). Additionally, 15% mentioned that sometimes materials are chosen based on what is commonly used for similar project types ("reliable/standard material"), and 11% mentioned that material availability is a factor. It is interesting that structural efficiency was one of the least-mentioned factors for both questions, as this is the focus of a structural engineer's work. However, in practice, there are many other factors that need to be considered besides structural efficiency.

It was also found that coordination with the architect and client also plays a key role in choosing between design schemes and materials. Architectural coordination was mentioned by 76% of respondents in Q1.7, and 67% of respondents in Q1.8. This includes responses in which working with the architect was explicitly mentioned, as well as when architectural plans/layouts, building use, and building shape were mentioned as driving the design decisions. 11 of the 26 responses included the words "architect" or "architectural". In Q1.8, structural span was cited by 41% of responses as a parameter that drives material selection. Structural depth was also mentioned by 22% of respondents.

Obviously, the client is also a key stakeholder in the design process, however, they were mentioned less than the architect. The client or owner was brought up by 16% of respondents in Q1.7 and 15% in Q1.8. This does not mean that the client or owner is a less powerful stakeholder compared to the architect. Many of the parameters listed under architectural coordination, such as spans, building use, and shape, are also influenced by the client. What is important, for the purpose of this study, is understanding that structural engineers do not have full power over all structural parameters. Therefore, even if they wish to consider sustainability during design, their power may be limited. These results could also explain why structural efficiency was not mentioned as often, as there are other stakeholders whose focus is not structural efficiency, but other factors such as constructability or time and/or cost.

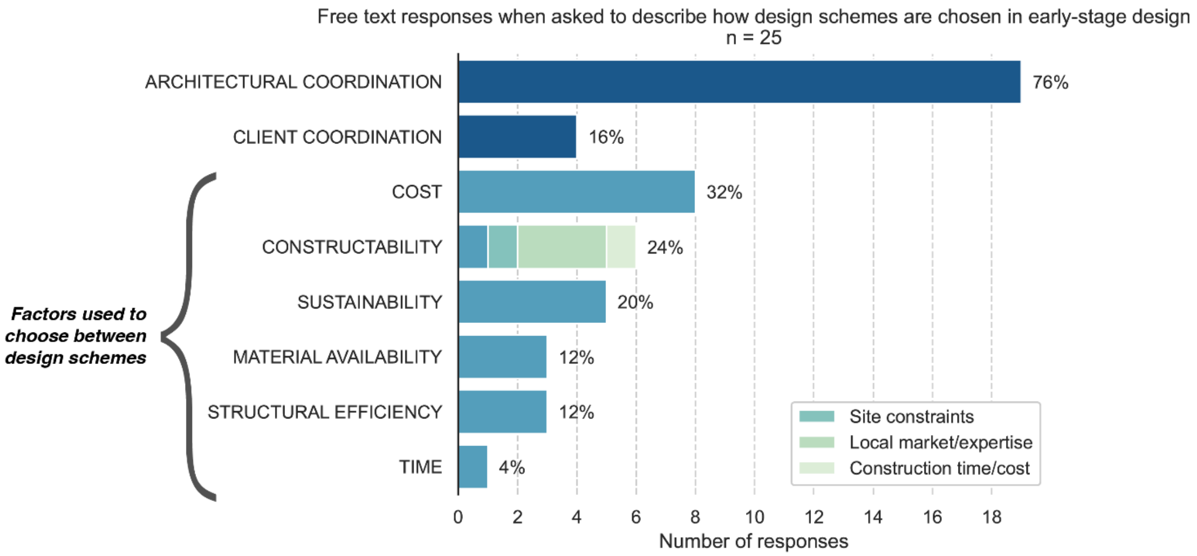

Figure 13. Coding results for free text question Q1.7. ("Describe the process of choosing between design schemes in early-stage design.").

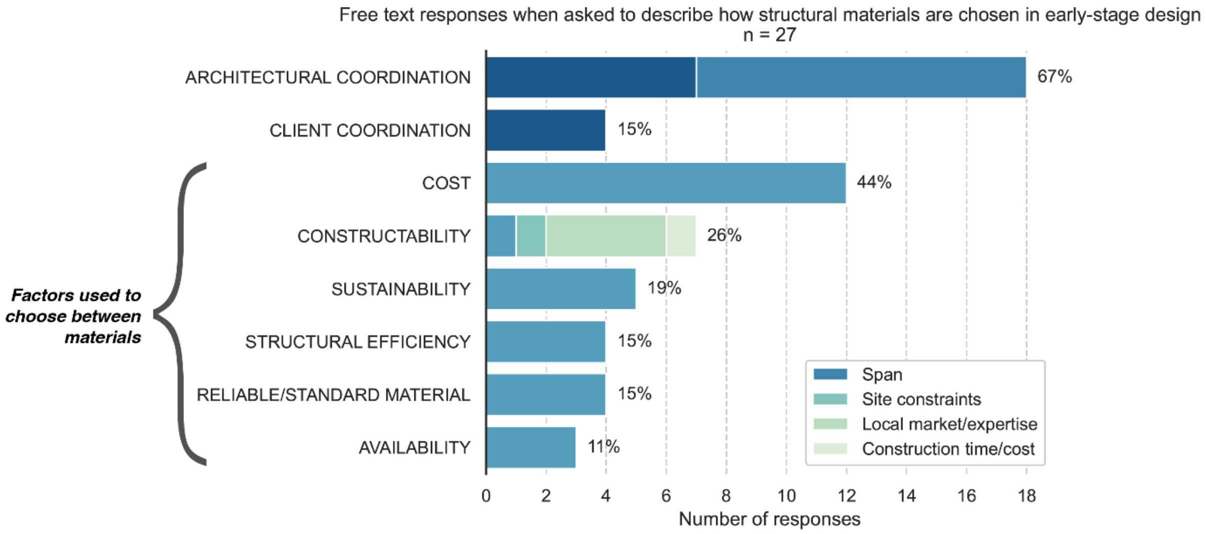

Figure 14. Coding results for free text question Q1.8 ("If you are considering several structural materials in early-stage design, how do you usually choose the one(s) to use?").

The role of other stakeholders in design was further examined in the next question, which asked if any other stakeholders determine structural parameters or impose constraints on them in early-stage design. Most respondents said that they do (87% of 37 respondents), and a follow-up free text question asked them to specify the stakeholders and structural parameters (see Figure 15). In keeping with the previous questions, the architect was the most frequently mentioned stakeholder (50% of 30 responses) followed by the owner or client (43%), the contractor (10%), and the MEP engineer (3%). The most frequently mentioned structural parameters were structural material (33%), layout and/or span (33%), and structural depth and/or floor-to-floor heights (27%). These results highlight how lack of power in the design process can limit a structural engineer's ability to decrease embodied carbon. They cannot always choose to use more sustainable materials or to use shorter structural spans, which, as discussed in the literature review, can have a significant impact on embodied carbon. Additionally, if there is a limit on structural depth or a desired floor-to-floor height, beams must be shallower, which makes them less structurally efficient. Therefore, solutions proposed in research to decrease embodied carbon, such as parametric studies that advocate for decreased spans, are not always feasible because they conflict with the design goals of other stakeholders. This will be further discussed in section 4.3.

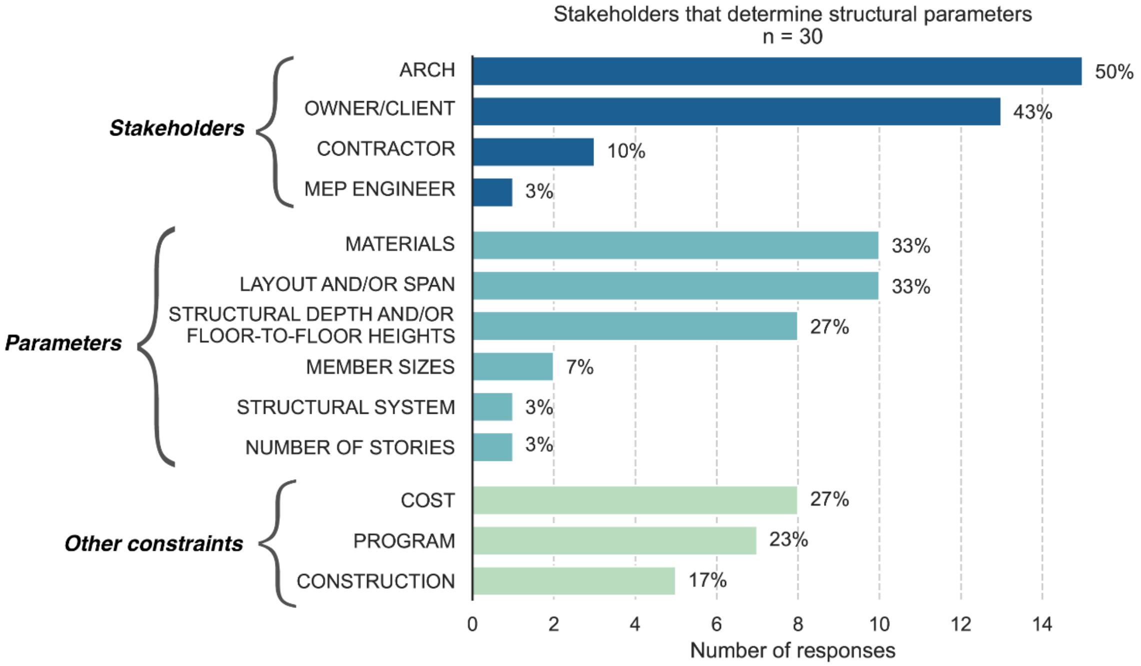

Figure 15. Coding results for free text question Q1.9 ("In any stage of the design process, do any other stakeholders (such as the client or architect) determine any structural parameters or impose constraints on structural parameters? Yes (please describe the stakeholder and the respective structural parameters):"). "Arch" stands for "architect". The other constraints listed at the bottom represent responses in which participants mentioned how these constraints, such as cost, program, or construction, can constrain structural parameters. "Program" includes mentions of serviceability requirements.

Finally, participants were asked how often they consider material efficiency and environmental impacts when making design choices. The results, shown in Figure 16, indicate that respondents tend to consider material efficiency frequently (chi-squared test with 99.9% confidence, n = 38). It is surprising that some said that it is not considered frequently, with 11% giving a rating of three or less, as material efficiency is a fundamental part of a structural engineer's job. As expected, participants consider environmental impacts less often, with 50% saying it is not considered frequently (a rating of three or less).

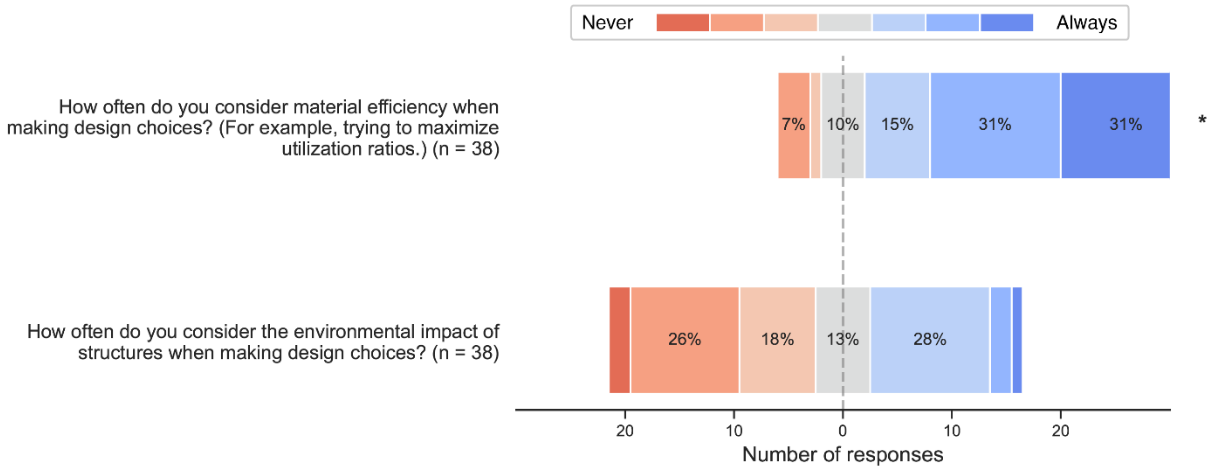

Figure 16. Responses to Q1.10 (top) and Q1.11 (bottom). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

4.3 Embodied carbon

The next section focused on participants' awareness of embodied carbon and its role during the design process. A chi-squared analysis showed that respondents tended to be familiar with embodied carbon (99% confidence with n = 37). When asked about the awareness of embodied carbon amongst structural engineers they work with, however, responses were more evenly split, and only 7% (two out of 38) described their colleagues as "Extremely aware". As expected, they rated their colleagues' awareness of climate change higher, with a chi-squared analysis showing that they tended to say their colleagues are more than somewhat aware (99% confidence with n = 38).

When asked how often embodied carbon is quantified, 38% of respondents said it never is, and only one said it is always quantified. A chi-squared analysis showed that the responses lean towards the negative side significantly (99.9% confidence with n = 38). Those who quantified it frequently were then asked what the data is used for and when it is calculated, with results shown in Figure 18. The construction documents phase was the most common time to calculate embodied carbon (41% of 22 respondents), but this was closely followed by design development and schematic design, then concept design. Ideally, most of the quantification would occur in the early design stages. It was found that embodied carbon data is commonly used to add to an internal database, compare the sustainability of different designs, and identify ways to reduce embodied carbon.

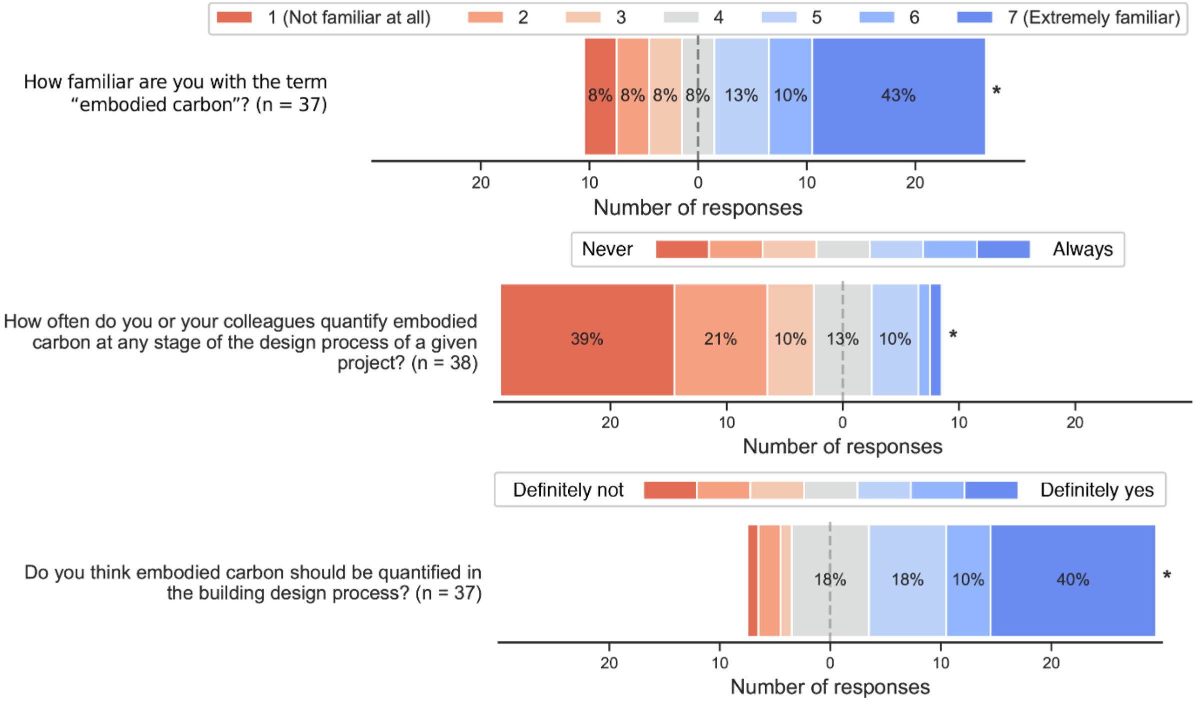

Figure 17. Results for Q2.1 (top), Q2.6 (middle), and Q2.9 (bottom). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

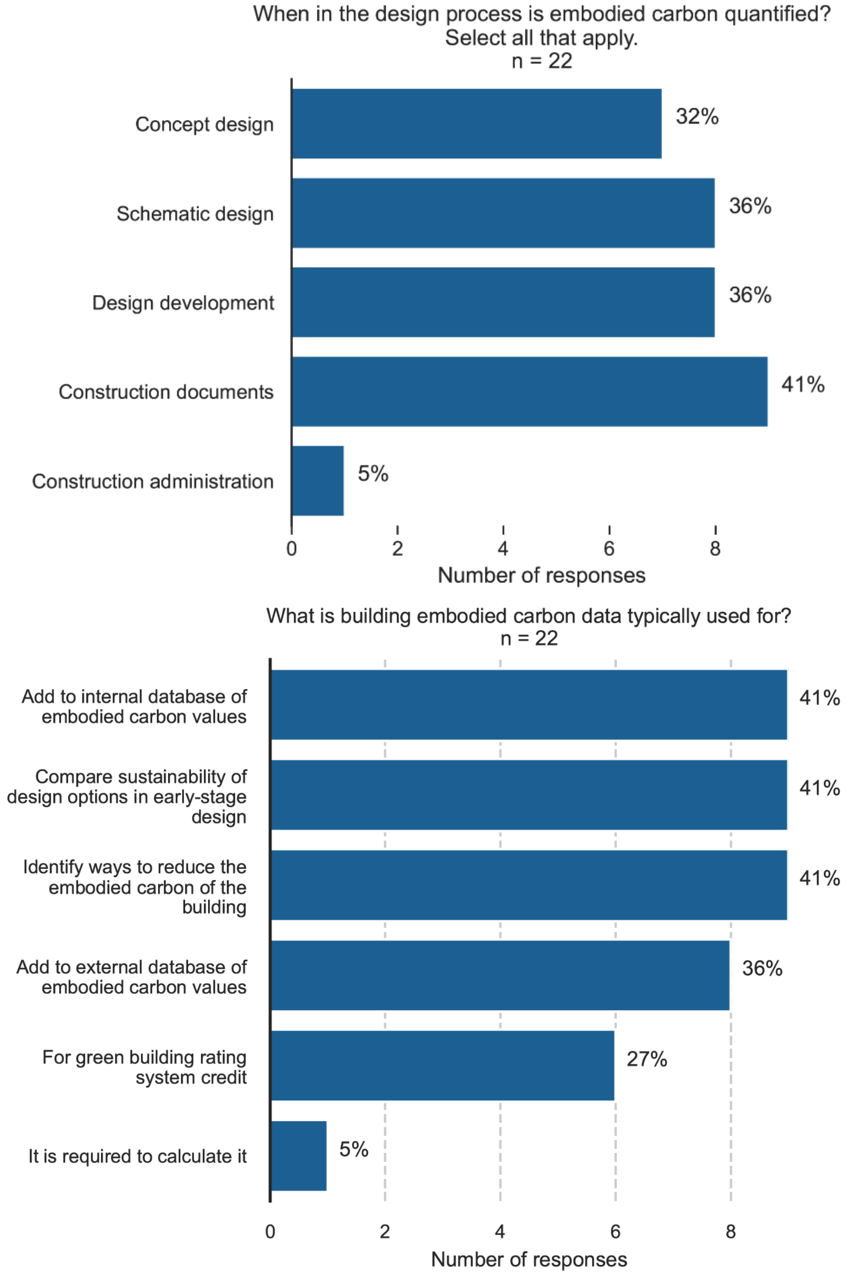

Figure 18. Results for Q2.7 (top) and Q2.8 (bottom). Both were select-all-that-apply questions.

Interestingly, although embodied carbon is not frequently calculated, respondents tended to think it *should* be quantified (chi-squared test for Q2.9 with 99.9% confidence, n = 37). This difference is clear when comparing Q2.6 and Q2.9 in Figure 17. These results indicate a huge potential for increased embodied carbon quantification, as although it is currently not quantified frequently, engineers think that it should be quantified more. However, there are also reasons as to why the difference between these questions is so large; in other words, why it is not being quantified as much as engineers want it to be.

For one, structural engineers may not know how to calculate embodied carbon or how to reduce it. When asked how confident they felt in calculating embodied carbon, responses were almost evenly split (see Figure 19), and 47% said they did not feel confident in calculating it. The majority of respondents, however, could think of a strategy to reduce embodied carbon (78% or 29 out of 37 respondents), and of those that could think of a strategy, 62% had tried to implement it in a project. Almost all respondents identified material choice as a strategy to reduce embodied carbon (93% of 29 respondents), however, only about half identified material efficiency (see Figure 20). Many respondents (34%) *only* identified material choice. Two respondents only mentioned embodied carbon quantification, which, although useful in understanding where embodied carbon can be reduced and quantify the reduction, is not a strategy to actively reduce it.

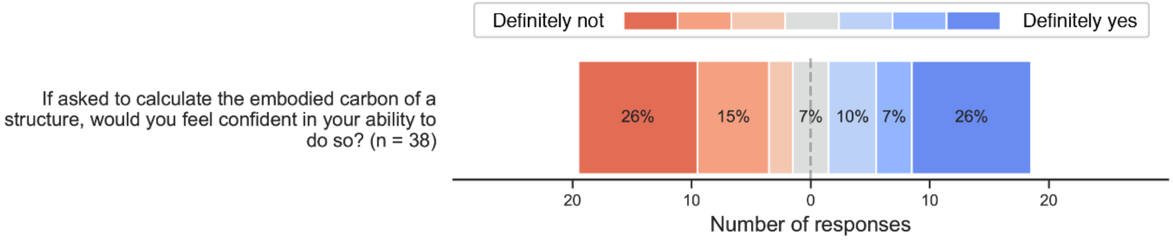

Figure 19. Results for Q2.11 ("If asked to calculate the embodied carbon of a structure, would you feel confident in your ability to do so?").

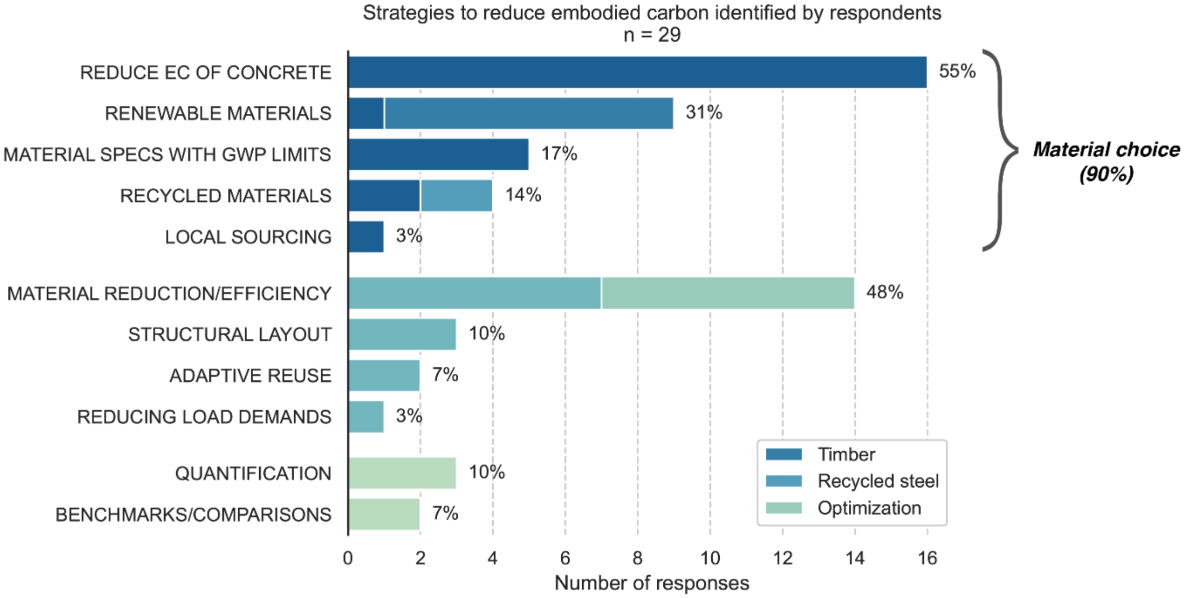

Figure 20. Coding results for the free text question Q2.12 ("If asked to reduce embodied carbon, do any strategies come to mind? Yes (please describe):"). "Reduce EC of concrete" includes reducing the cement content, using lower strength concrete, using normal weight concrete instead of lightweight concrete, and using carbon-sequestering concrete. "Structural layout" is not included in the category of "Material reduction/efficiency" because some respondents did not seem to be referring to material reduction, but rather reframing the structure so that lower carbon materials could be used. "Benchmarks/comparisons" refers to comparing the embodied carbon of design options or comparing against benchmark values.

These results show that there is a gap between awareness of the strategies of material choice and material efficiency. Material choice is important; however, it is only one part of the equation to calculate embodied carbon – the other part being material quantities. Therefore, there is a need to educate structural engineers on how reducing material usage also reduces embodied carbon. The strategy of material efficiency has the benefit of working in parallel with one of the main goals of a structural engineer: to increase structural efficiency. This benefit becomes clear when one examines Figure 16, which, as described previously, shows that respondents consider material efficiency much more often than environmental impacts. Thus, many engineers already consider material efficiency during design, and making a clear case for its positive impact on sustainability can further promote it.

Those who said they had tried to implement a strategy to reduce embodied carbon were asked in a free text follow-up if this was successful. Most respondents said that it was (81% or 13 out of 16), while only 13% (two respondents) said it was unsuccessful. Those who said it was not successful cited pushback from other parties, such as internal company management, the contractor, or the owner. Additionally, one participant gave a neutral response, saying that they did not have success with "getting architects to make big changes, but smaller ones that produce slight savings sometimes work". The fact that those with neutral or no success with implementing these strategies mentioned pushback from other parties shows that lack of power is a strong barrier that prevents structural engineers from reducing embodied carbon. On the other hand, one respondent who had success implementing these strategies mentioned that they were able to convince owners to consider adaptive reuse. The respondent with the neutral response also stated that "it's all about suggesting things before the architect really gets used to one of their design decisions". Both responses point to the need for early involvement from the structural engineer with both the client and architect in order to implement design changes to reduce embodied carbon.

This barrier of power was examined in more detail through two questions: Q2.15 ("Do you think **structural engineers** have the power to influence the embodied carbon of a building during the design process?") and Q2.16 ("Do you think **you** have the power to influence the embodied carbon of a building through your project involvement?"). Respondents tended to feel that structural engineers in general could influence embodied carbon, however, responses were more evenly split when asked if they felt they had power as an individual (see Figure 21). In a free text follow-up (Figure 22), half of respondents indicated that they feel that structural engineers lack power in the design process (out of 24 respondents). One respondent even said that "The Architects control the project. Engineers have no control", while most said that although they have some power, at the end of the day it comes down to the wants of the architect and/or client. Three engineers acknowledged that they could influence the embodied carbon of the structure, however, the structure is only one part of the project. One stated that "The embodied carbon of the structure is a small percentage of the overall project so while we can impact that it's small part compared to the architects or mep engineers". This generalization does not tend to be true. A study by Kaethner & Burridge (2012) examined the embodied carbon of commercial, hospital, and school buildings with a variety of structural framing solutions. It was found that the contribution of the superstructure, on average, accounted for 40-45% of a project's embodied carbon, and if the substructure is included, this increases to 51-62%. Although it is possible that this respondent works on projects of a specific use type in which this statement is true, stating this as a general fact is a misconception, and points to a need for increased education on the importance of the structure when considering whole-building embodied carbon.

It was also clear that cost to the client is an important design factor that can inhibit sustainable design measures. One respondent noted that "Our industry is dictated by money … I have witnessed our firm lose a project bid when we pushed to add sustainability measures to the scope. We received explicit feedback stating that the owner does not appreciate us pushing for costly measures that they do not want". The bid process is one example of a systemic barrier that may limit engineers' ability to impact embodied carbon. Five other respondents also cited systemic barriers, with four noting that embodied carbon standards and/or regulations are needed. One of these respondents said that regulations are important because the "industry as a whole is reluctant to change", reflecting the conservative industry culture that was explored in Giesekam et al., 2016. Finally, two respondents mentioned that there needs to be a strong economic incentive for clients to prioritize it, while one said that there is a need for more education and research.

The results of Q2.5 (Figure 23) show that currently, the strongest incentive to reduce embodied carbon is green building rating systems like LEED (59% of 37 respondents). The client is the next strongest (49%), which further shows that the client is an important stakeholder who can drive embodied carbon reductions. Additionally, it seems that local code or regulatory incentives are already driving embodied carbon reductions (46% of respondents).

While many respondents listed ways that structural engineers do not have power during the design process, ten respondents mentioned how they do have power, both through their design decisions (eight responses) and by educating the architect and client on embodied carbon (two responses). One noted that the structural engineer should inform the client that most of the embodied carbon comes from the structure. Given that these results have shown that the clients and architects can prevent structural engineers from implementing strategies to reduce embodied carbon, increased education targeted at these populations could have a significant impact.

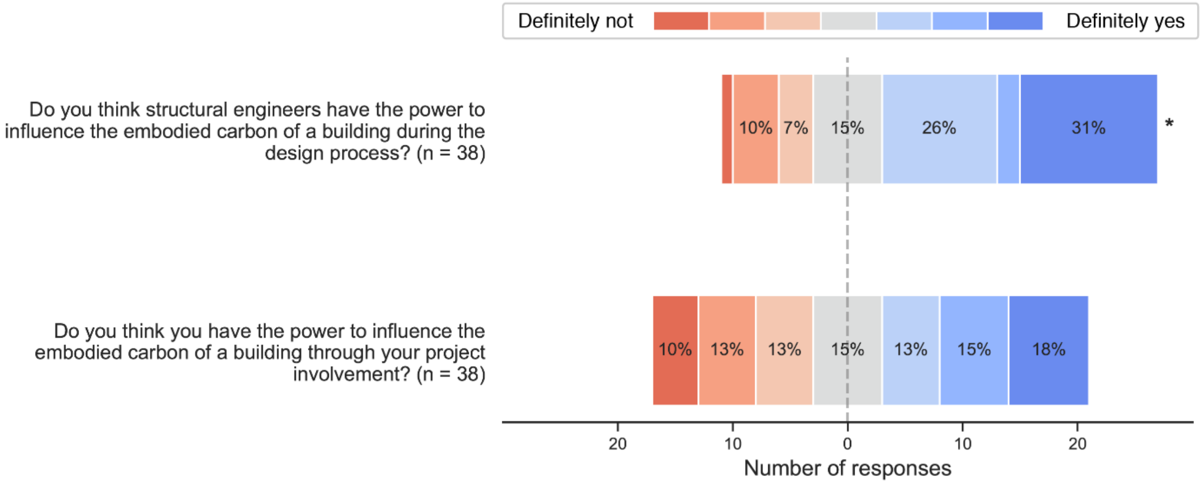

Figure 21. Responses to Q2.15 (top) and Q2.16 (bottom). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

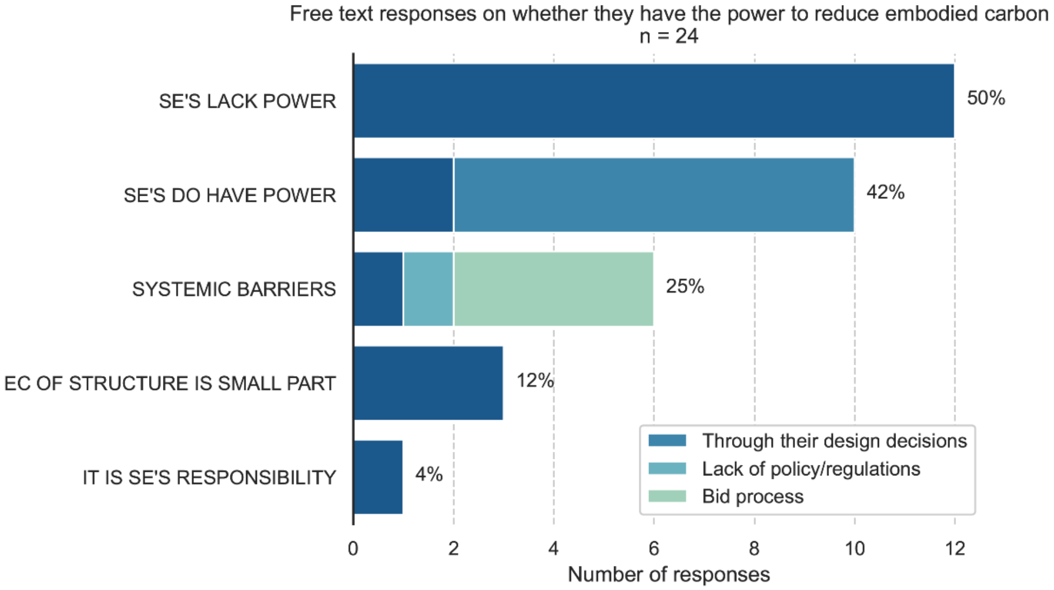

Figure 22. Coding results for free text question Q2.17 ("Please elaborate on your responses to the previous two questions.") which followed Q2.15 and Q2.16. "SE's lack power" refers to responses that mentioned that structural engineers do not have complete control over the embodied carbon of the structure. "Systemic barriers" includes lack of incentives to reduce embodied carbon, such as policy and economic incentives; the bid process; and a lack of research on embodied carbon. "It is SE's responsibility" refers to responses in which it was clearly stated that reducing embodied carbon is within the scope of a structural engineer's job.

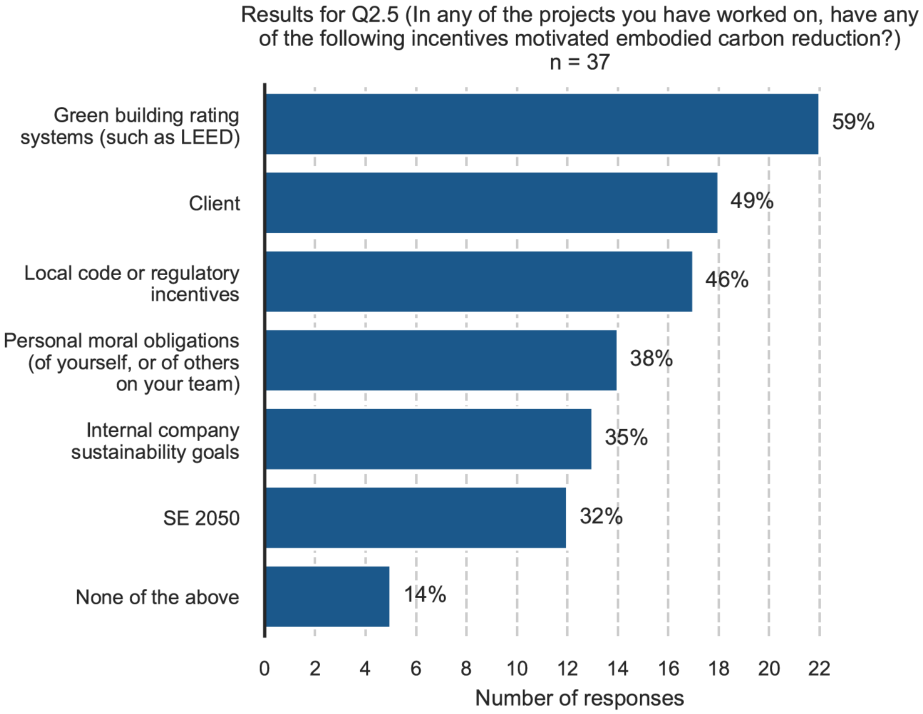

Figure 23. Results for Q2.5 on incentives to reduce embodied carbon.

After reading about the case studies, respondents were asked again whether they feel that structural engineers can influence embodied carbon. Because each case study showed how structural engineers could reduce embodied carbon through material efficiency, it was expected that respondents would respond more positively when this question was repeated. However, as shown in Figure 24, the distribution of responses was very similar, with only a slight increase in positive responses at the end of the survey. A one-tailed Wilcoxon signed-rank test showed that this difference was not significant with a confidence level of only 93% (less than the 95% threshold). The scatterplot in Figure 25 shows that while eleven respondents increased their rating, five decreased their rating. It is unclear why the case studies made some respondents feel less confident that structural engineers can reduce embodied carbon.

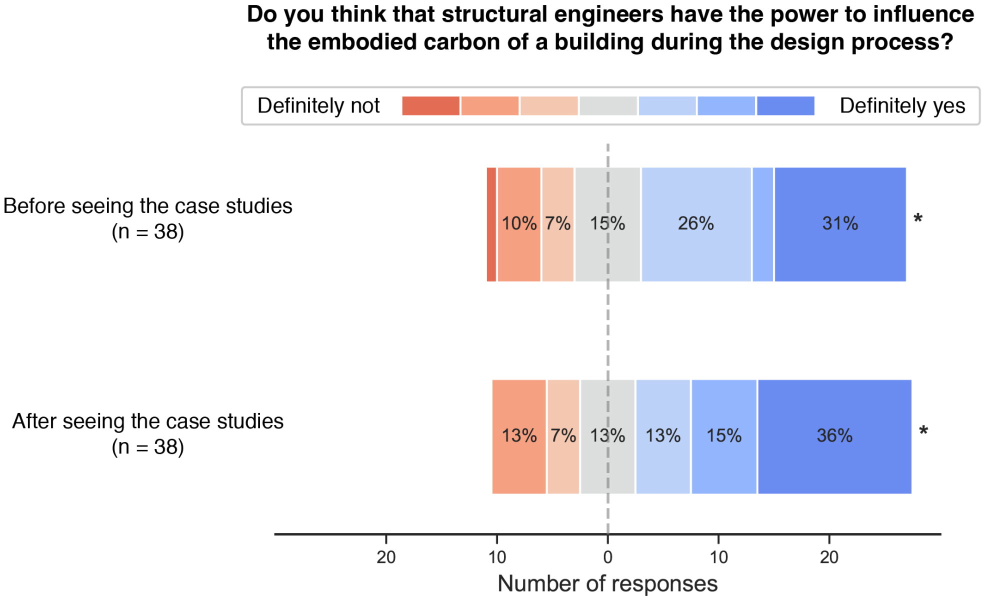

Figure 24. Results for Q2.15 (top) and Q8.2 (bottom). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

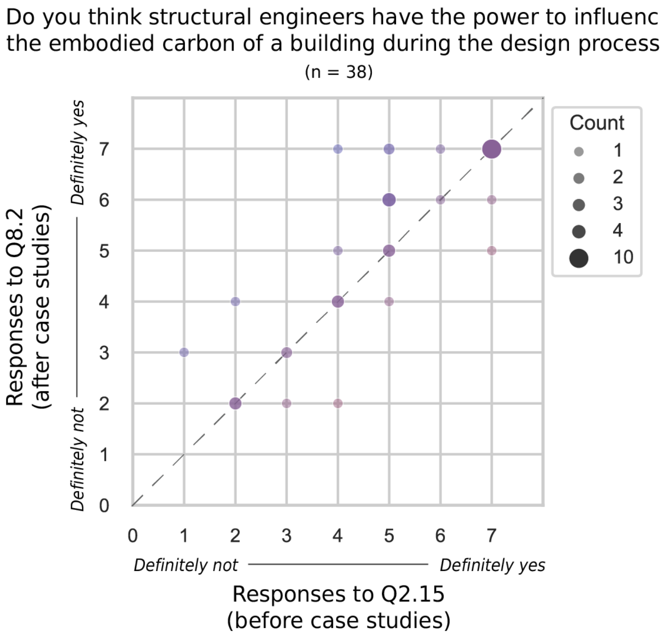

Figure 25. Comparison of responses to Q2.15 and Q8.2, before and after the case studies were presented. Each point represents one (or more) respondent(s). Points along the dashed line represent individuals who had the same response to both questions. Points are colored by their distance from this line, i.e., how much an individual changed their response.

4.3.1 Comparing responses from SE2050 signatory and non-signatory firms

The responses from participants at signatory and non-signatory firms were compared to understand if the two groups view embodied carbon differently. Although any differences in responses may be due to the signatory status of the firm, this cannot be determined for certain. As described previously, signatory firms tend to be larger, work on more high-rise projects, and are primarily located in MA and NY. These variables, among others, could also impact differences in responses. Company size in particular could contribute, as larger firms tend to have more resources to devote to hiring sustainability consultants or educating their engineers on embodied carbon.

As expected, for Likert scale questions on embodied carbon, respondents from signatory firms tended to respond higher than those not from a signatory firm. This difference is clearly visible in the results for Q2.1 (Figure 26). For this question, a chi-squared test found that the difference between responses of the two groups is significant with a >99.9% confidence level. Chi-squared tests on other results showed that those from signatory firms described their colleagues as being more aware of climate change and embodied carbon (>99.9% confidence for both). Additionally, they felt more confident in their ability to quantify it (>99.9% confidence) and felt more strongly that it should be quantified in the design process (99.5% confidence).

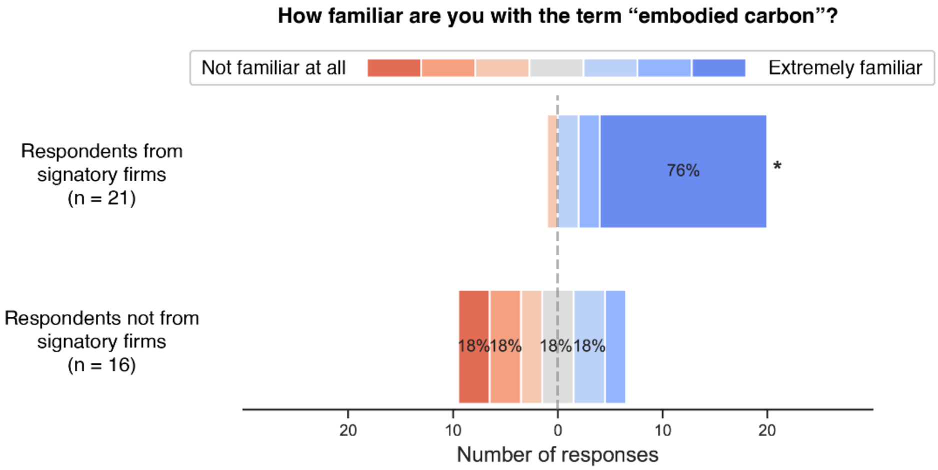

Figure 26. Responses to Q2.1 ("How familiar are you with the term "embodied carbon"?) for respondents from SE2050 signatory firms and those not from signatory firms. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

Those at signatory firms also said that embodied carbon was quantified more often at their firms (99.1% confidence), however, 52% said that it is quantified less than “Sometimes”. This indicates that even at signatory firms, there is room for increased embodied carbon quantification.

The only question for which the difference between responses fell below 99% confidence was Q2.15 (Do you think structural engineers have the power to influence the embodied carbon of a building during the design process?), which had a confidence of 96% (which is still above the 95% confidence threshold). However, when asked if they think they have the power to influence embodied carbon through their project involvement, those from signatory firms felt more strongly that they could, with >99.9% confidence. Figure 27 shows that for each group, people respond less favorably to the second question on individual power. However, for signatory firms, the decrease between the two questions is much smaller. It makes sense that those at signatory firms are more confident in their power as an individual to reduce embodied carbon, as these firms have publicly stated their commitment to embodied carbon reduction and work to education their employees on the topic.

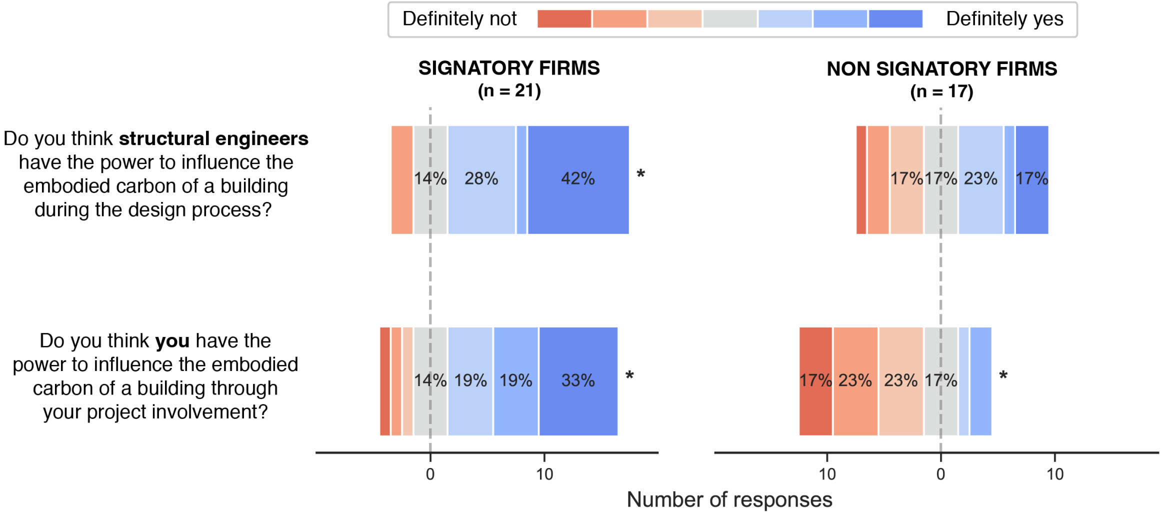

Figure 27. Comparison of responses to Q2.15 and 2.16 for those from SE2050 signatory firms (left) and those not from a signatory firm (right). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

4.3.2 Takeaways from the embodied carbon section

In summary, although embodied carbon is not quantified frequently during design, respondents tended to think that it *should* be quantified, indicating that there is great potential for increased quantification. Respondents also tended to be aware of embodied carbon, and most (78%) could name a strategy to reduce it. However, material efficiency was listed as a strategy less often than material choice, indicating that there is an opportunity for education on the benefits of material efficiency on embodied carbon. These results also showed the reasons why embodied carbon is not quantified as much as engineers think it should be. Firstly, 47% of participants did not feel confident in calculating embodied carbon. Secondly, many noted that their power to reduce it is limited because of the role of other stakeholders in the design process, especially the client and architect. Several argued that economic or regulatory incentives are necessary to make clients prioritize embodied carbon reduction.

These results also showed that structural engineers at SE2050 signatory firms tend to be more aware of embodied carbon, calculate it more frequently, and feel more strongly that they can impact it through their project involvement. This does not necessarily mean that they are more aware of embodied carbon *because* they are at a SE2050 signatory firm: it could also be because these firms tend to be larger, and therefore have more resources to devote to embodied carbon reduction. However, it is likely that the firm's commitment to SE2050 caused their employees to be more aware of embodied carbon. This shows the importance of programs like SE2050 in increasing awareness of embodied carbon and encourage firms to quantify and reduce it. There is still, however, much work to be done – ideally, all participants should be able to name a strategy to reduce embodied carbon, given that it can be as simple as specifying a different concrete mix or trying to reduce unnecessary material.

4.4 Use of computational tools in design

Before any of the case studies were presented, participants were asked if they think computational tools should be used more often during the design process to understand their views before reading about the case studies, as the studies could bias their response. It was found that respondents tended to think that computational tools should be used more often by structural engineers (99.9% confidence with n = 37) (see Figure 28). Results from a follow-up free text question showed that making the design process faster and easier was a key reason to use computational tools (52% of 29 responses). The next most common reason was to increase material efficiency (38%). Six respondents (21%) said they would use computational tools to quantify embodied carbon or find ways to reduce it. Therefore, many engineers are aware of the benefits of using computational tools, and some identified their ability to impact embodied carbon even before the case studies were presented. It should be noted that this question's placement after the embodied carbon section likely brought it to the forefront of peoples' minds.

There can, however, be drawbacks to using such tools, which was examined in the next free-text question. Interestingly, time/cost increase was one of the primary barriers to their use (21% of 24 responses), even though speed was previously identified as a key benefit. Those that mentioned time increase said that for some problems or projects, it is not worth the time to use a computational tool. One respondent said that on small projects, it may not be worth the cost, which could refer to increased costs to the client due to increased design time. Another respondent in the "cost increase" category stated that they may not have the budget for the software license.

The learning curve associated with these tools was also identified as a key barrier (21% of 24 responses). Not only does the person using the tool need to understand how it works, but others that check their work must understand it as well – and as one respondent noted, "Often, the stamping engineers (older) do not know how to check analysis completed with computational tools". Even if engineers know how to use the tool, they may not want to use it for a given problem. Some respondents said that they sometimes prefer to make manual changes to the design or design by hand instead or that it can be better to rely on previous project experience (17%, or 4 responses). Using a computational tool is not always appropriate for the problem at hand, and any engineer who uses software for design also runs the risk of "los[ing] sight that they are solving structural problems". Three respondents brought up this danger of the software becoming a "black box" that prevents them from understanding the structure's behavior. Additionally, the tool may not fit an engineer's design needs either because they are not made for existing construction projects (two responses) or because the tool is not integrated into a software that they are familiar with and trust (one response).

Some barriers did not have to do with the use of the tool, but rather, concerns over the results it outputs. One respondent who was concerned about the software becoming a "black box" was also concerned that results may not be accurate. Two respondents were concerned that the tools do not save enough embodied carbon to be worth it, and three respondents mentioned that the results may not be constructable. Three noted that optimization could limit the future use of the component, which will be further discussed in section 5.2.

Figure 29 and Figure 30 show other reasons that were given to use or not use computational tools as well as their frequencies. The benefits and barriers associated with using computational tools in design will be further explored in later sections.

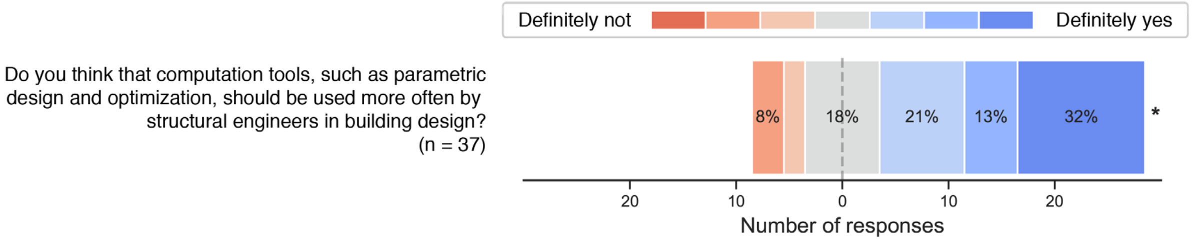

Figure 28. Results for Q3.1. An asterisk denotes that a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

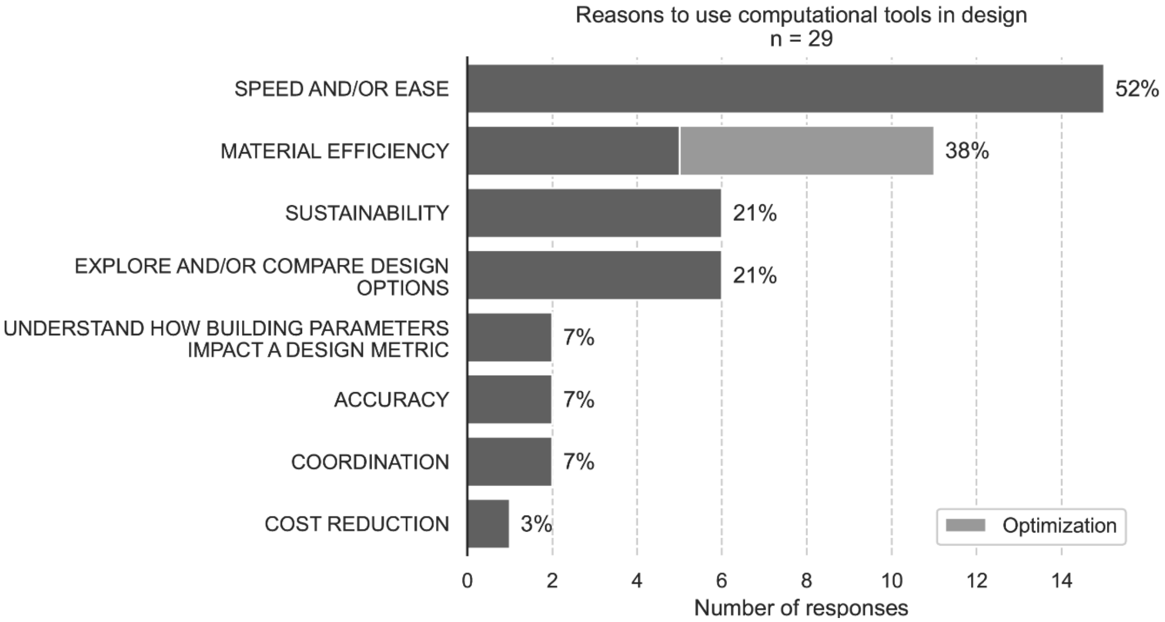

Figure 29. Coding results from the free text responses to Q3.1 (What are the main reasons, if any, that you would use computational tools in building design?). "Cost reduction" refers to reducing the cost of the structure, not reducing design time costs (which were coded under "Speed and/or ease" instead). "Coordination" means that the respondent mentioned using these tools to assist in working with other project stakeholders.

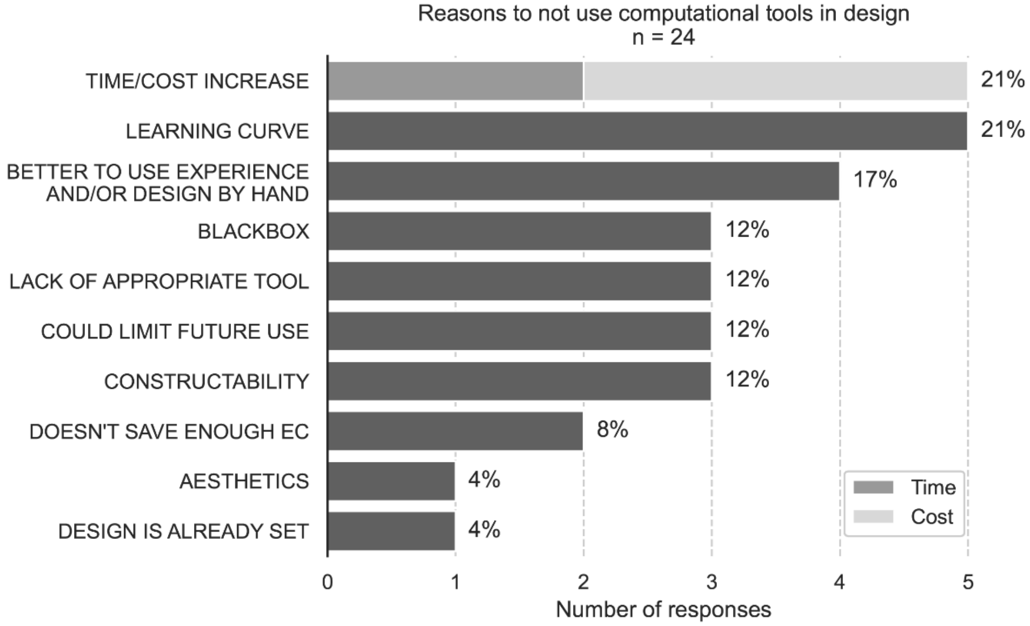

Figure 30. Coding results from the free text responses to Q3.2 (What are the main reasons, if any, that you would not use computational tools in building design?). Of the two respondents that mentioned cost increase, one specified that the software license cost was a barrier. "Blackbox" refers to the concern that software can be used without understanding how it is working. One of the responses under "Blackbox" also mentioned that results may be inaccurate. Responses categorized under "Lack of appropriate tool" either said that it is difficult to use these tools with existing structures (two responses), or that the current tools do not integrate with software that engineers use and trust (one response). "Design is already set" means that the design is too inflexible or constrained to necessitate using computational tools.

4.4.1 Use of optimization

Respondents were asked how often they use optimization tools in the design process after the parametric design case study. They tended to say that tools for automatic member sizing were frequently used (99.5% confidence), with 65% saying they are used more than sometimes. However, when asked how often they use optimization tools for any other purpose besides member sizing, only 36% said they are used more than sometimes, while 32% said they are used less than sometimes. In a follow-up free text question, respondents mentioned optimizing structural layouts (three responses out of 25), lateral systems (three responses) and connection material (one respondent) as other uses for optimization tools.

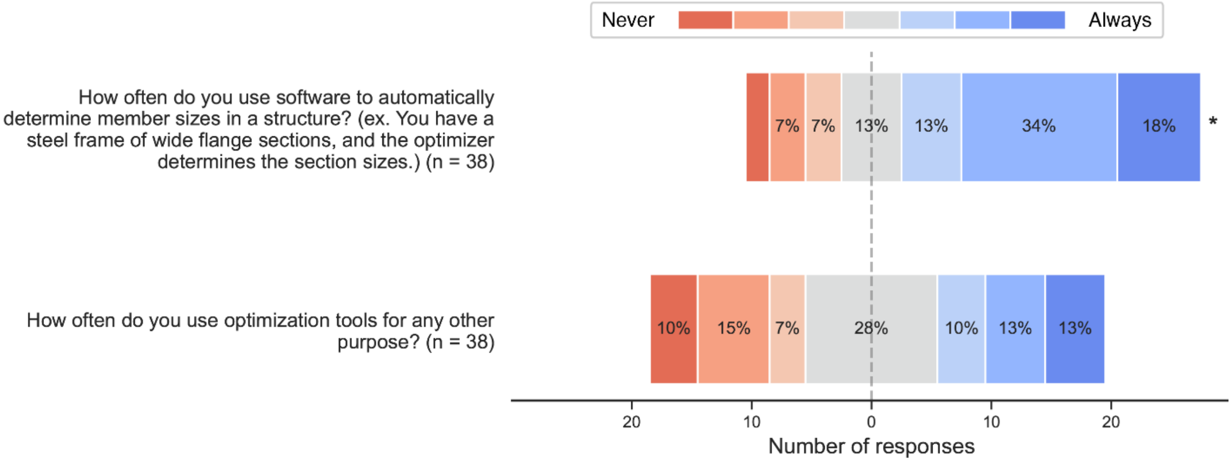

Figure 31. Results for Q5.1 (top) and Q5.2 (bottom). An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

4.5 Case Studies

As described previously, a similar set of questions was repeated in each case study section. The results of these questions are summarized in Figures 32 through 35.

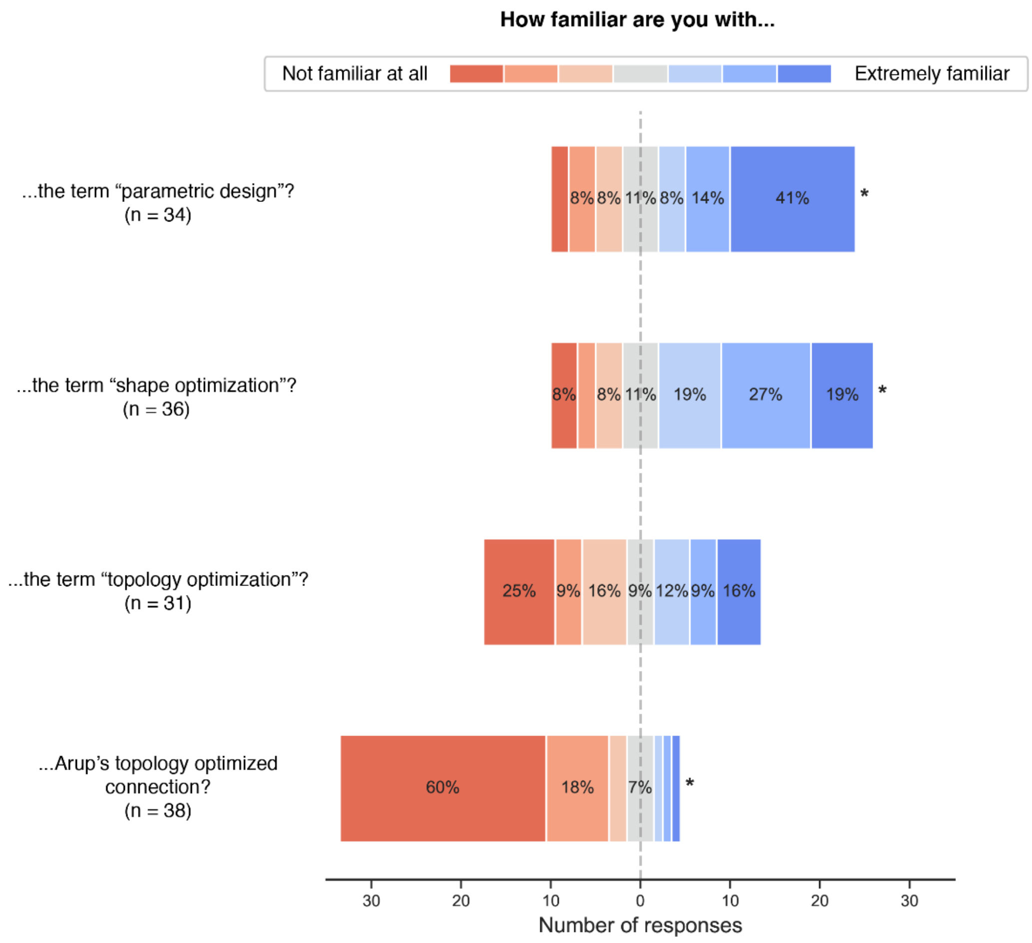

Figure 32. Results for case study questions asking about participants’ familiarity with the given topic. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

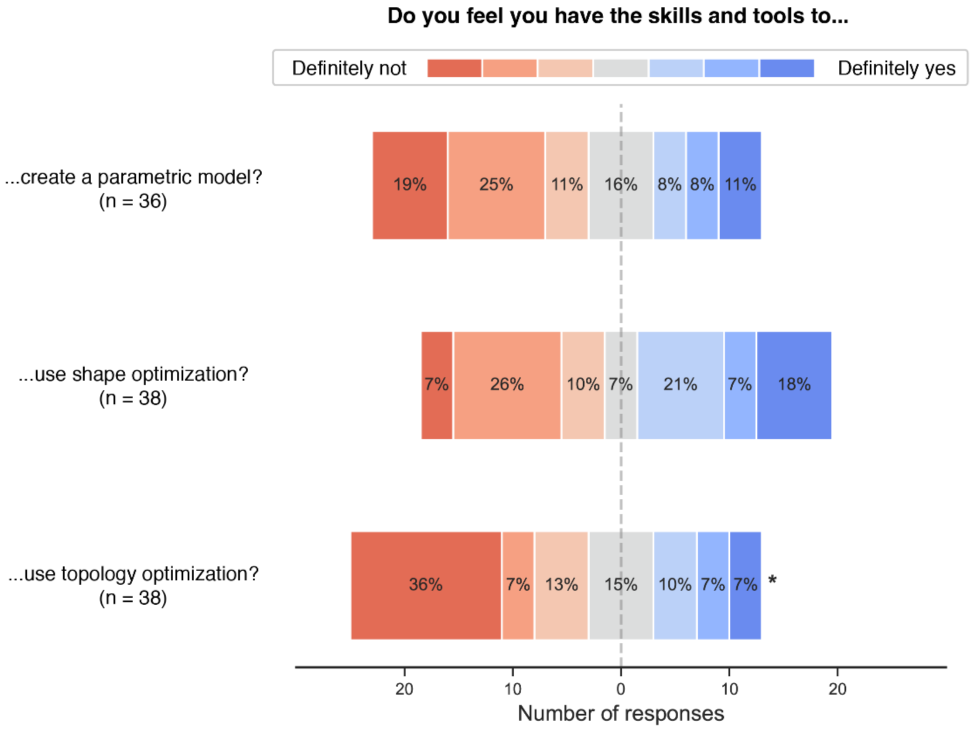

Figure 33. Results for case study questions asking about participants' confidence in using the given tools. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

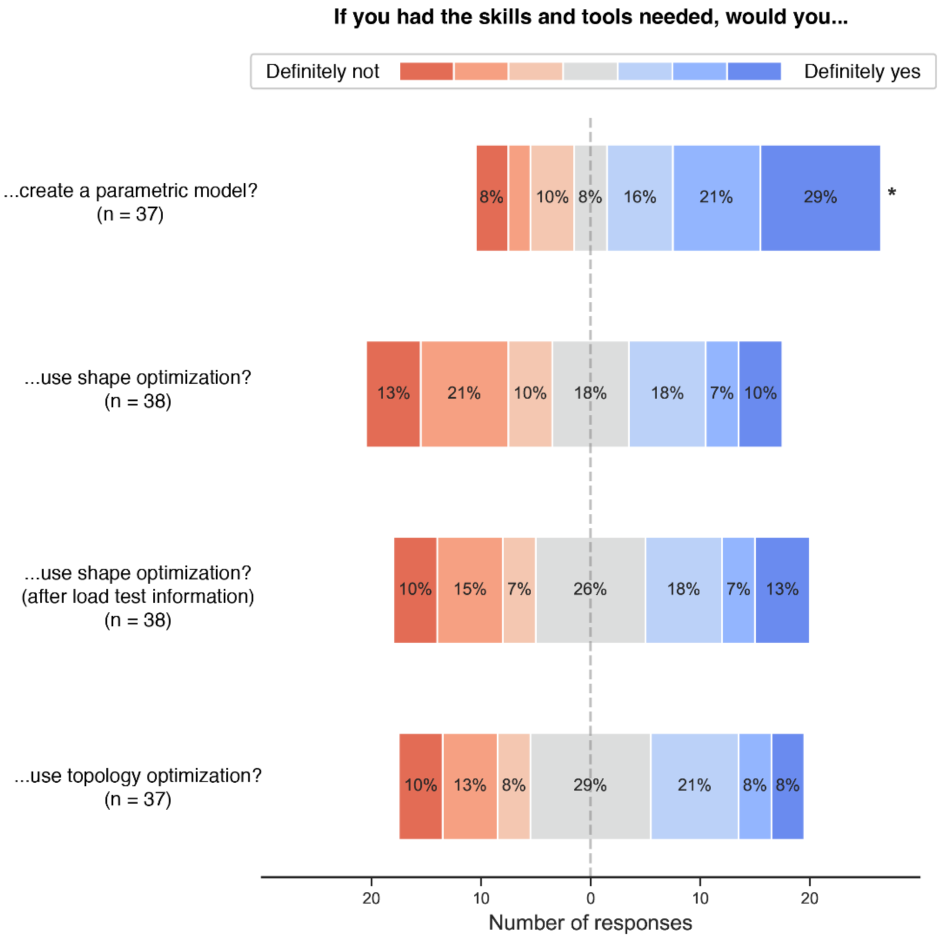

Figure 34. Results for case study questions asking if participants would use the given tool. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

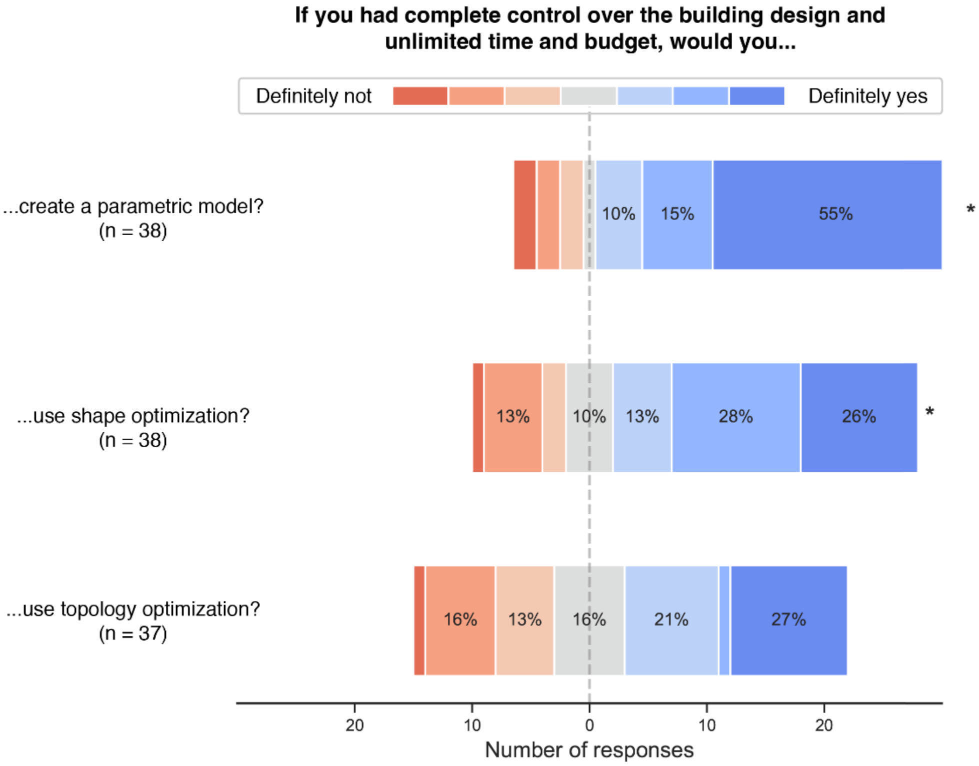

Figure 35. Results for case study questions asking if participants would use the given tool if they had complete control over the design and unlimited time and budget. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

4.5.1 Parametric design

Participants tended to be familiar with parametric design (chi-squared test with 98% confidence, n = 34), however, they tended to say it is not used often, as shown in Figure 36 (chi-squared test with 98% confidence, n = 38). When asked what these models are used for, the most common reason was to explore or compare design options (60% or 9 out of 15 responses). The metrics used to compare design changes include material efficiency (33%), cost (20%), and embodied carbon (13%). Although only two mentioned embodied carbon, material efficiency was the most mentioned metric, which tends to positively benefit the embodied carbon of the structure.

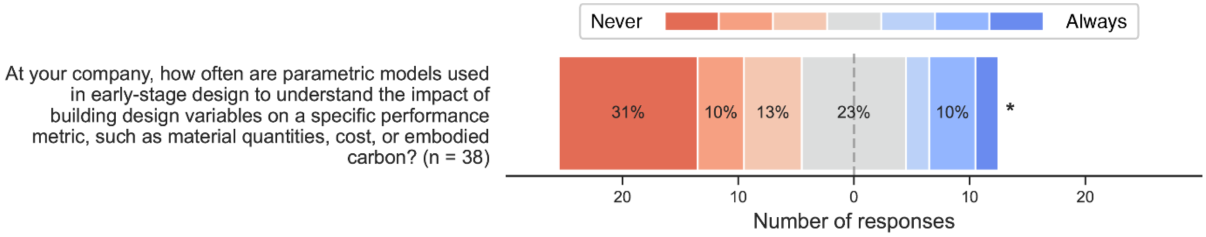

Figure 36. Results for Q4.2. An asterisk denotes that a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

Over half of respondents did not feel confident that they could create a parametric model (55% of 36 respondents), while only 27% felt that they could. However, a chi-squared analysis showed that this difference was not great enough to be significant (assuming the 95% confidence threshold). When asked if they would use a parametric model in early-stage design if they had the skills and tools to do so, respondents tended to say that they would (chi-squared analysis with 99% confidence, n = 37). Comparing this to Q4.2, in which participants tended to say that parametric models are not used often, points to a potential for increased use of parametric models in the future given increased education.

The most common reason to use a parametric model was speed (38% of 21 respondents), as these models enable engineers to quickly examine different design options. Similar to the previous question about what these models are currently used for, material efficiency was the design metric that respondents were most interested in (14% of 21 responses) followed by cost and carbon (both 10%, or two responses).

Even though time was the strongest reason to use a parametric model, it was also a strong reason to *not* use a parametric model. 35%, or 8 out of 23 respondents, cited time or cost increases as a barrier. Almost all of these respondents explicitly mentioned design time or budget, except for one who said "not enough budget". However, it could be assumed that this is referring to the design budget. Three respondents noted that it is sometimes better to use experience to inform early design options, and four said that for small or simple projects, it is not worth it, because manual changes can be made instead. Even if the project is not small or simple, there may be a limited number of design choices, making it less practical to use a parametric model, which five respondents brought up. This could be because it is a retrofit of an existing building, which can leave few design options (one response), or there are many project constraints set by the architect or other parties, such as minimum floor-to-floor heights and structural depths (four responses). Two respondents felt that the architects are the ones driving the creation of these models. As one respondent put it, "these tools may be more impactful in the hands of architects […] Owners often just retain architects at the beginning of a project for these early studies and subconsultants, like structural engineers, don't have a chance to give input until the building shape and program is defined". Finally, if the design is changing very quickly in early-stage design, it may not be worth it to set up the model (one response).

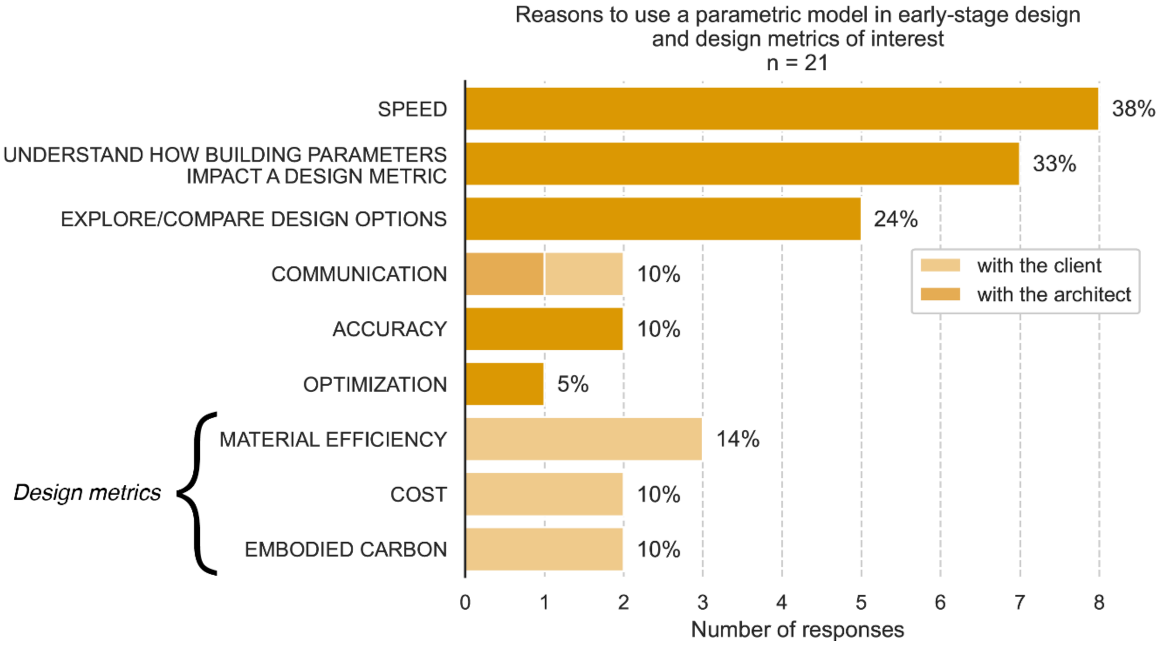

Figure 37.Coding results from the free text responses to Q4.7 (What are the main reasons, if any, that you ***would*** *create a parametric model in early-stage design?).*

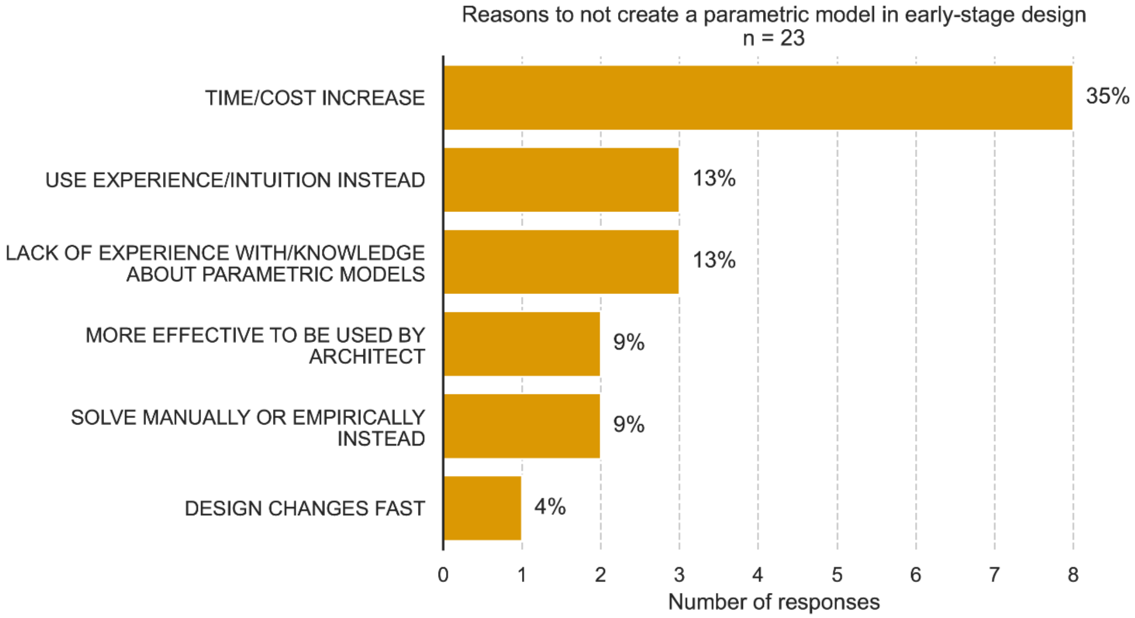

Figure 38. Coding results from the free text responses to Q4.8 What are the main reasons, if any, that you ***would not*** *create a parametric model in early-stage design?*

The final question in this section asked participants if they would use a parametric model if they had complete control over the building design and unlimited time and budget. This question eliminates the primary barrier of design time and budget, and as expected, respondents tended to be more willing to use a parametric model under these conditions (see Figure 34 and Figure 35). However, four respondents were less likely to want to use a parametric model as compared to the previous question, represented by the points below the dashed line in Figure 39. This could be because it was not explicitly stated in the question that they should assume they have the skills and tools to create the model. It is likely that this is the case, as none of these four respondents indicated that they felt confident in creating a parametric model in Q4.5.

The four points in the upper left-hand corner of Figure 39 represent individuals who at first were unwilling to use a parametric model but changed their minds in the second question. One respondent increased their rating from one to seven between the two questions. Examining the free text responses of these four respondents explains their change in response. Of the three that responded to the free text question asking why they would not use a parametric model, all mentioned that other disciplines or the architect specifically are driving the design, which constrains the design and doesn't make it worth it for the engineers to create the models. Therefore, it seems that a lack of power in the design process is a key barrier to the use of parametric models, based on the dramatic effect it had on these three responses.

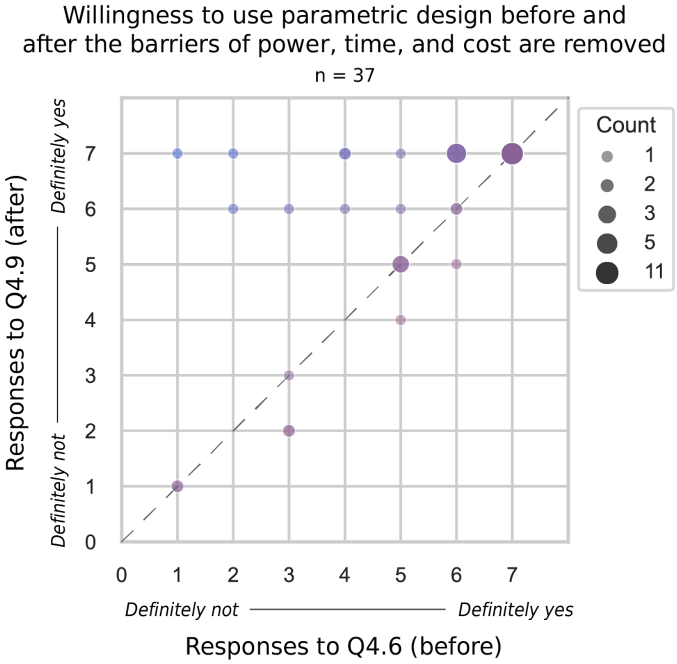

Figure 39. Comparison of responses to Q4.6 () and Q4.9(). Each point represents one (or more) respondent(s). Points along the dashed line represent individuals who had the same response to both questions. Points are colored by their distance from this line, i.e., how much an individual changed their response.

Spearman rank-order tests showed statistically significant correlations between all questions in the parametric design section (95% confidence or greater). This means that those that responded positively to one question also tended to respond positively to the other questions. Of particular interest is that those who were familiar with parametric design or felt they had the skills and tools to use them were more willing to use parametric models in design (correlation of 0.40 between Q4.1 and Q4.6 and 0.57 between Q4.5 and Q4.6). Additionally, the strongest correlation (of 0.70) existed between how often parametric models are used at their company and their willingness to use a parametric model if they had the skills and tools to do so (Q4.6). These findings suggest that increased awareness and training could be key in increasing the usage of such models.

In summary, even though respondents did not tend to use parametric models often, they tended to be willing to use one if it was assumed that they had the skills and tools to do so, or if they had unlimited time, budget, and control over the project. Several respondents who were unwilling to use a parametric model changed their minds when the barriers of time, budget, and lack of power were removed, and the free-text responses from these individuals indicated that lack of power in early-stage design was a key barrier. From the free text responses, the time required to set up and use the models, and the associated design costs to the client, were identified as key barriers.

4.5.2 Shape optimization

Respondents tended to be familiar with shape optimization, as shown by a chi-squared analysis with 99.5% confidence (n = 36). Responses were more evenly split when asked if they felt they had the skills and tools to use shape optimization to design a structural component and when asked about their willingness to use shape optimization, assuming they did have the skills needed.

After these questions, information about the load test performed on a shape optimized slab was presented. Because of the encouraging load test results, it was expected that this information would increase participants' willingness to use this system. Figure 34 shows that responses shifted a small amount in the positive direction, however, a Wilcoxon signed-rank test found that this difference was not great enough to be significant, with a confidence level of 90% (which does not meet the 95% threshold). In other words, seeing the load test information did not have a significant impact on responses.

To better understand how individuals changed their responses, Figure 40 shows a scatterplot comparing responses before and after the load test information. Out of the 38 respondents, ten were more likely to use shape optimization after reading about the load test. These respondents are represented by the points above the dashed line Figure 40. The blue point in the upper left is particularly interesting, as this respondent said they definitely would not use this technology before the load test was presented (a rating of one) but after, said they definitely would (a rating of seven). However, this point is an outlier, and there were also four respondents who were less likely to want to use this system after reading the load test information (represented by the four red points in Figure 40). One respondent said they would maybe use shape optimization before seeing the load test information (rating of four), but after seeing the information, they said they definitely would not use it. One respondent who lowered their response, when asked why they would not use shape optimization in the free text follow up, said the formwork is more complex. It is possible that seeing images of the prototype and its formwork made them more doubtful about its feasibility. It is also possible that these individuals who lowered their responses were disappointed by the load test results, however, in the free text responses, no one expressed concerns about the load test results or the safety of the system, and so it is unlikely that this caused responses to decrease. These respondents also could have simply thought of another reason to not use this tool unrelated to the load test.

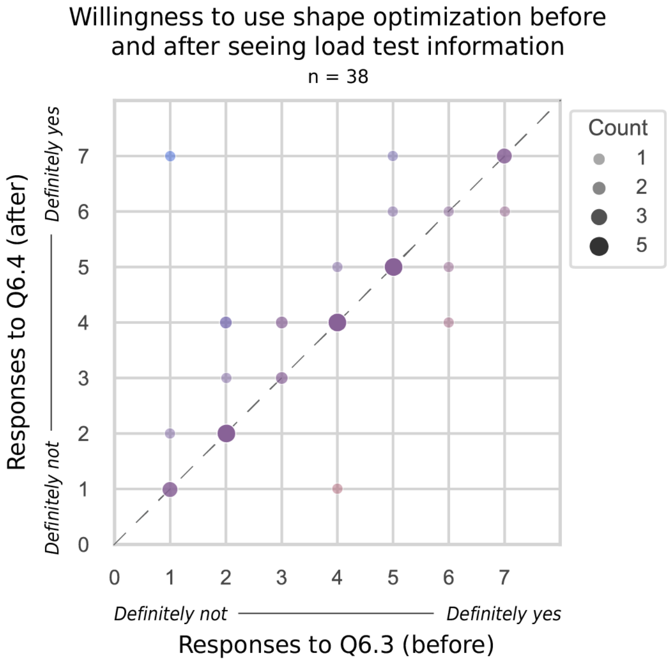

Figure 40. Comparison of responses to Q6.3 ("Would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so?") and Q6.4 ("Given this new information, would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so?"). Each point represents one (or more) respondent(s). Points along the dashed line represent individuals who had the same response to both questions. Points are colored by their distance from this line, i.e., how much an individual changed their response.

When asked why they would use shape optimization to design a floor slab, increasing material efficiency was the most common response (62% or 15 of 24 responses) followed by embodied carbon reduction (42%). Shape optimization not only reduces the weight of the floor slab, but as a result can also decrease the amount of material needed for downstream structural components, like foundations, which one respondent noted. Three respondents also said that they liked how the shaped slab looked or that it could be used to achieve a desired architectural effect.

When asked why they would not use shape optimization, respondents were most concerned about speed and costs (69%, or 18 of 26 responses). The majority of the responses about speed and cost were about construction costs (14 responses) with some concerned about increased design time (3 responses). Constructability was also a major concern (38%). Four respondents were concerned about either finding a contractor willing to build the system or receiving pushback from contractors. Additionally, one was concerned about the complexity of the formwork, and one was worried that the system may not be built correctly. Note that if the responses are re-categorized so that constructability includes construction time/costs, this category includes 70% of responses.

There were several other concerns about using shape optimization, including that if a component is optimized for one load case, it may not be usable in the future if the use of the building changes (three respondents). Figure 42 summarizes these barriers as well as three others mentioned by respondents.

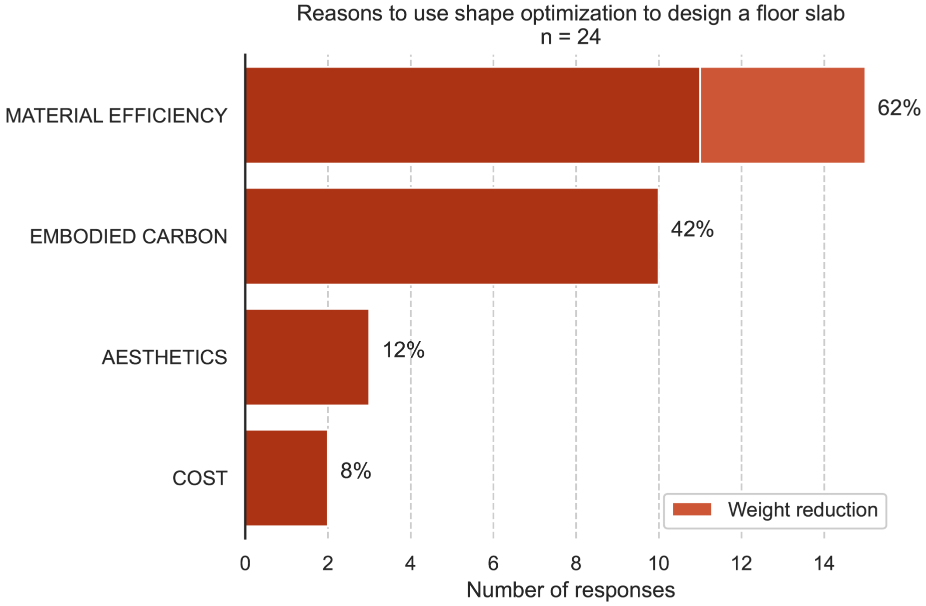

Figure 41. Coding results from the free text responses to Q6.5 (What are the main reasons, if any, that you would use shape optimization to design a floor slab?).

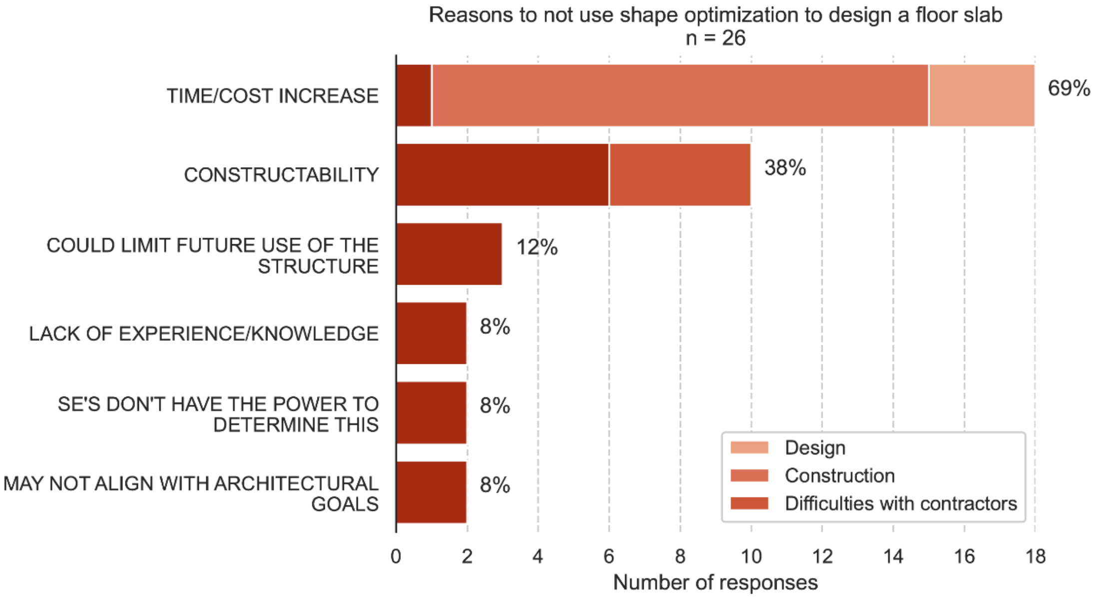

Figure 42. Coding results from the free text responses to Q6.6 (What are the main reasons, if any, that you would not use shape optimization to design a floor slab?). "Difficulties with contractors" includes difficulties in finding a contractor or receiving pushback from them.

Because speed and costs were found to be a significant concern, it makes sense that when the barriers of time and budget were removed in Q6.7, respondents were more likely to want to use shape optimization. A chi-squared analysis showed that for Q6.7, respondents tended to respond positively (99.5% confidence with n = 38), whereas for Q6.4, the chi-squared analysis showed that the difference in positive and negative responses was not great enough to be significant. This confirms that cost and time are key barriers to the use of this technology. As shown in Figure 43, no respondents were less willing to use shape optimization when these barriers were removed.

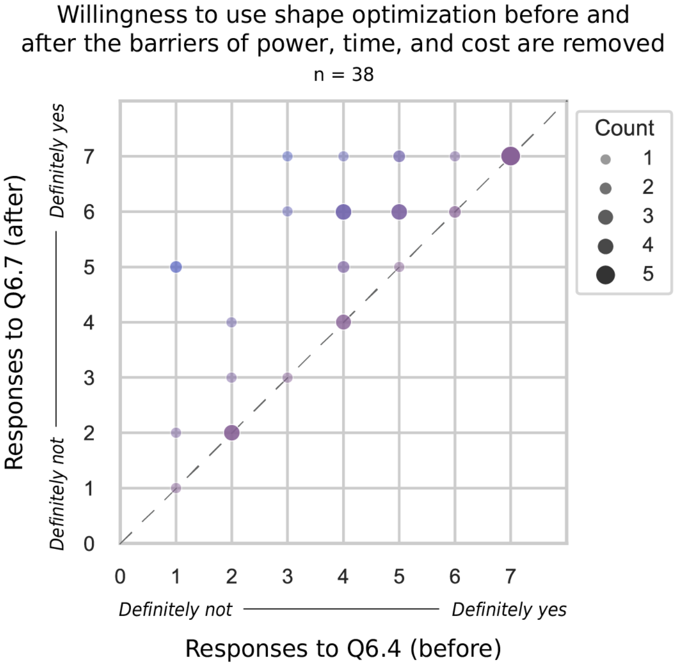

Figure 43. Comparison of responses to Q6.4 ("Given this new information, would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so?") and Q6.7 ("If you had complete control over the building design and unlimited time and budget for the project, would you use shape optimization to design structural components?"). Each point represents one (or more) respondent(s). Points along the dashed line represent individuals who had the same response to both questions. Points are colored by their distance from this line, i.e., how much an individual changed their response.

In summary, respondents tended to be familiar with shape optimization but did not necessarily want to use it in design, even after the load test information was presented. However, once the barriers of time, cost, and power were removed, they tended to be willing to use it. The primary concern about using shape optimization was speed and costs as well as constructability.

4.5.3 Topology optimization

As expected, participants were less familiar with topology optimization than parametric design and shape optimization and were very unfamiliar with Arup's topology optimized connection, as shown by a chi-squared analysis with 99.9% confidence (n = 38). A chi-squared analysis also showed that respondents tended to feel they did not have the skills and tools to use topology optimization to design a structural component (95% confidence with n = 38).

When asked if they would use topology optimization in design, assuming they had the skills and tools to do so, the distribution of responses was relatively even and looked very similar to the distribution of responses in the shape optimization section (see Figure 34). The most common reason to use topology optimization was to increase material efficiency (36% of 22 responses) which was also found to be the primary reason to use shape optimization. The next most common reason was aesthetics (23% or 4 responses). As one respondent put it, they liked the "organic shapes of topology optimized structures".

One respondent noted that topology optimization could lead to a "greater understanding of load path and feasible manners in which to provide equivalent support". This is an interesting usage of topology optimization – not using the results directly, but using them to better understand how forces flow within the structure to inform the design. Additionally, four respondents said that they would only use topology optimization on specific, "suitable" projects, and two said they would use it for a custom issue like the Arup connection.

In the shape optimization section, embodied carbon was the second most common reason to use it, however, this was not mentioned at all in the topology optimization section. This could be because respondents had already identified in the previous study that optimization led to lower embodied carbon, and by just saying material efficiency, they thought embodied carbon was implied. However, it is important to note that the shape optimization case study optimized to reduce embodied energy, while the topology optimization case study only optimized for volume reduction, and embodied carbon reduction was not a design goal. That no one mentioned embodied carbon reduction as a benefit to using topology optimization could indicate that reducing material usage is not commonly regarded as a way to reduce embodied carbon. This was also seen in the embodied carbon section, where only 48% of respondents identified material efficiency as a strategy to reduce embodied carbon, while 90% identified material choice.

Just as in the shape optimization section, time/cost increase was the main reason to not use topology optimization (48% or 10 out of 21 responses) followed by constructability (29% or 6 responses). Of the ten responses under time/cost increase, nine mentioned cost, while only three mentioned time, suggesting that cost is of greater concern. Three respondents explicitly mentioned construction cost, while one mentioned design time. Of those who listed constructability as a barrier, two said that they were concerned about finding a manufacturer willing to make the component. Three respondents were concerned that the optimized component could limit the future use of the structure, and two thought it would be more worth it to use a more conventional solution. Note that if the responses are re-categorized so that constructability includes construction time/costs, this category includes 43% of responses.

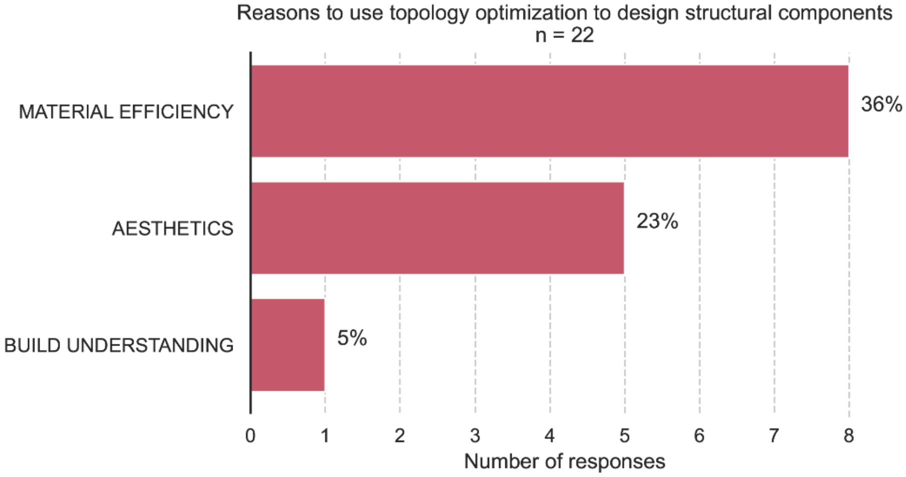

Figure 44. Coding results from the free text responses for Q7.5 ("What are the main reasons, if any, that you would use topology optimization to design structural components?"). "Build understanding" means using the optimization results to better understand load paths in the structure.

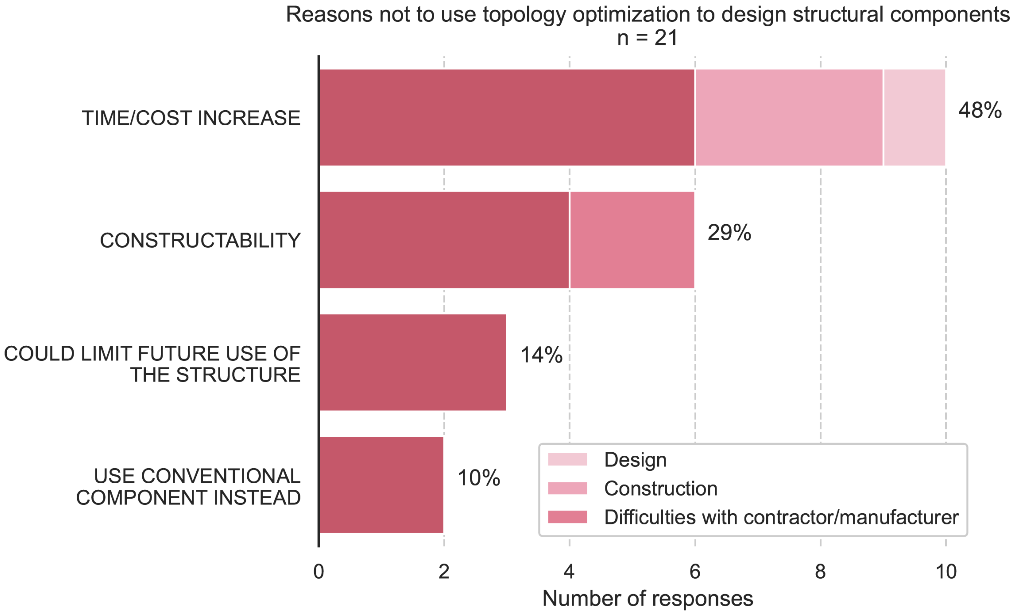

Figure 45. Coding results from the free text responses for Q7.6 ("What are the main reasons, if any, that you would not use topology optimization to design structural components?"). "Difficulties with contractor/manufacturer" includes difficulties in finding a contractor/manufacturer or receiving pushback from them.

When the barriers of lack of power, time, and budget were removed, more respondents were willing to use topology optimization, however, a chi-squared analysis showed that the difference between positive and negative responses was still not great enough to be significant. As shown in Figure 46, five respondents were less willing to use topology optimization when these barriers were removed. As discussed in the parametric design section, this may be because they do not feel confident in using topology optimization. This could be true for three of these five respondents, who said they did not feel confident in using topology optimization in Q7.3 (a rating of 3 or less). However, the other two respondents said that they did feel confident in using topology optimization (a rating of 6 and 7 in Q7.3). It is therefore unclear why they would be less willing to use topology optimization when barriers of power, time, and budget are removed.

In summary, respondents were less familiar with topology optimization than parametric design and shape optimization and tended to not feel confident in using it. While overall more people were willing to use topology optimization when the barriers of power, time, and budget were removed, five respondents were less willing to use it. Speed and costs, as well as constructability, were the main reasons to not use topology optimization in design. Finally, embodied carbon reduction was not mentioned as a reason to use topology optimization, which perhaps further shows that material efficiency is not commonly viewed as a strategy to reduce embodied carbon.

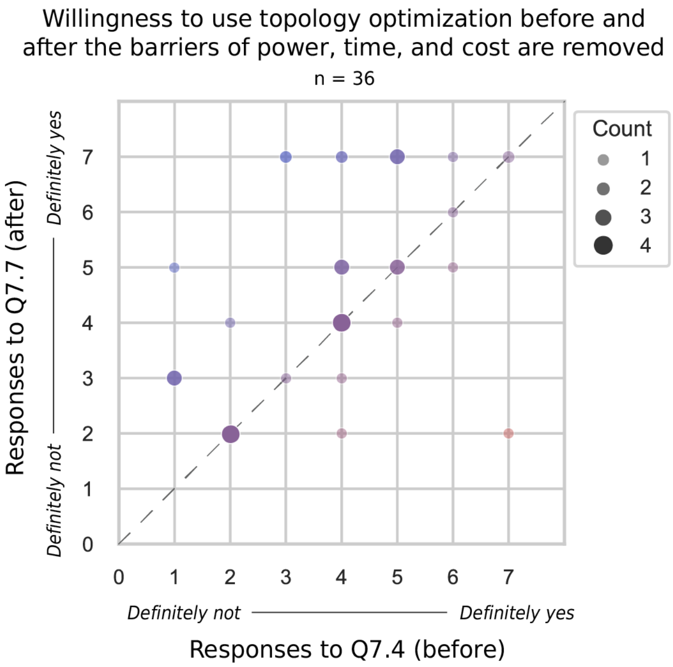

Figure 46. Comparison of responses to Q7.4 ("Would you use topology optimization to design structural components in a future project, assuming you have the skills and tools to do so?") and Q7.7 ("If you had complete control over the building design and unlimited time and budget for the project, would you use topology optimization to design structural components?"). Each point represents one (or more) respondent(s). Points along the dashed line represent individuals who had the same response to both questions. Points are colored by their distance from this line, i.e., how much an individual changed their response.

5. Discussion

5.1 Barriers to using computational tools to reduce embodied carbon

Several common themes emerged in both the embodied carbon and computational tools sections. First, it is clear that there is an opportunity for increased education on how material efficiency can decrease embodied carbon. Second, cost was often mentioned as a barrier to the implementation of more sustainable design practices and of computational tools to increase material efficiency. Finally, another barrier that appeared consistently was structural engineers' lack of power in the design process.

Material efficiency as a strategy to decrease embodied carbon

Survey results showed that not all structural engineers view material efficiency as a strategy to reduce embodied carbon, although awareness of material choice is quite high. Of the 29 respondents who could think of a strategy to reduce embodied carbon, about one third *only* identified material choice. In the topology optimization section, no one mentioned embodied carbon reduction as a benefit of creating topology optimized components. It is true that material reduction is not guaranteed to lead to embodied carbon reduction – for example, even though thinner floor slabs can be achieved with high strength concrete, the increased embodied carbon coefficient can lead to a net increase in embodied carbon (Feickert & Mueller, 2023; Sory, 2023; Hartwell, 2023). However, in the case of Arup's topology optimized connection, in which the steel volume was decreased dramatically, and the material was kept the same, the embodied carbon of the connection would also decrease. The focus on material choice, rather than material efficiency, is also seen in academic literature. Fang et al. (in prep) found that of 53 top cited papers on embodied emissions, the most commonly mentioned strategy by far was using low-carbon or carbon-sequestering materials, while material reduction appeared less than half as often.

In section 4.2, it was shown that respondents tended to consider material efficiency frequently during the design process. Educating structural engineers on how material efficiency can reduce embodied carbon could therefore be very effective, as it is not adding much complexity to their design workflow, but is simply asking them to prioritize material efficiency more. This is a basic part of the structural engineer's job. One respondent stated that "The goal of engineering simply put, is the most efficient use of material to accomplish the specific goal or challenge of the item being designed". However, not all participants said that they consider material efficiency frequently, and when asked how design schemes and structural materials are chosen in early-stage design, structural efficiency was not commonly mentioned, as other factors, such as cost and constructability, were more important. This could pose a fundamental barrier to embodied carbon reduction and the use of computational tools which aim to increase material efficiency. These results call for increased education on the importance of material efficiency, and not just for sustainability purposes – as one participant said: "Environmental impact is not the only reason for using modeling tools as described in this study. There are a lot of inefficiencies in structural engineering design that can be address *[sic]* with these tools". Using material efficiency to decrease embodied carbon goes hand-in-hand with making efficient, structurally elegant forms.

Additionally, material efficiency does not necessarily need to be achieved through computational tools. The thin-shell vaults of the mid-1900s, such as those designed by Felix Candela and Heinz Isler, were created before such tools existed. Virtual work methods can also be used in the conceptual design of high-rise buildings (Baker, 1992). Furthermore, more conventional forms can be used instead of highly optimized shapes. Jayasinghe et al. (2022) found that using two-way slabs on beams or hollow-core slabs instead of the more commonly used concrete flat slab can reduced the embodied carbon by 21-36%[4]. These savings, although smaller than what can be achieved with more innovative technologies, are still significant, especially if they are achieved at a large scale. As discussed previously, the lack of repetition and standardization of optimized components is a barrier to their use, and this strategy addresses this barrier. There is a need, therefore, for education on all ways that material efficiency can be increased, not just through the use of the computational tools presented in this survey.

Barrier of cost increase

Across all survey sections, it was apparent that cost is an important factor when trying to reduce embodied carbon or use computational tools in design. When asked what factors are used to choose between design schemes or structural materials, cost was the most common response (section 4.2). When asked whether they feel they have the power to reduce embodied carbon, one respondent said that "Our industry is dictated by money. Sustainable measures are almost always more expensive than any alternative and are therefore not selected" while another said that "the clients always want to chose *[sic]* a less cost approach". These responses show that some associate sustainable measures with increased cost, however, this is not always the case. It is possible that the *perception* of increased costs, rather than costs actually being higher, dissuades some engineers from implementing strategies to reduce embodied carbon.

As previously discussed, increased design and construction costs were also key barriers for the case studies. Again, it is not only the cost of these technologies that is a barrier, but the perception of increased costs. Even if optimized components are economically viable, many engineers view them as being more expensive, which may dissuade them from using these components. This points to a need for demonstration projects to show the feasibility of a proposed system. Although it was found that construction and load testing of a shape optimized slab did not significantly impact participants' willingness to use it, implementing a component in a built project would prove that it is possible, and inform structural engineers of the associated costs.

Barrier of lack of power

Finally, these results show that lack of power is a major barrier to the reduction of embodied carbon. As one respondent put it, "Structural engineers do have the ability to specify cleaner materials, i.e. cement replacements. But a large impact on the carbon of the structure is primarily driven by the architect's choice of programming. Structural engineers also do not always have a say in the material chosen, or the size of structural bays.". The study by Trinh et al. (2021), among many others, has shown that decreased spans lead to decreased embodied carbon; however, as this quotation and other survey results show, often the structural engineer is not able to determine structural spans. Many other structural parameters, like material, are determined by the architect, client, or the contractor, as seen in section 4.3 and section 4.5.1. One way to address this barrier is to encourage architects and clients to involve structural engineers early in the design process.

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[4] They considered cradle-to-gate embodied carbon for one story of the building, which includes the slabs, beams, and columns.

5.2 Other barriers to the use of computational tools

Figure 47 compares the barriers to the use of computational tools raised in each survey section. For all questions, time and cost increase was identified a strong barrier, representing 21% of responses for the question on computational tools in general, 35% for parametric design, 69% for shape optimization, and 48% for topology optimization. For parametric design, time/cost primarily refers to the time required to set up and use the model and the associated design costs to the client. For shape and topology optimization, the focus was on construction costs rather than design time. Constructability was the next most important barrier for optimization tools (38% for shape optimization and 29% for topology optimization), followed by concerns that optimization could limit the future use of the structure (12% and 14%, respectively). In addition, for parametric design, lack of power did not come up frequently in free text responses, however, based on the responses of those who dramatically changed their answers between Q4.6 and Q4.9, it seems that this barrier is also important. Finally, learning curve was one of the strongest reasons provided to not use computational tools in design (21%); however, it was mentioned less frequently in the case study sections. Each of these barriers will now be explored in more detail.

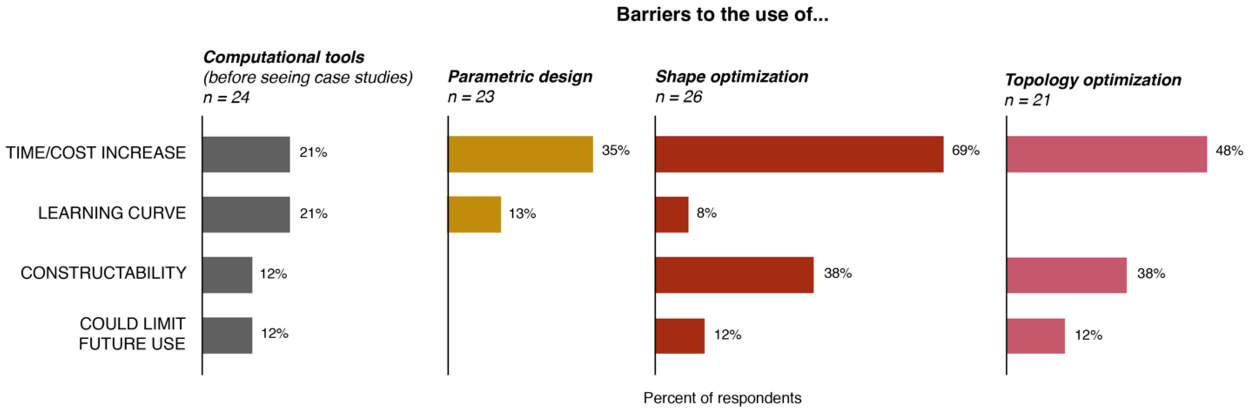

Figure 47. Comparison of free text results of questions asking why respondents would not use computational tools. Bars are scaled based on the percentage of respondents they represent for each question. Note that the question on computational tools was asked before reading about any of the case studies, while the rest were asked after reading about each respective case study.

Increased design time and considering when it is appropriate to use a computational tool

These results show that decreasing design time is an important factor when structural engineers are choosing whether to use a given tool, especially if it is a parametric model. Not only was time commonly listed as a reason to not use these tools, but when asked why they would use computational tools, 52% of respondents cited speed and/or ease.

For the questions on computational tools and parametric design, many respondents mentioned that it is not always worth it to use a computational tool, for example for very simple projects, or that they sometimes prefer to use previous project experience or design by hand. Indeed, it is not always appropriate to use a computational tool, and as noted by some respondents in Q3.3, engineers that use these tools may use them blindly, not understanding the structure's behavior or how the tool is working. In a discussion of the use of computers in structural design in *The Tower and the Bridge*, Billington notes that the "great danger … in complex mathematical formulations is that they can lead inexperienced designers away from evaluation and conception, and into the labyrinths of complex numerical analysis".. However, Billington also notes the benefits of such tools, quoting an article by Abel (1982): "the machine takes on the tedious calculations, data manipulation, and figure drawing, while the person visually integrates and evaluates patterns of behavior and makes conceptual decisions".

This will always be a risk associated with using any computational tool, however, one way to minimize this risk is through increased training and clear documentation on how each tool works and the underlying assumptions.

Learning curve and lack of awareness

Learning curve was also commonly mentioned in the question about using computational tools (21%), however, it was brought up infrequently in the case study questions (13% in parametric design, 8% in shape optimization, 0% in topology optimization). It is interesting that it was mentioned most often in parametric design and least often in topology optimization, as respondents were more familiar with parametric design and more confident in using it than topology optimization. Furthermore, a Spearman rank coefficient showed that those with greater familiarity or confidence with parametric design were more willing to use it, suggesting that if one is educated on parametric design, their willingness to use it will increase. However, this was not the case with shape or topology optimization, as shown by Spearman rank-order tests. This does not necessarily mean that lack of training is *not* a barrier to the use of shape and topology optimization, rather, it is just not as strong as other barriers. Concerns about constructability and limiting the future use of the structure were commonly raised for both shape and topology optimization, and these did not come up for parametric design. If those concerns did not exist, perhaps lack of awareness and training would feature more prominently in the optimization sections.

The barrier of lack of awareness can also be understood by comparing responses to Q3.1 ("Do you think that computational tools, such as parametric design and optimization, should be used more often by structural engineers in building design?") which asked before the case studies and at the end of the survey. Most respondents (24 out of 37) kept their response the same, and only one lowered their response (by one point). A one-tailed Wilcoxon signed-rank test showed that respondents tended to give a higher rating to the question at the end of the survey (99.8% confidence). Therefore, just reading about these case studies made respondents feel more strongly that computational tools should be used more often, showing the importance of increased awareness and education.

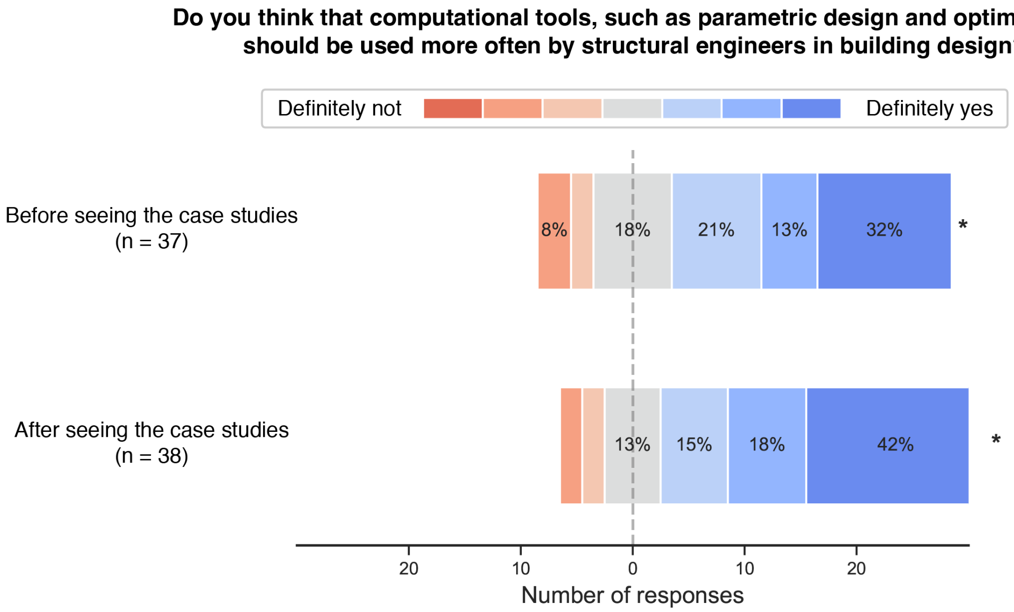

Figure 48. Results of Q3.1 and Q8.1. An asterisk denotes that for the given question, a chi-squared test found that the difference between positive and negative responses was found to be significant with at least 95% confidence.

Participants were also asked how often they read or hear about research related to embodied carbon (Q9.3) or structural optimization (Q9.4), with results shown in Figure 49. Chi-squared tests showed that responses did not lean either way for these questions. When asked how they learn about such research, the main way was through a speaker at a professional event hosted by ASCE, SEI, or other organizations (61%, 22 out of 36 responses) followed by a speaker external to their company (56% or 20 responses) and reading about it in the news (50% or 18 responses). These results suggest that speaker events at companies or at a structural engineering organization is the most effective way to communicate research to practitioners. Figure 50 shows other ways that participants hear about embodied carbon or structural optimization research.

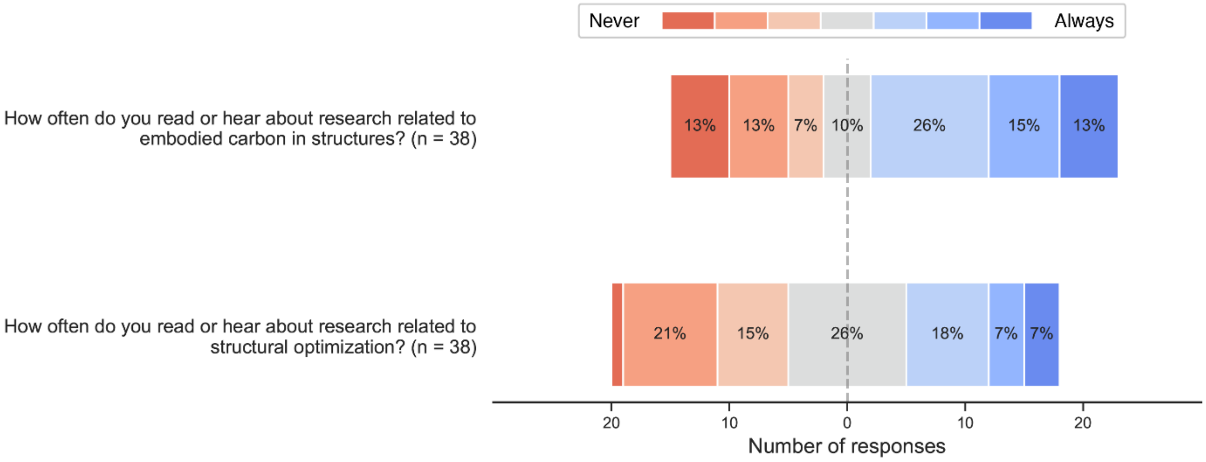

Figure 49. Results for Q9.3 and Q9.4.

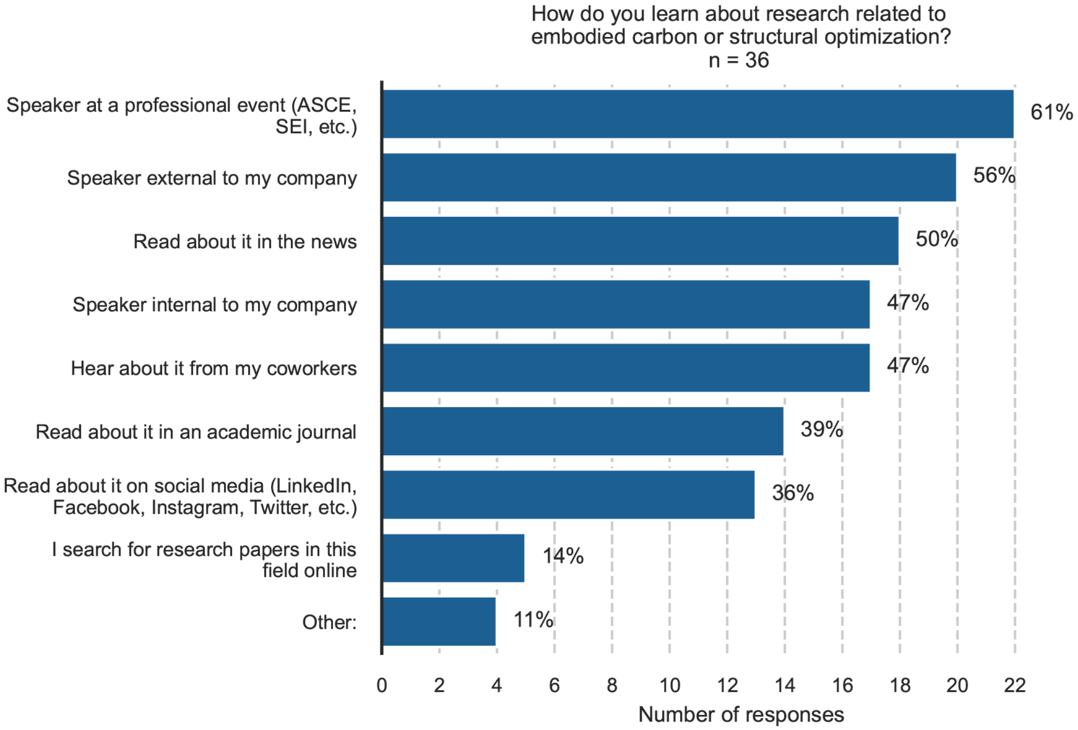

Figure 50. Results for Q9.5 ("How do you learn about research related to embodied carbon or structural optimization? Select all that apply.").

Robustness of optimized designs

One barrier to the use of shape and topology optimization is that optimization can limit the future use of the structure. This was identified by three participants in the question on computational tools, the shape optimization section, and the topology optimization section. It was not always the same three people – across all three sections, a total of five individuals brought up this issue. As one respondent put it, "A fully optimized structure may not be useful beyond it's *[sic]* initial purpose and inhibit potential adaptive reuse in the future". As identified previously, adaptive reuse is a way to reduce carbon emissions associated with construction, and although an optimized structure or component can save embodied carbon initially because of its reduced material usage, if it prevents adaptive reuse, this will minimize or potentially cancel out these benefits. This is an active area of research in topology optimization, and it has been shown how random loading fields (Chen et al., 2010) and probabilistic loading directions (Csébfalvi, 2016) can be implemented to create more robust designs.

Constructability and construction costs

For shape and topology optimization, constructability was a main barrier, and it was also mentioned in the question about computational tools in general. If construction time and costs are included in the category of "constructability", this category accounts for 70% of responses for shape optimization and 43% of responses for topology optimization. In the field of topology optimization, many studies have examined ways to increase manufacturability by accounting for the limitations of the additive manufacturing technologies. This includes implementing overhang constraints to minimize the use of support material (Gaynor & Guest, 2016), multi-axis milling constraints (Langelaar, 2019), and constraints for cast parts (Harzheim & Graf, 2006). For truss topology optimization, studies have focused on reducing the number of unique members (Lu & Xie, 2023) and constraining the number of joints and specifying a minimum angle between members (Fairclough & Gilbert, 2020) to simplify construction.

Several respondents were concerned about either finding a contractor or manufacturer or receiving pushback from them (four in shape optimization and two in topology optimization). In the shape optimization section, one respondent said that "Concrete subcontractors in the US would balk at this since they would be required to build custom formwork for every job. It needs to be repeatable on nearly all jobs before it will be adopted". Across the topology and shape optimization sections, four respondents mentioned that repeatability is needed to justify using optimized components, either repeatability within one project or across multiple projects. As another respondent put it, "One of the largest hurdles is finding ways to demonstrate cost-effectiveness of these options. If a specific optimized shape could be selected for a project typology that would have a lot of repeatability, it could be more regularly argued to be a benefit to the project from a cost perspective". In addition to the four respondents who mentioned repeatability, one said that they would only use a shape optimized component if it were provided as a standard shape. These responses show that increased repeatability or standardization of optimized shapes could be key in increasing their adoption. Furthermore, designing one component for multiple load cases could also address the issue of robustness, as components would be more resilient to future changes in loading.

However, optimization tools are able to achieve large reductions in material usage because they are creating forms that are specially made for the given support conditions, loads, and other constraints. If these components are made for multiple load cases or spans, perhaps so that they can be used in different areas of the same structure, they will become less materially efficient. Therefore, the conflicting goals of customization and repeatability must be balanced to encourage their adoption while still increasing structural efficiency. This balance will not look the same on all projects, as the stakeholders or budget could determine how much customization is deemed acceptable. This calls for optimization tools that allow the user to control how much customization they want, and they need to communicate to practicing structural engineers that these tools can be used as such.

5.3 Limitations and future work

The primary limitation of this work is that results are not necessarily representative of all structural engineers in the northeast US. Those that are more interested in sustainability and computational tools are more likely to take the survey, and as explained previously, the author reached out to some personal contacts to facilitate responses from larger firms, which introduces additional bias. However, the population questions show that there is a good distribution of engineers from firms of different sizes, years of experience, and project types, and therefore the results are not entirely unrepresentative of structural engineers.

Additionally, in any survey there is a risk that respondents may misunderstand a question, even if it is clearly worded. The coding of free text questions into categories is also a potential source of error, as free text responses can be misinterpreted by the researchers. However, this was minimized by having two individuals analyze the free text responses and by avoiding assigning a code word if the response was deemed too vague.

Finally, the sample size is relatively small. Future studies could verify these results using a much larger sample that is more representative.

6. Conclusion

Rapid reductions in carbon emissions associated with the built environment are needed to stay below the 1.5ºC global average temperature increase set by the IPCC. Embodied carbon emissions are becoming increasingly important as operational carbon emissions decrease, and as key stakeholders in the design process, structural engineers must play an important role in embodied carbon reduction.

To reduce embodied carbon, it must first be quantified, and this study found there is opportunity for increased quantification: although it is not currently quantified frequently, respondents tended to think it should be quantified more. Once embodied carbon has been calculated, there are many strategies by which structural engineers can reduce it, as described in Fang et al. (in prep). Most strategies fall into one of two categories: choosing low-carbon materials or reducing material usage. However, the results of this study have shown that many structural engineers only think of material choice as a strategy to reduce embodied carbon. Additionally, it was found that structural engineers' power to reduce the embodied carbon of the structure is often limited, as other stakeholders, such as the client and architect, can constrain structural parameters such as material and minimum spans. The associated costs of these solutions, or the *perception* that sustainable measures lead to increased costs, is also a limiting factor. This makes it even more essential that structural engineers are aware of the plethora of strategies to reduce embodied carbon that are available to them. This would allow them to choose another strategy if one is not possible due to the preferences of other stakeholders or the project budget.

The efforts of the SE2050 to increase embodied carbon awareness and reduction amongst structural engineers has already proven to be successful, as respondents from SE2050 signatory firms tended to be more aware of embodied carbon and quantified it more frequently. However, there is still a need for increased education, especially on the use of other strategies to reduce embodied carbon besides material choice. Material efficiency in particular is a promising strategy that should be promoted. Results showed that it is already frequently considered during design, and so it does not require structural engineers to learn a new skill or add many steps to their workflow. Education on how this benefits sustainable design could further emphasize its importance. In addition, several respondents noted that economic and regulatory incentives are needed to promote embodied carbon reduction.

Increased material efficiency can be achieved in many ways. Perhaps the simplest is to increase utilization ratios. Virtual work methods, form finding, and other techniques can also be used. Furthermore, much work in academia has focused on the development of computational tools to increase material efficiency. Although it is not always appropriate to use a computational tool (as discussed in section 5.2), they can speed up the design process, allow for exploration of many potential solutions, and result in dramatic material savings. Results showed that structural engineers are aware of these benefits, and they tended to think that computational tools should be use more often in the design process even before they read about the case studies. There is clearly room for increased usage, as it was found that parametric models are not used often in early-stage design, and while optimization is commonly used to determine member sizes, it is not used as much for other purposes.

This study surveyed practicing structural engineers to understand why computational tools, such as parametric design and optimization, are not used frequently in practice. Speed and ease of use were found to be of great importance, and time and/or cost increase was identified as one of the strongest barriers for all of the computational tools presented. In addition, lack of power in the design process was a key barrier to the use of parametric models, as structural parameters can be highly constrained by other stakeholders. For shape and topology optimization, constructability was a major concern, as well as the robustness of optimized designs. Overall, respondents tended to be willing to use parametric models, but only tended to be willing to use shape optimization if it was assumed that they had complete control over the project as well as unlimited time and budget. They tended to not be willing to use topology optimization even when these barriers were removed. Based on these results, the following recommendations can be made for computational tools being developed with the goal of being adopted in industry. To encourage adoption, a tool must:

- Be fast and easy to use: It is clear that speed is a key factor when structural engineers choose whether to use a computational tool. One way to make a tool easier to use is to integrate it within software that structural engineers are already familiar with.
- Avoid being a “blackbox”: This includes having a clear user interface as well as thorough documentation such that engineers can use these tools properly and understand how they work so that they feel confident in the results.
- Output constructable results: The complexity of optimized components inhibits their adoption. Although decreasing complexity may decrease efficiency, it is needed to make these solutions more applicable. To be commonly adopted, solutions must not be extremely expensive to manufacture or construct and contractors must be willing to make them.
- Have flexibility for future use: For optimized components, several respondents were concerned about the longevity of optimized components if the use of the structure changes. It is important to address this concern, as fully optimized component could inhibit adaptive reuse in the future.

Additionally, results suggest that increased awareness of these tools is an essential first step, as respondents tended to be more willing to use computational tools after reading about the case studies. Increased communication and knowledge transfer is needed to facilitate the use of these tools, as researchers are not always aware of the constraints involved in building design, and practitioners are not always aware of the tools developed in academia. Through this survey, some practitioners were informed of these tools, and by publishing this study, researchers can understand how to improve their technologies to encourage their adoption. While this is an important first step, this knowledge transfer must continue. It was shown that practicing structural engineers hear about research most often through speakers at events of structural engineering organizations, indicating that this could be an effective way for researchers to communicate their work to practitioners.

These tools have great potential to decrease the embodied carbon of structures, and by formalizing the barriers to their use, as well as to the reduction of embodied carbon in general, this study has shown what steps need to be taken such that this potential can be realized to create a more sustainable built environment.

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8. Appendix 1: Survey questions and accompanying text

Section 1: Design Process

1.1 What types of design projects do you have the most experience in? (Select all that apply)

- New construction
- Retrofit
- Historic preservation
- Other: ______

1.2 In most of your projects, what is the end-use of the building (ex. education, office, health care, residential)? ***(Free text)***

1.3 Do you typically work on high-rises or low- to mid-rises?

- I typically work on high-rises
- I typically work on low- to mid-rises
- I work on both an equal amount

1.4 How often do you work with the following structural materials?

- Masonry ***(Never to Always)***
- Concrete (includes reinforced concrete) ***(Never to Always)***
- Steel ***(Never to Always)***
- Timber ***(Never to Always)***

1.5 Which of the following softwares do you typically use for **structural analysis** and/or **design**? Select all that apply.

- SAP 2000
- ETABS
- RAM (Structural System, Concept, etc.)
- Tekla Structural Designer
- RISA 3D
- Strand 7
- SAFE
- Grasshopper/Karamba 3D
- In-house software
- Excel
- Other:

1.6 How often are you involved in early-stage structural design (concept and schematic design phases)? ***(Never to Always)***

> If they answer 4 or greater:
> 1.7 Describe the process of choosing between design schemes in early-stage design. ***(Free text)***
>
> 1.8 If you are considering several structural materials in early-stage design, how do you usually choose the one(s) to use?

1.9 In any stage of the design process, do any other stakeholders (such as the client or architect) determine any structural parameters or impose constraints on structural parameters?

- No
- Yes (please describe the stakeholder and the respective structural parameters):

1.10 How often do you consider material efficiency when making design choices? (For example, trying to maximize utilization ratios.) ***(Never to Always)***

1.11 How often do you consider the environmental impact of structures when making design choices? ***(Never to Always)***

Section 2: Embodied Carbon

2.1 How familiar are you with the term "embodied carbon"? ***(Not familiar at all to Extremely familiar)***

The built environment contributes to carbon emissions in two ways: operational carbon and embodied carbon.

- *Operational carbon is the carbon emissions emitted during the building's operational lifetime, and includes electrical use and on-site combustion energy.*
- *Embodied carbon is the carbon emissions associated with the building materials, including production, transportation, manufacturing, construction, maintenance, and demolition. It is expressed in units of global warming potential, kgCO2e, where one kgCO2e is the equivalent global warming potential of one kilogram of CO2.*

2.2 How would you describe the overall awareness of **climate change** among structural engineers that you work with? ***(Not at all aware to Extremely aware)***

2.3 How would you describe the overall awareness of **embodied carbon** among structural engineers that you work with? ***(Not at all aware to Extremely aware)***

2.4 Select your level of familiarity with the following benchmarks for embodied carbon performance. ***(Never heard of it; Heard of it but have never used it;*** **or** ***Heard of it and used as a reference in a project*** **for each question*)***

- Benchmark from a green building rating system
- SE 2050 database
- Carbon Leadership Forum benchmarks
- Benchmarks internal to your firm
- Other:

2.5 In any of the projects you have worked on, have any of the following incentives motivated embodied carbon reduction? Select all that apply.

- SE 2050
- Client's design goals
- Personal moral obligations (of yourself, or of others on your team)
- Green building rating systems (such as LEED)
- Local code or regulatory incentives
- Internal company sustainability goals
- None of the above

2.6 How often do you or your colleagues quantify embodied carbon at any stage of the design process of a given project? ***(Never to Always)***

> ***If they answer 4 or greater:***
>
> 2.7 When in the design process is embodied carbon quantified? Select all that apply.
>
> - Schematic design

    - Design development
    - Construction documents
    - Construction administration

    2.8 What is the building embodied carbon data typically used for? Select all that apply.

    - Add to internal database of embodied carbon values
    - Add to external database of embodied carbon values
    - Compare sustainability of design options in early-stage design
    - Identify ways to reduce the embodied carbon of the building
    - For green building rating system credit
    - It is required to calculate it
    - Other:

2.9 Do you think embodied carbon should be quantified in the building design process? ***(Definitely not to Definitely yes)***

2.10 Why or why not?

2.11 If asked to calculate the embodied carbon of a structure, would you feel confident in your ability to do so? ***(Definitely not to Definitely yes)***

2.12 If asked to reduce embodied carbon, do any strategies come to mind?

- No
- Yes (please describe):

    If "Yes":
    2.13 Have you tried to implement any of these strategies in a project?

    - No
    - Yes

        If "Yes":
        2.14 Was this successful, i.e. did the strategy have an impact on the final design? Please describe. ***(Free text)***

2.15 Do you think **structural engineers** have the power to influence the embodied carbon of a building during the design process?

2.16 Do you think **you** have the power to influence the embodied carbon of a building through your project involvement?

2.17 Please elaborate on your responses to the previous two questions. ***(Free text)***

Section 3: Computational Tools

The following sections will focus on the use of computational tools, specifically parametric design and optimization, in structural engineering through three case studies. We will first ask about your views on the use of computational tools in general.

3.1 Do you think that computational tools, such as parametric design and optimization, should be used more often by structural engineers in building design? ***(Definitely not to Definitely yes)***

3.2 What are the main reasons, if any, that you would use computational tools in building design? ***(Free text)***

3.3 What are the main reasons, if any, that you would not use computational tools in building design? ***(Free text)***

Section 4: Parametric Design (Case Study 1)

4.1 How familiar are you with the term "parametric design"? ***(Not familiar at all to Extremely familiar)***

In parametric design, design decisions are represented by parameters, such as column spacing or floor slab type. In early-stage design, parametric modeling of buildings can help designers explore design options as well as understand the impact of structural parameters on the overall building design and on a specific performance metric. For example, if material quantities is the performance metric, a "high-performing" design option would have low material quantities compared to the other designs.

The image below shows an example of a parametric model in Grasshopper, where column spacing of a hybrid steel-timber frame can be changed and member sizes automatically update. Material quantities and the embodied carbon of the frame are also calculated.

Parametric design can also be performed in Excel, for example, in a spreadsheet that calculates the required size and amount of rebar of a simply supported concrete beam given applied loads and material strengths. However, this survey will focus on early-stage parametric models, which are often of whole building systems, rather than models used to size members in later design stages.

We will now describe one example of an early-stage parametric model done in Excel. This study, published in the Journal of Cleaner Production in 2021, investigates the impact of column spacing, concrete strength, reinforcement ratio of the columns, and post-tensioning on embodied carbon in flat plate buildings.

Study details:
- *Examine a 10-story building that is 133x133 ft*
- *11.5 ft floor-to-floor heights*
- *Square grid of columns*
- *Lateral loads are ignored (assume that central core resists them)*
- *The following parameters are varied:*
- *Concrete can be reinforced or prestressed*
- *Column spacing is 22, 26, 33, or 44 ft*
- *Slabs can have a concrete strength of 4.6, 5.8, 7.3, or 9.4 ksi*
- *Columns can have a concrete strength of 5.8 or 9.4 ksi*
- *Columns can either have the minimum or maximum allowable amount of longitudinal reinforcement*

For each set of values above, the slabs and columns were designed in Excel according to Australian standards and the embodied carbon of the resulting building was calculated. Therefore, the authors could understand how each parameter impacts embodied carbon, and which parameters have the greatest impact.

After reading about the parametric model described above, consider the current use of parametric models in your practice through the following questions.

4.2 At your company, how often are parametric models used **in early-stage design** to understand the impact of building design variables on a specific performance metric, such as material quantities, cost, or embodied carbon? ***(Never to Always)***

If they answer 2 or greater:
4.3 What are these models used for? ***(Free text)***

4.4 What tool(s) are typically used to perform these studies?

- Grasshopper
- Dynamo
- Excel
- Other:
- I don't know

4.5 Do you feel you have the skills and tools to create a parametric model to understand how building parameters impact a performance metric? ***(Definitely not to Definitely yes)***

4.6 Would you create a parametric model in early-stage design for a future project if you had the skills and tools to do so? ***(Definitely not to Definitely yes)***

4.7 What are the main reasons, if any, that you would create a parametric model in early-stage design? ***(Free text)***

4.8 What are the main reasons, if any, that you would not create a parametric model in early-stage design? ***(Free text)***

4.9 If you had complete control over the building design and unlimited time and budget for the project, would you use a parametric model in early-stage design to explore high-performing designs? ***(Definitely not to Definitely yes)***

4.10 Any final comments on this study or the use of parametric models in building design? ***(Free text)***

Reference:
Trinh, H. T. M. K., Chowdhury, S., Doh, J.-H., & Liu, T. (2021). Environmental considerations for structural design of flat plate buildings – Significance of and interrelation between different design variables. Journal of Cleaner Production, 315, 128123. https://doi.org/10.1016/j.jclepro.2021.128123

If you are interested in the results of this parametric study, a link to a summary will be provided at the end of this survey.

Section 5: Structural Optimization

Parametric models reveal how a structure changes with varying parameters, however, they do not give the optimal solution for a given performance metric. This can be done with structural optimization tools, which can find the best-performing structure, whether 'performance' is cost, material usage, or embodied carbon. Member sizing is one form of optimization in which the lightest member size is chosen that fulfills strength and serviceability requirements. This can be done manually, for example by iteratively changing *the size until the utilization ratio reaches the desired value; or automatically with design software or custom scripting.*

5.1 How often do you use software to automatically determine member sizes in a structure? (ex. You have a steel frame of wide flange sections, and the optimizer determines the section sizes.) ***(Never to Always)***

5.2 How often do you use optimization tools for any other purpose? ***(Never to Always)***

5.3 For both member sizing and other forms of optimization, please describe what tool you are using and what you are using it for. ***(Free text)***

Section 6: Shape Optimization (Case Study 2)

6.1 How familiar are you with the term "shape optimization"? ***(Not familiar at all to Extremely familiar)***

Another type of structural optimization is shape optimization, in which geometry can be varied to best meet the performance metric. This can be understood through the example of a cantilever beam with a point load applied at the end. If the depth of the beam can be varied over its length, the most materially efficient solution (in which moment demand equals moment capacity at each point along the beam's length) would be to provide the greatest depth at the support, where the moment is the largest. This problem can be solved analytically, and results in the form shown below.

In a 2021 study, published in Engineering Structures, reinforced concrete ribbed slabs for use in residential floor systems in India are shape-optimized to reduce embodied energy (see footnote 1). This is done by defining up to five cross-sections along its length which are continuously interpolated to create one volume, as shown below.

Study details:

- *The slab is modeled as a simply supported beam with a uniformly distributed load of 42 psf*
- *T-beam methods given in ACI 318 and the National Building Code (NBC) of India are used*
- *Each cross-section is checked for flexural/shear capacity, ductility, minimum flange width and thickness, and clear cover*
- *The optimization algorithm uses the control points shown in the figure above to change the shape of the slab. It finds a solution that meets structural requirements and has the lowest embodied energy.*
- *The embodied energy of the final design is then compared to the equivalent one-way flat slab designed for the same loads and span using the NBC of India.*

1 Embodied energy is the energy consumption associated with the same life cycle stages as embodied carbon. For widely available materials, embodied energy is typically proportional to embodied carbon.

After reading the shape optimization example above, consider the current use of shape optimization in your practice through the following questions.

6.2 Do you feel you have the skills and tools to use shape optimization to increase the material efficiency of a structural component, such as a slab, beam, or column? ***(Definitely not to Definitely yes)***

6.3 Would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so? ***(Definitely not to Definitely yes)***

Section 6: Shape Optimization (continued)

The authors of the study constructed and load-tested one shape-optimized ribbed slab with a span of 16.4 ft. The optimized design was modified to meet builder's concerns, which included adjusting the geometry to be singly curved instead of doubly curved, and increasing the flange thickness. A sheet metal mold of laser-cut steel (shown below) was used. The prototype was simply supported and two point loads were applied 5 ft from each support.

Results:

- *Reached the service load (1.8 kips) and ultimate design load (2.6 kips) without deflecting beyond L/250*
- *At the ultimate design load, it had deflected approximately 0.5 inches (L/385)*
- *Ductile failure mode*
- *Experimental results aligned with the predicted performance*

The image below shows the load test configuration after testing. The final maximum displacement was 3 inches at a load of 4.7 kips.

6.4 Given this new information, would you use shape optimization to design a floor slab in a future project if you had the skills and tools to do so? ***(Definitely not to Definitely yes)***

6.5 What are the main reasons, if any, that you would use shape optimization to design a floor slab? ***(Free text)***

6.6 What are the main reasons, if any, that you would not use shape optimization to design a floor slab? ***(Free text)***

6.7 If you had complete control over the building design and unlimited time and budget for the project, would you use shape optimization to design structural components? ***(Definitely not to Definitely yes)***

6.8 Any final comments on this study or the use of shape optimization to reduce embodied carbon? ***(Free text)***

Reference:
Ismail, M. A., & Mueller, C. T. (2021). Minimizing embodied energy of reinforced concrete floor systems in developing countries through shape optimization. Engineering Structures, 246, 112955. https://doi.org/10.1016/j.engstruct.2021.112955

If you are interested in the results of this shape optimization study, a link to a summary will be provided at the end of this survey.

Section 7: Topology Optimization (Case Study 3)

7.1 How familiar are you with the term "topology optimization"? ***(Not familiar at all to Extremely familiar)***

The final case study focuses on topology optimization. In this form of optimization, there are no constraints on the shape of the final structure. The user starts by defining a design domain (a geometric region where the structure is allowed to exist), applied loads, and support conditions, which is shown below for a simply supported beam with a point load. The user also defines an objective, which often is to maximize the stiffness of the structure with a constraint on material volume. The optimizer then figures *out where to "place" material such that the stiffness is maximized. In other words, it generates a structure that has the highest stiffness for a given amount of material. An example of a 2D topology-optimized simply supported beam is shown below.*

Topology optimization is more commonly used in the aviation and aerospace industries to create components that are as light as possible while still meeting performance criteria. However, it is starting to be used in structural engineering. One example is Arup's topology-optimized steel connection, shown below. The un-optimized design is on the left, with two versions of the optimized design on the right.

7.2 How familiar are you with Arup's topology-optimized connection? ***(Not familiar at all to Extremely familiar)***

This connection was designed for a tensegrity structure in which many cables connect to the same node. In this structure, reducing the weight of the nodes could significantly impact the member sizes and structural weight, which is why the authors decided to explore the possibility of using topology optimization and additive manufacturing to design the node.

Study details:

- *Altair Optistruct was used to perform the optimization*
- *The objective was to minimize weight*
- *Used the material properties of stainless steel*
- *Stress limits were imposed so that the solver would find a solution with acceptable stresses*
- *Accounted for some manufacturability constraints so the connection could be additively manufactured*
- *Two versions of the optimized node were produced by direct metal laser sintering of stainless steel*

After reading the above example of topology optimization of a structural connection, consider the use of topology optimization in your practice through the following questions.

7.3 Do you feel you have the skills and tools to use topology optimization to increase the material efficiency of a structural component (such as a beam, column, slab, or connection)? ***(Definitely not to Definitely yes)***

7.4 Would you use topology optimization to design structural components in a future project, assuming you have the skills and tools to do so? ***(Definitely not to Definitely yes)***

7.5 What are the main reasons, if any, that you would use topology optimization to design structural components? ***(Free text)***

7.6 What are the main reasons, if any, that you would not use topology optimization to design structural components? ***(Free text)***

7.7 If you had complete control over the building design and unlimited time and budget for the project, would you use topology optimization to design structural components? ***(Definitely not to Definitely yes)***

7.8 Any final comments on this study or the use of topology optimization to reduce material usage and embodied carbon? ***(Free text)***

Reference: Galjaard, S., Hofman, S., Perry, N., & Ren, S. (2015, August). Optimizing structural building elements in metal by using additive manufacturing. In Proceedings of IASS Annual Symposia (Vol. 2015, No. 2, pp. 1-12). International Association for Shell and Spatial Structures (IASS).
Access here.

Optional: If you are interested in the results of the study, they are summarized below. Otherwise, you can continue onto the next page. (Please do not change your answers after reading the results.)

The final optimized node, shown on the right in the previous image, is 75% lighter than the original design on the left, but it can take the same design loads.

Section 8: Final Thoughts

After this, there is one more quick section.

8.1 Do you think that computational tools, such as parametric design and optimization, should be used more often by structural engineers in building design? ***(Definitely not to Definitely yes)***

8.2 Do you think structural engineers have the power to influence the embodied carbon of a building during the design process? ***(Definitely not to Definitely yes)***

8.3 If you have any other thoughts on the role of parametric modeling and optimization in building projects, or on the embodied carbon of structures, please provide them here: ***(Free text)***

Section 9: Population Questions

9.1 Which office location (region/city) are you primarily associated with? ***(Free text)***

9.2 How many years of experience do you have as a structural engineer?

- Less than 2 years
- 2-5 years
- 6-10 years
- 11-15 years
- 16-20 years
- 21-25 years
- 26-30 years
- Over 30 years

9.3 How often do you read or hear about research related to embodied carbon in structures? ***(Never to Always)***

9.4 How often do you read or hear about research related to structural optimization? ***(Never to Always)***

9.5 How do you learn about research related to embodied carbon or structural optimization? Select all that apply.

- Speaker internal to my company
- Speaker external to my company
- Speaker at a professional event (ASCE, SEI, etc.)
- Read about it in the news

- Read about it on social media (LinkedIn, Facebook, Instagram, Twitter, etc.)
- Read about it in an academic journal
- Hear about it from my coworkers
- I search for research papers in this field online
- Other:

We would greatly appreciate the opportunity to speak to you further about these topics. If you are willing to be interviewed, please let us know below and we will reach out to you via the email you provided in the consent form.

9.6 Are you interested in participating in an interview?
- No
- Yes

If would like to learn more about the first two case studies on parametric design and shape optimization, summaries of their results can be found here and here.

9. Appendix 2: Glossary of statistical terms

Term	Definition
Population	“The overall group of people you want to know about in a study.” (Holt and Walker, 2009) In this study, the population is structural engineers in the northeast US.
Sample	The subset of the population participating in the study.
Random sample	“A sample of a population chosen by selecting people at random. Strictly speaking, everybody in the entire population should have an equal chance of being included.” (Holt and Walker, 2009)
Ordinal data	“numerical data which can be put into order but where the intervals between numbers are meaningless.” Example: Likert scale data (Holt and Walker, 2009)
Two-tailed hypothesis	“Predicts that there will be an effect in your data” (Holt and Walker, 2009 Example: There will be a difference in how respondents from SE 2050 signatory firms and those not from SE 2050 signatory firms rate their familiarity with embodied carbon.
One-tailed hypothesis	“Predicts that there will be an effect in your data, and what that effect will be.” (Holt and Walker, 2009) Example: Respondents from SE 2050 signatory firms will rate themselves as more familiar with embodied carbon as those not from SE 2050 signatory firms.
Significance	Put in simple terms, significance in statistics means “the probability that you have found nothing of interest is low enough that you reject that possibility and instead conclude that you have found something of interest.” (Holt and Walker, 2009)
Alpha	The level of risk you are willing to accept. For example, an alpha of 0.05 means that there is a 5% chance that the conclusion you found is incorrect. The corresponding confidence level is 95%. An alpha of 0.05 is commonly used. (Holt and Walker, 2009)