How much does your building (model) weigh?
On heightening awareness of embodied carbon in the design studio

Mike Christenson
Malini Srivastava
University of Minnesota, Minneapolis, Minnesota

ABSTRACT: *This paper describes an academic exercise of our own design, conducted in our graduate-level architectural design studio in a professional architecture degree program. We designed the exercise to highlight the importance of embodied carbon in architectural decision-making processes as taught in the studio context. We report on the background and our pedagogical approach, placing the work in a context of relevant literature. We describe the academic exercise and suggest questions for the next phases of our research work.*

KEYWORDS: embodied carbon, physical models, net-positive

INTRODUCTION

As educators in building design and construction, we aim to heighten our students' awareness of embodied carbon in their academic design-studio projects. In this context, we use the term embodied carbon to refer to the total carbon equivalent (CO2e) associated with constructing and maintaining a building during production, construction, operation (except utilities), and demolition and disposal, i. e., life-cycle embodied carbon (Hu and Esram 2021; Spector et al 2021; Dewolf et al 2017). Specifically, as studio teachers in a professional school of architecture, our responsibilities include educating our students in the kinds of decision-making processes they are likely to encounter in professional practice. We are pedagogically interested in highlighting factors that can inform design decision-making processes, and specifically in the physical models students construct as part of those processes.

Our work is guided by our long-standing research interests in architectural studio pedagogy (Christenson and Srivastava 2005; Christenson and Aly-Ahmed 2007; Christenson and Barnhouse 2008; Christenson 2013; Srivastava, Christenson, and Atwood 2015; Christenson and Srivastava 2016; Christenson 2017; Srivastava and Christenson 2018; Srivastava 2020; Srivastava, Barton, and Christenson 2020; Christenson 2021). We also recognize that architecture students are expected to possess a growing and evolving set of knowledge, skills, theories, and analytic methods (Thompson and Soccio 2022; Khodeir and Nessim 2020; Mari et al 2019). They should also be proficient in working at various scales, from details to systems, and understand the complex factors that impact their readiness to join professional practice (Akimova et al 2021). Within this expansive context, our prior work has suggested the value of cooperative work structures in creating new knowledge within the architecture studio (Srivastava 2020).

These interests led us to design and implement the approach described in this paper: an extended exercise in which we asked our students to consider the weight of their physical models as proxy registers of embodied carbon in their evolving architectural design projects. While the work is at an early and speculative stage, we have preliminary indications of its promise for our next implementation.

1. BACKGROUND

1.1 Pedagogies of physical models in architecture

Briggs (1929) expressed a traditional assumption about architectural models when he insisted that models are valuable registers for posterity only to the extent that they enable us "to realize how an artist transmitted his [sic] ideas to those who were charged with carrying them out" (Briggs 1929: 174). In this view, models are primarily useful for communicating concepts to others and only secondarily as tools for the working-out of ideas. Contemporary literature has expanded this view to allow for recognizable and useful distinctions between different kinds or types of models and their respective roles in architectural pedagogy. For example, Nour Afify et al (2021) distinguish between "concept models," "schematic models," and "presentation/finished models," associating specific pedagogical expectations with a defined project timeline. Distinctions such as between "spatial models" and "structural models" (Dunn 2011) or between "sketch models" and "massing models" (Mills 2011) can help to clarify a particular model's focus, i. e., to the exclusion of issues deemed extraneous or distracting. Dunn (2011) also distinguishes between "descriptive," "projective," "evaluative" and "explorative" models, thus usefully identifying models with specific kinds of questions, echoing Echenique's (1970) categories of "descriptive," "predictive," "explorative," and "planning" models.

An alternative approach to categorizing architectural models is to de-emphasize distinctions between *types of models,* highlighting instead the *distinct uses which models are brought to serve* within extended design decision-making processes. To illustrate this point, consider that any given physical model can be conceptually framed as both a tool for iterative development and as an artifact supporting public presentation, e. g., in cases when physical models resulting from iterative decision-making processes are exhibited publicly, or in cases when models constructed for presentation purposes are framed as momentary concretizations of ideas and concepts, as steps along the way toward something not yet fully defined. We might call these "provisionally final" models. In this way, it is possible to distinguish architectural models' *epistemic* function ("what they are for") from their representational nature ("what they are of") (Gouvea and Passmore 2017; Cannaerts 2009). Similarly, Starkey (2007) differentiates between "building a model" and "modelling a building" (Starkey 2007: 239). While the former creates a speculative space for design research and materiality, the latter involves a scaled-down or full-scale representation of a building.

1.2 Physical models and embodied carbon

Frei Otto is recognized as a pioneer investigator of relationships between modelmaking and what we now refer to as "embodied carbon." Although "embodied carbon" terminology was not available to Otto, his interests in pursuing lightweight, mobile structures clearly indicate his sympathy with contemporary aims to reduce embodied carbon through addressing material waste and inefficiencies (Whitehead 2021). Similarly, Gaudi's approach to modelmaking (Tomlow 1989; Tomlow 2011), or that of Heinz Isler (Chilton and Chuang 2017), insofar as these approaches pursue formal and material optimization, are early examples of physical models as devices for material exploration and particularly material minimization in building and construction. Otto's work in particular is remarkable for its transcendence of "purely physical haptics" in achieving results of political and cultural significance (Vrachliotis 2020: 15).

Questions of optimizing model weight or of maximizing material efficiency are commonly addressed in structural engineering pedagogy (Guerguis and Pitts 2021; Schmucker 1998). Transcending optimization as a sole criterion for success, engineering pedagogy also engages physical models in "playful" and generative situations (Vrontissi et al 2018: 1-2).

In the context of our studio, we positioned physical models as having several specific epistemic functions, the principal one of which was to support an iterative development of ideas and concepts. This aim is not necessarily directly connected to material efficiency. For this reason, we asked students to construct "Re-Use Strategy Models" in pursuit of identifying a specific strategy for re-using the existing building at the core of our studio. Re-Use Strategy Models are constructed from found or recycled materials, and are expected to be "sketch" or "pedagogical" models, as defined by Johnson (2007), meaning that they should "incorporate a subset of the [building's] authoritative dimensions, or ... simplify the geometric forms in published drawings" (Johnson 2007: 2). To state this expectation differently: the Re-Use Strategy Model is constructed at a specific scale; it is a formal abstraction or simplification; it is speculative, even as it makes reference to the existing conditions. A student, in an early-semester conversation, aptly characterized our approach to the Re-Use Strategy Models as being concerned with "the "quantity(?) and quality of ideas rather than the quality of craft."

Figure 1: Students collecting Re-Use Strategy Models, January 2023. Source: Author's photo

Centrally to the question in this research, we also positioned physical models to increase student awareness of embodied carbon impact on design decisions.

1.3 Embodied carbon in digital models

With respect to their role in heightening awareness of embodied carbon, digital models are much more thoroughly explored in the literature than physical models. Pedagogies of building information modeling (BIM) and its connections to life-cycle analysis (LCA) are particularly prevalent in the literature (Farid Mohajer and Aksamija 2019), and BIM's integration into the architectural discipline continues to open opportunities for embodied-carbon analysis (Soust-Verdaguer et al 2017). Integrating LCA into pedagogy, supported by BIM, engages students with sustainability assessments, making it possible for them to routinely incorporate them in their decision-making processes (Gomes et al 2022). Tools such as EC3, Athena Impact Estimator and the Tally Carbon Calculator (Yan et al 2022; Cameron 2020) provide visualization methods for embodied carbon impacts. Furthermore, custom tools and particularly parametric methods can provide robust methods for querying digital models (Hollberg, Genova, and Habert 2020; Hollberg et al 2016).

2. THE STUDIO

The work we describe here concerns an architectural design studio which we co-taught in the spring semester of the second year in the three-year professional Master of Architecture (M. Arch.) program at the University of Minnesota. Considered as a semester-long experience, the studio introduces professional graduate students to the integration of architectural design, environmental technology, and high-performance regenerative practices.

2.1 Half-Semester Modules

The studio is organized into two half-semester modules, namely, “net positive design” and “integrated design.” “Net positive design,” the focus of the studio’s first half-term, relies on Mang and Reed’s (2015) definition of net positive, i. e., referring to “buildings that ‘add value’ to ecological systems and generate more than they need to fulfill their own needs” (Mang and Reed 2015: 7). Although students in the studio are free to make design decisions in pursuit of zero-energy use or positive energy production, the “net positive design” studio aims more broadly to engage approaches such as biophilia (Guzowski 2015, Guzowski 2021a, Guzowski 2021b, Guzowski 2022). “Integrated design,” the focus of the studio’s second half-term, is generally agreed to refer to the decision-making processes involved in integrating “building envelope systems and assemblies, structural systems, environmental control systems, life safety systems, and the measurable outcomes of building performance” (NAAB 2020).

In a typical year, the second-year M. Arch. students are organized into three or four sections of nine to 12 students, each section led by two instructors, one of whom is assigned to teach the first half of the semester (“net positive”) and the other to the second half (“integrated design”). While all of the second-year M. Arch. students share a common, aligned schedule (e. g., common lectures, consultant workshops, and energy modeling training), each of the studio sections addresses a unique project.

2.2 Our pedagogical approach

In spring of 2023, we co-taught a section of the net-positive and integrated design studio. Our section enrolled ten graduate students. In our studio section, we chose to position existing buildings as *congealed repositories of matter* (material) and *effort* (labor and energy). In this view, existing buildings are understood to be capable of operating as instruments of net positive impact, whereby matter and effort are fluidly coaxed into responsive, regenerative and resilient configurations. Processes of coaxing, so defined, necessarily involve second-guessing and hindsighting those decisions that led to the construction and operation of the building under study. Framed in this way, our approach aimed to engage students in understanding building science principles, systems, and performance frameworks. In this context, we framed a studio project to materially transform an existing (1936) three-story building in Minneapolis with the potential for a cold climate courtyard. We challenged our students, in addressing the existing building, to work within a range of operations within three strategic extremes: reincarnation (-100%), existing as-is (0), and reconfiguration (+100%), without adding either footprint or program. We positioned the program as transitory: while we left the question of program open, students could choose to work with the building’s existing use (university offices, classrooms, and study spaces) or propose new uses. We posited a new form of practice, where architects are commissioned to not add or subtract program but to reconfigure the existing for better performance. Performance, in this case, was defined qualitatively (enhancing experience, comfort, and function) and quantitatively (reducing footprint in terms of operational and embodied carbon).

Similarly to our past studios, we worked with our students to form *cooperative work structures,* trading drawings and models, teaching/learning concepts and skills (Srivastava and Christenson 2018). This approach is aimed at prompting operative questions such as: how do we foster and encourage the “shifting allegiances” to ideas and concepts that inevitably occur in the design studio in order to maximize learning (Srivastava 2020)? In addition to cooperative work structures, we proposed a combination-drawing and combination-making method of work and study, in which each student took ownership of a segment of the existing building, researching, observing and documenting understanding of the whole through an in-depth understanding of a part of the building. Students taught each other what they are learning from the deep examination of that one segment of building that they are working on. With this work method, we hoped to understand the relationship between work quality in the studio and wellness of the students in the studio. Could a cooperative work structure not just be a method to enhance learning (Srivastava 2020) but also improve wellness?

The Net Positive studio brief was originally proposed by our colleagues, Mary Guzowski and Richard Graves, based on Mang & Reed's approach towards net positive, as buildings that add value to the ecological systems that they exist within (Mang & Reed 2015, Srivastava 2020). As such, the process of iteratively achieving modeled Net Zero performance based on Architecture 2030 goals, was only part of the pedagogical consideration of the studio. In our section, we developed the "net positive" consideration through random assignments of each of the the aspirational AIA Framework of Design Excellence, providentially ten frameworks, one for each of our students. This assignment of one framework for each student also allowed us to further examine the potential of cooperative work. We asked the question, can depth emerge from the ability to focus on a single framework and can breadth emerge from the students teaching each other the framework that they were responsible for researching?

2.3 Description of the extended exercise

Within this overall context, we designed an exercise to highlight the presence of embodied carbon in student decision-making processes. Through this exercise we ask students to again examine questions that we had previously asked in a class called Architecture as a Catalyst through a full scale investigation of materiality (Srivastava 2023). Examples of questions included the following. How can we incorporate formal geometries that help reduce the amount of materials being used (Srivastava 2022)? How can we examine local material systems and minimize or make redundant energy-consuming systems (Maierhofer et al 2022, Srivastava 2022)? How can we change the composition of materials to include bio-based, responsive materials? How can we position the reuse of materials to promote local circularity without creating a waste-intensive system? How can we see local vernacular and craft cultures and practices irrespective of industry and potentially apply them to the building industry? However, in this studio we deliberately asked students to examine these questions through scaled representations as having a material effect on the architectural form and geometry, the quantified footprint of the structure as a whole and the potential experience and comfort of occupants.

As part of the studio's iterative design activity, we asked our students to construct physical models of their evolving design projects at various moments in the course. In our first attempt to initiate this exercise in the studio environment, five of our students completed full sets of models over a round of three iterations. We asked the students to weigh their models and report the results (Table 1).

Table 1: Average model weights, first three iterations.

	Student 1	*Student 2*	*Student 3*	*Student 4*	*Student 5*
Iteration 1: Average	15g	31g	25g	224g	43g
Iteration 2: Average	27g	37g	23g	241g	56g
Iteration 3: Average	46g	35g	11g	19g	68g

Following the initial implementation of the exercise, we asked students to respond to several questions, with responses ranked on a five-point scale, numbered 1 through 5, the extreme ends of which were labeled "strongly agree" (at 1), and "strongly disagree" (at 5). The questions and the most frequent responses, sorted in order from greatest agreement to least agreement, are included in Table 2.

Table 2: Survey questions.

Question	mode response (1 = strongly agree; 5 = strongly disagree)
Being asked to weigh my models increased my awareness of embodied carbon.	2
In the future, I am more likely to weigh my models as part of my design decision process.	2
I feel that there are important connections between model weights and the decisions I will make about building design.	2
The model-weighing exercise has helped me to understand the importance of material selections in design.	3
My understanding of embodied carbon improved as a result of the model-weighing exercise.	3
After weighing my models, I will be more conscious of my material choices for future models.	4
The model-weighing exercise helped me to understand the consequences of early-stage design decisions.	4

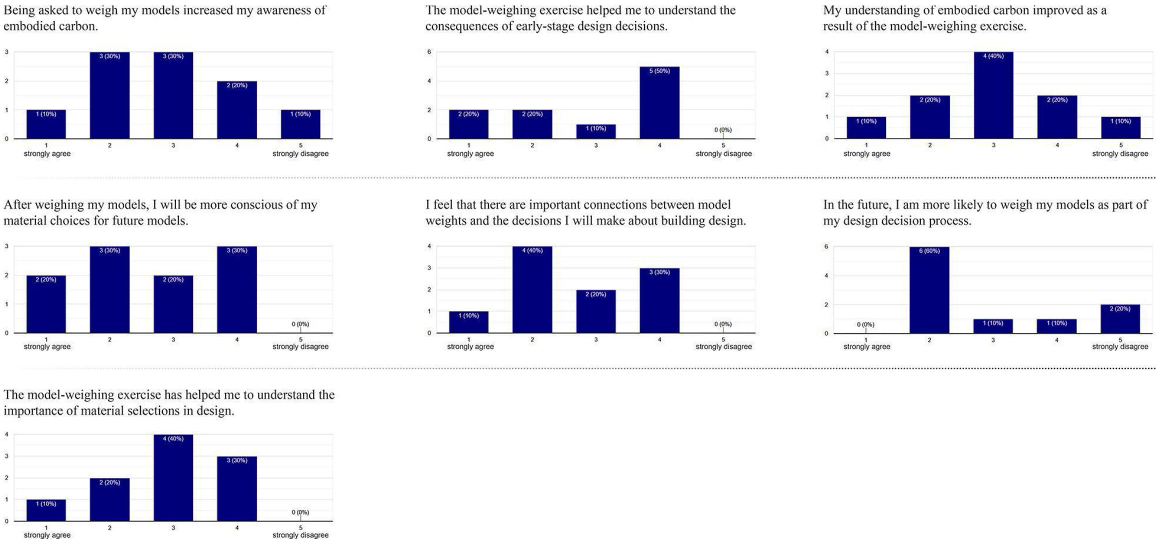

Figure 2: Summary of responses to survey questions.

Acknowledging the small sample size (n=10) and the likelihood of distorted results (e. g., due to central tendency bias, acquiescence bias, social desirability bias, etc.), we observe per Figure 2 that in general, the students were more likely to agree with the following statements: “Being asked to weigh my models increased my awareness of embodied carbon”; “In the future, I am more likely to weigh my models as part of my design decision process”; and “I feel that there are important connections between model weights and the decisions I will make about building design.” Students were least likely to agree with the following statements: “After weighing my models, I will be more conscious of my material choices for future models” and “The model-weighing exercise helped me to understand the consequences of early-stage design decisions.”

2.4 Opportunities for pedagogical development

As we look ahead to future implementations of the exercise, we acknowledge that our informal survey results are not yet sufficient to demonstrate that our strategies were effective in increasing awareness of resource usage in comparison to alternative methods, or even in comparison to a standard class baseline. The questions we asked in the survey could be too suggestive, and we suspect that a comparable outcome could arise even within a control group. In a situation such as a design studio, where the sample size is small, we expect that it could also be valuable to collect written or oral feedback from students, instead of depending solely on numerical data which may not be statistically meaningful. In the future, we will aim to obtain this kind of qualitative data in the hope that it will be more insightful as well as beneficial in terms of improving the approach.

We also aim to engage the exercise with greater rigor and specific constraints. For example, the materials used by students in their physical models varied, presumably corresponding to “real-life” materials with differing amounts of embodied carbon per unit weight. Thus, in the future, we will ask students to calculate both the total weight and the per-material weight of their finished models as well as any material acquired for the purpose of building models but ultimately not used (i. e., the “waste material”). We will ask our students to weigh (a) the model and (b) the waste material. The sum of these two quantities is (c) the total material weight. Finally, we will ask them to calculate the material efficiency (d) of the model by dividing the total weight (c) by the model weight (a).The calculations will be recorded and compared across student projects, and we will re-ask our survey questions, tabulating the results for comparison.

Fundamental to our ongoing development of this exercise is the decided ambiguity between (a) the open-ended conceptual development that the models are designed to support, and (b) their quantifiable weight. However, we feel that this kind of ambiguity is characteristic of architectural decision-making processes, and in the future, we intend to problematize it more openly and directly.

DISCUSSION

In a collaborative and iterative effort, we guided our students through a cyclical process of quantification and creation. Our pedagogical position is that this cyclical process is uniquely capable of providing prompts and provocations on the iterative development of architectural concepts. The purpose of this exercise is not to accurately measure the embodied carbon in the student models or design proposals they represent. Instead, our hope is that the exercise, once fully developed pedagogically, will raise students’ awareness and encourage them to consider possible impacts of their material choices. Beyond this, the exercise could prompt the students to recognize relationships between their model-making decisions and corresponding building design decisions. In these ways, the exercise promises to provide a worthwhile provocation on what would otherwise be an unquantified pursuit of conceptual development.

Because we rely on model weight and material weight as proxies for embodied carbon, we are specifically exempting the students from directly analyzing the extent and impact of such factors as extraction, processing, transportation, and recycling of building materials. Nevertheless, we expect that students will as a result of the exercise begin to articulate and develop questions concerning the lifecycle of their model-building materials. Furthermore, that the student research will both prompt students to conduct research on the larger-scale question of (real) building materials, and that it will provide them with exposure to -- and experience with -- tools and methods for lifecycle analysis of their academic projects.

When Buckminster Fuller asked “How much does your building weigh,” he provoked new ways of understanding decision processes in building design and construction (Zung 2001). We envision this exercise becoming a formalized part of our studio process, as a way to heighten student awareness of embodied carbon and to trigger questions about it, much in the same spirit. While Fuller’s interests were driven by efficiency, ours are driven by the concerns identified earlier in this paper, specifically a concern for carbon emissions, contextualized by our expectation that cooperative work structures will improve work quality.

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