Embodied Carbon As A Path To Embodied Wisdom

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To rapidly reduce climate impacts from the built environment, architects must develop both expert knowledge to measure impacts, and the wisdom to interpret results and integrate them into design. This paper describes the application of quantitative life cycle assessment in a studio to advance design synthesis and integration by cultivating intuition about the embodied impacts of structural systems. Students in an integrative studio modeled life cycle impacts of their projects, focusing first on the carbon embodied in the structure and then integrating other systems as the designs developed. Meaningful analysis depends on comparison, and professional judgement develops from repeatedly connecting new knowledge generated through skilled application with prior knowledge. Students compared their results to a collaboratively-developed baseline building with typical construction, and across the diverse projects of the studio. An industry benchmark of 500 kg CO_2e/m^2 contextualized studio projects relative to empirical data and challenged students to manage the carbon intensity of their evolving designs. However, neither declarative knowledge about embodied carbon nor the procedural skill of using simulation tools are learning objectives of the integrative studio: the abstraction of quantitative analysis serves only to enable a rich qualitative discourse about design synthesis and integration. Case studies in this paper describe the range of outcomes for students engaged in this reflexive practice and the opportunities and challenges for faculty and students to discern wisdom embodied in benchmarks and to cultivate intuition about designers' agency and material impacts.

BACKGROUND

Constructing and operating buildings comprise a significant portion of the greenhouse gas emissions driving global climate change.[1] Life Cycle Assessment, (LCA) provides a systematic method to tabulate the environmental impacts of human activities across their entire life from extraction and processing of raw materials through manufacturing, construction, use, and eventually destruction and disposal. International standards like ISO 14040 provide a framework for the LCA process in four numbered steps: defining goal and scope; inventorying materials and energy throughout the lifecycle; assessing the impacts; and interpreting results.[2]

Even after decades of effort to improve efficiency, operations typically contribute most of buildings' lifetime emissions. However, increasing efficiency means choices about materials and construction constitute an ever-larger proportion of total impacts,[3] as do the resources needed to achieve these operating efficiencies.[4] Larry Strain and the Carbon Leadership forum use the term *Time Value of Carbon* to express the urgency to avoid catastrophic climate change by limiting short-term emissions associated with construction as compared to cumulative future emissions from operations, arguing that "when you save matters."[5] The widely-accepted European Standard EN 15978 divides the lifecycle of a building into four main stages denoted with letters: A for products and construction, B for use, C for end of life, and D for benefits and loads beyond the building's life cycle.[6] Because the components tend to be big, heavy, and made of highly processed materials like steel and concrete, structural systems tend to dominate the embodied (stage A) impacts.[7] Although the structural system may represent the largest share of upfront emissions—and perhaps financial costs—structural system selection typically occurs quite early in design, with materials and arrangements based on rules of thumb and experience well in advance of quantitative design of specific members.[8] Though not a lifecycle stage, architects' earliest decisions (after choosing to build at all) disproportionately affect emissions long before quantitative, or even systematic, analysis occurs. Architectural education must prepare future practitioners accordingly.

A defining characteristic of expertise in experienced practitioners, intuition or System 1 *thinking* [9] describes the way much of our thinking works: relying on assumptions quickly accessed from memory.[10] While enviably rapid, intuition can stagnate into deeply ingrained beliefs, such that "we stop being curious… we see them as self-evident truths."[11] To prevent that, teaching and learning intentionally engages slower, more deliberate *System 2* thinking, which questions assumptions, collects additional information, and reflects on it.[12] Postulating that developing wisdom or intuition about carbon emissions enables better design decisions amid the limited time and high uncertainty characteristic of early design, this research tests a learning experience designed to develop intuition.

All intuition depends on memory, so experts' quick-thinking intuition belies the time needed to not only acquire diverse personal experience, but to do so systematically, as Kahneman warns, "Intuition adds value… only after a disciplined collection of objective information and disciplined scoring…"[13] In fact, algorithms can match or exceed the accuracy of expert judgment of clinicians in "low validity fields" where there is a high degree of uncertainty and unpredictability (e.g. clinical diagnosis).[14] Even simple algorithms, e.g. equally weighted variables calculated on the back of an envelope, can be as effective as sophisticated multi-variable regressions, at least enough to outweigh unaided expert judgment.[15] These heuristics can form a sort of assistive intuition, not unlike rules-of-thumb in architecture and engineering—simplified guides used to make good-enough predictions appropriate in most circumstance. With these aides, expert judgment based on quick-thinking intuition can be sufficient for stages of work where decisions need to be made quickly or iteratively. When sufficient information and time are available, higher-fidelity methods take over. However, experts also recognize unique aspects of each situation that invalidate the rule of thumb, so expert judgement includes understanding the limits and reliability of heuristics in each situation, in other words applying system 2 thinking to the act of system 1 thinking. Kahneman's conclusion here is important: "Whether professionals have a chance to develop intuitive expertise depends essentially on the quality and speed of feedback, as well as on sufficient opportunity to practice."[16] This seems well aligned with the methods of studio-based education.

Discussing the limits of technical rationality, Donald Schön suggests professional practice in the twentieth century emphasized problem solving at the expense of problem setting—"the process by which we define the decision to be made, the ends to be achieved, the means which may be chosen"[17]—thus inhibiting the application of expert knowledge to situations of uncertainty. Unlike solving defined problems, future-looking design is inherently uncertain. Drawing from settings including design studios, Schön's seminal book about education argues that iteration, feedback, and reflection-in-action can develop a form of expertise applicable the messy unpredictable reality of the world.[18] Extending this argument suggests teaching quantitative tools in the context of uncertainty could be more effective than teaching them in isolation. That approach aligns with Edward Allen's long-standing concern about the dominance of quantitative analysis in architectural education, poetically expressed as "make math the servant, not the master." Allen also believed in the importance of quick thinking in early stages of projects, and especially in paying attention to "that part of the mind that works by itself and spits out crazy ideas without warning."[19] Allen credits that form of thinking with his creation of one of the most useful rule-of-thumb handbooks in architectural education, *The Architect's Studio Companion*, which "reduces complex engineering and building code information to simple formal and spatial approximations that are readily incorporated into design explorations."[20] Similarly, in LCA, The *reliability* of assessment depends on an accurate inventory and the quality of the impact data in steps 2&3 both daunting and time consuming tasks. However, *significance* emerges through the Scope Definition and Interpretation which bookend the process,[21] and are perhaps amenable to lower-fidelity approaches.

METHOD

This study took place in the integrative design studio, a summative experience which serves as the capstone for the undergraduate Bachelor of Science degree, and immediately proceeds the final synthesis year for students pursuing Master of Architecture degree. Students in the studio enroll in a co-requisite technology course which aligns readings, lectures, and discussions to inform and reflect upon the learning happening in studio. Work from these two courses demonstrates the NAAB student criteria 5 and 6 by synthesizing multifarious considerations (e.g. measurable environmental impacts) and then making design decisions that integrate multiple building systems (e.g. measurable performance).[22] The shared schedule is organized into three phases beginning with the most durable and known elements of structure and situation, followed by the constantly evolving enclosure and ecology, and concluding with the changeable and uncertain active systems and human use. Organizing the design process from the enduring to the ephemeral helps students prioritize decisions and manage the iterative refinement to develop buildings that adapt graciously for future change.

Spring 2021 included three sections of about 10 students, engaging with their instructor and each other primarily though synchronous digital modality due to the COVID-19 pandemic. This modality reduced the extensive and intensive physical modeling that hitherto characterized the studio, offering an opportunity to intentionally broaden the definition of *modeling*, and to explicitly embrace the idea of synthesizing quantitative performance to inform integrated design. In addition to the LCA described here students also simulated the operation of passive and active comfort systems. Yet all these models, like their chipboard predecessors, exist in service of integrative design.

The Life Cycle assignment occurred in week four of the semester, and faculty defined a narrow scope:

(1) Students analyzed the site, selected a primary construction system, and developed a structural pattern on site considering code and zoning limitations; site and building circulation; and orientation and massing, although not enclosure or building services.

(2) As a guest in the corequisite course, an LCA expert introduced Life Cycle Assessment concepts, as well as some methods and limitations. Although the lecture covered the wide array of

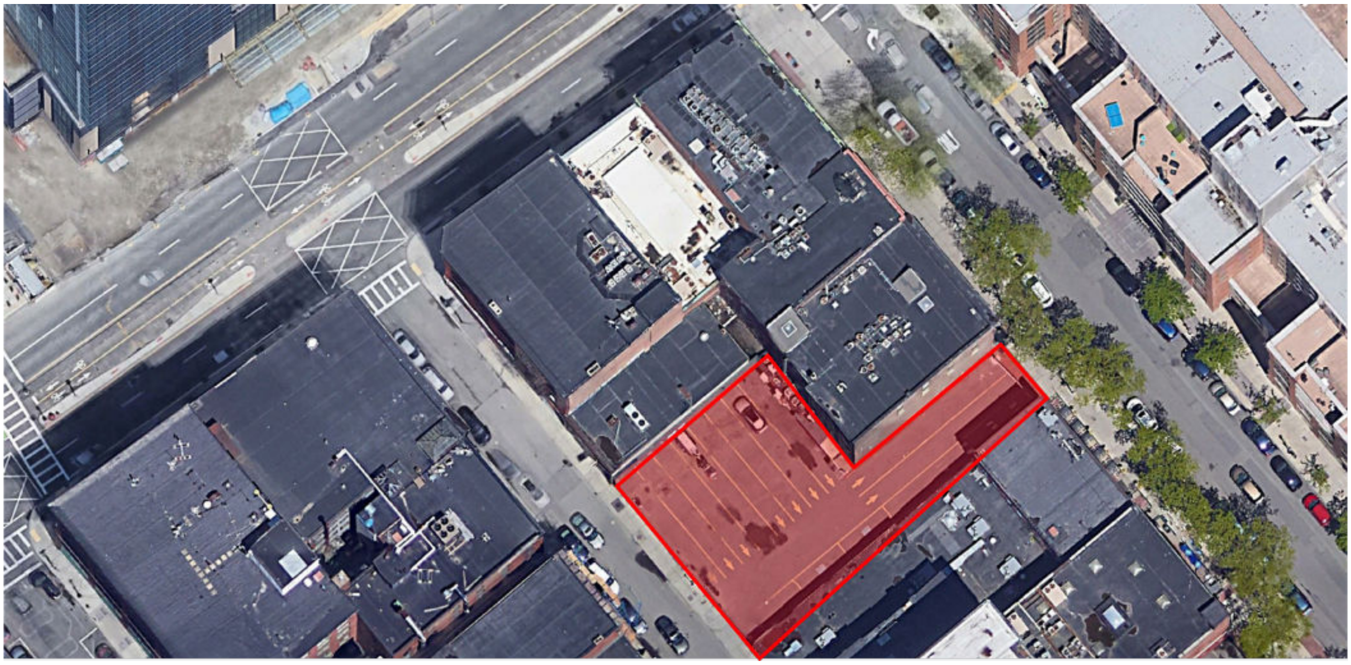


Figure 1. Block-scale map showing site boundry and context.

possible environmental impacts to consider, the assignment defined a narrow scope focused on the contribution to climate change from constructing (but not operating) the building. It introduced a metric of embodied carbon intensity, measured in terms of the mass of carbon dioxide that would have equivalent Global Warming Potential (GWP), divided by floor area (kg CO_2eq/m^2).

(3) Students used software tools (and accompanying learning resources) from the Athena Sustainable Materials Institute, to quantify materials, choosing the spreadsheet-based Athena *EcoCalculator* or the fully-featured *Impact Estimator* software. For impact assessment, both tools use Athena's comprehensive life cycle database of construction materials. While obviously limited to the available materials and locations, the database is building-specific and regionally responsive within North America, and research for manual impact

(4) The studio faculty developed step-by-step tutorial to support a quick start, and individual instructors walked through the assignment and defined a baseline at the start of studio class, and then students worked collaboratively to create the "typical" baseline[23] as well as developing their own models. The zoning of the 7,000 ft² (650 m²) urban infill site (figure 1) allowed heights of 80 feet and FAR of 6 as of right, with possible increases to 100 feet and FAR of 7. The baseline covers the site using construction systems typical in this area: namely a six story steel frame with 12-foot (3.7 m) floor-to-floor heights, a roughly 25-foot (7.6 m) spans, a concrete foundation, and two concrete cores. The baseline structure (without enclosure) showed a GWP of 170-200 kg CO_2e/m^2.

(5) Students entered their total GWP results, as well as construction type and building area into a shared spreadsheet (see table 1) to compare the embodied carbon intensity

(6) Sections reconvened at the conclusion of that day's class to compare initial results with the baseline and each other, interpret the findings, and address questions as students worked that week to refine the analysis for their first phase presentation.

(7) Students continued to use these models to recalculate embodied carbon at each phase of the studio, in response to adjustments and refinements in the design.

In addition to the baseline of "typical" construction, the studio adopted 500 kg CO_2e/m^2 of embodied carbon as a maximum threshold for construction and materials from version four of The International Living Futures Institute's Living Building Challenge standard[24] and the Carbon Leadership Forum's study to benchmark the carbon embodied in buildings.[25]

RESULTS

For numeric results this paper analyzes students' LCA results collected in the shared spreadsheets (step 5) and values submitted in the design documentation at each phase (step 7), along with a parallel set of models constructed by faculty. To illuminate attitudes and experiences, this paper draws from students' weekly written reflections on their learning and design process submitted in the corequisite course. The discussion emerges from faculty's notes and reflections on teaching, as well as the comments and questions of guest critics and consultants who engaged with projects throughout the semester. Taken together,

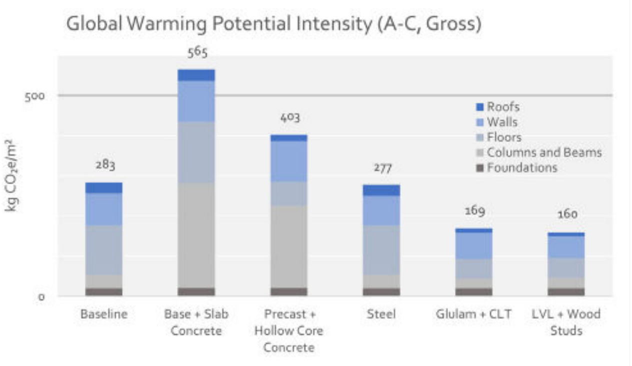


Figure 2. Chart of global warming potential of the baseline building constructed with various structural systems

these data paint a rich picture that while not a representative sample,illustrate the breadth of student outcomes in using LCA.

Research and practice generally compare alternatives by varying one parameter at a time, as in figure 2 comparing impacts of the same building geometry with different structural materials. Conversely, the diversity of project geometries and construction systems (although similar in scale and use) across studio shown in table 1 and figure 4 demands deep engagement with and nuanced understanding of complex assumptions, results, and exceptions. Fostering these critical conversations across projects as well as within them challenged students' assumptions (e.g. wood is always good), expanded projects to consider broader concerns of industrial ecology (e.g. harvesting practices), and elucidated performance trade-offs (e.g. life safety).

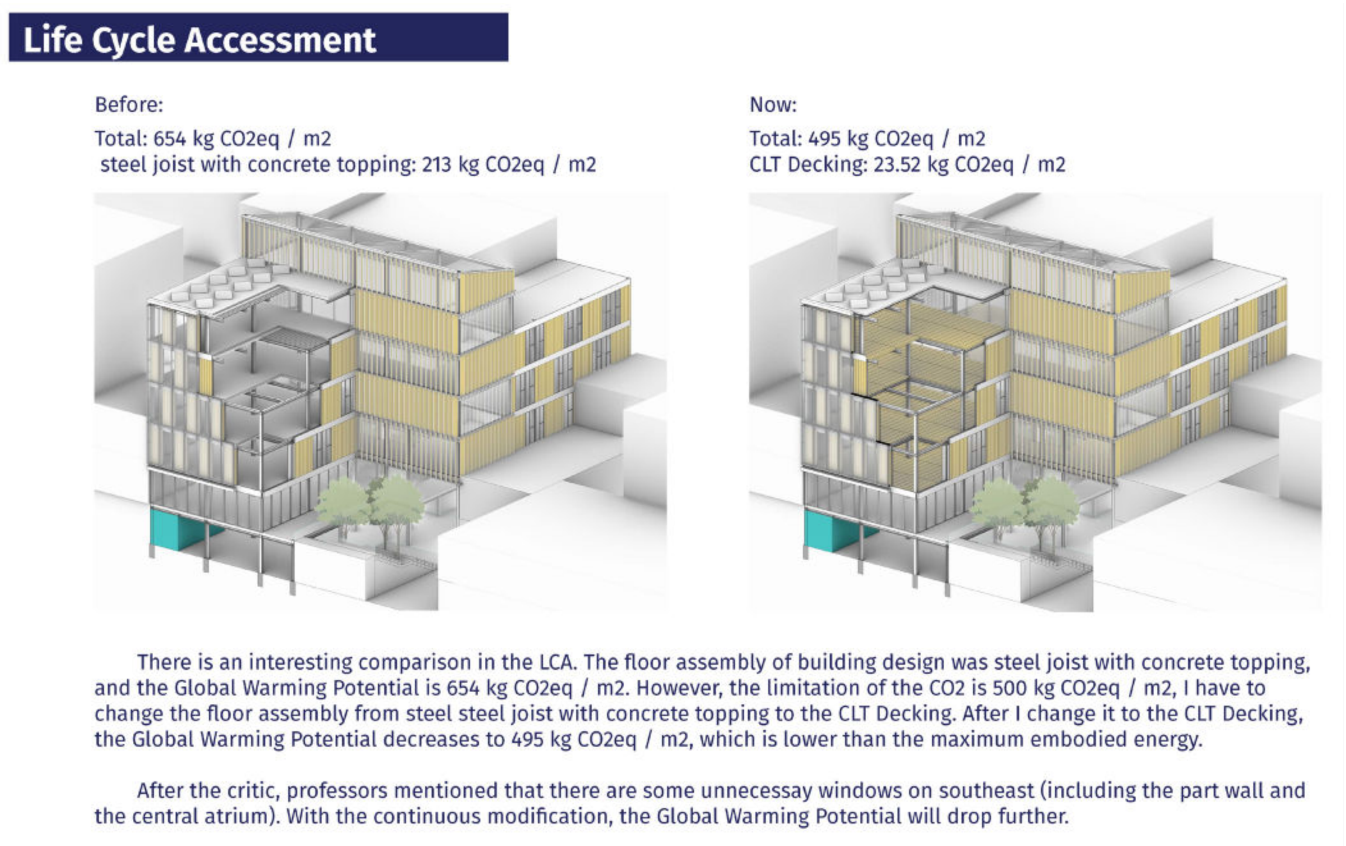
Xavier (all names have been anonymized) had a simple but profound realization about errors after using incorrect units to input values yielded results much larger than all others. Not only did the comparison among student projects reveal an absolute value approximately 2500 times greater than the next-largest total, this difference also dwarfed the variation among other projects, which ranged between 1.5 to 25 times smaller than that same next-largest number (see Table 1). The simple mistake offers multiple lessons: in terms of modeling skills, simply seeing the results together confronted students with the possibility of error while encouraging them to look deeper at the process and their assumptions. Further, even for novices with little domain knowledge, the presence of an obvious outlier in the comparison invites students to immediately begin building possible explanatory theories and thus find meaning in all the observed differences. The diversity of projects across the studio exposes students to much greater breadth than a single project could find by serially testing alternatives. Finally, although even a single comparison against a standard or a baseline model might indicate whether a result is reasonable or realistic, by connecting the range of results possible to the breadth of design alternatives considered, the comparison among projects become the basis to imagine subsequent iterations by hypothesizing design changes that might reduce impacts.

Yvonne decided early in the semester to use a steel braced frame with concrete slab on deck to become more familiar with a common construction system, and ended up revealing the critical importance of system selection. The first phase LCA showed this design expended nearly half of the carbon budget on structure alone (see figure 3 left). A similar choice to use a "typical" all glass curtain wall as the enclosure immediately pushed the embodied carbon far above the carbon budget, and indeed even above than the code-minimum baseline. The realization prompted various revisions tweaking the systems: first reducing the area of glass on the curtain wall, then changing systems to a rain screen with punched windows, and then replacing the metal rain screen with wood siding. However, none of these swaps offered the scale of reductions required. At last, an innovative case study presentation about a recent dormitory building designed by NADAA at Rhode Island School of Design,[26] inspired Yvonne to reconsider the structural design. Swapping the concrete slabs for Cross Laminated Timber (CLT) brought the project much closer to the carbon budget (Figure 3). This experience offers evidence of both commendable persistence in striving to make a design work and remarkable willingness to revisit early decisions in light of new knowledge. In prior years that kind of mid-semester structural change in the was virtually unheard of, and generally a response to frustration rather than consideration. Naturally, this change does not necessarily prove Yvonne cared about carbon, only that the seemingly arbitrary constraint forced creative reconsideration of the project and successfully challenged normative assumptions.

Aaron evinced a deep faith in the promise of LCA as a process to drive design, writing at the conclusion of the first phase that "Remaining intentional in using carbon-sensitive materials at every step of material specification can yield new solutions to structural requirements." The design reflected this carbon-focus not only through selection of heavy timber as structure

Name	Area (m²)	GWP (kg CO₂e)	Intensity (kg CO₂e/m²)
Xavier	2,796	1,890,110,000	676,008.2
Alice	2,624	609,000	232.0
Yvonne	1,672	460,000	275.1
April	2,235	418,000	187.0
James	2,230	332,464	149.1
Jeffery	2,245	118,000	52.6
Mary	1,951	45,400	23.3
Christopher	2,431	26,110	10.7
Jane	1,867	-	-

Table 1. One section's LCA results after the first day workshop. Note the large difference caused by an error in Xavier's units.



Life Cycle Accessment

Before:

Total: 654 kg CO2eq / m2

steel joist with concrete topping: 213 kg CO2eq / m2

Now:

Total: 495 kg CO2eq / m2

CLT Decking: 23.52 kg CO2eq / m2

There is an interesting comparison in the LCA. The floor assembly of building design was steel joist with concrete topping, and the Global Warming Potential is 654 kg CO2eq / m2. However, the limitation of the CO2 is 500 kg CO2eq / m2, I have to change the floor assembly from steel steel joist with concrete topping to the CLT Decking. After I change it to the CLT Decking, the Global Warming Potential decreases to 495 kg CO2eq / m2, which is lower than the maximum embodied energy.

After the critic, professors mentioned that there are some unnecessay windows on southeast (including the part wall and the central atrium). With the continuous modification, the Global Warming Potential will drop further.

Figure 3. Exerpt from Yvonne’s documentation showing the reduction in GWP by changing the floor assembly from steel (left) to CLT (right)

but an almost single-minded effort to use wood everywhere. Enabled and perhaps encouraged by the seductive precision and seemingly objective authority of quantitative analysis, Aaron embraced the LCA modeling to the point that minimizing embodied carbon became an ideology dominating all other aspects of design. Reflecting on a class discussion about adapting to multiple future uses, Aaron focused on how LCA accounts for future change, writing, “One piece that I felt was mostly missing from this discussion was the engagement with the inevitable future of demolition, no matter how adaptable a building is… I think we should also engage with deconstruction and framing reuse through a capitalist sense.” Perhaps this claim also reflects Aaron’s desire to include stage D, which tabulates the benefits and loads beyond the end of the building life, because accounting for the (potential) benefits of sequestration or fuel use push the GWP of a wood design into low or even negative numbers! (See figure x). Unfortunately, this striking model output did not prompt further interrogation or skepticism about the cause, meaning, or veracity. This deterministic use of LCA—striving for the smallest number as necessarily best—foundered in the final week of the semester with the realization that the presence of wood studs throughout the building made it type V, rather than type IV construction, and that life safety demanded reducing the size below the project brief, or the changes to materials and their calculated impact. In spite, or perhaps because of the late realization, the experience presented a powerful lesson about balancing multiple, sometimes conflicting objectives in integrated design. It is easy to imagine the converse case, an all-concrete design readily satisfying the code requirements but without regard for the embodied carbon.

Alice chose a concrete structure and thanks to LCA dived more deeply than anyone expected into revealing the importance of materials, and the challenge of integrating novel research in design. The initial robust and heavy building design featured long-span precast floors and hollow, cast-in-place concrete perimeter columns for vertical distribution of services, but the LCA of the structure alone exceeded the carbon budget. Looking for ways to meet the budget without changing the design, Alice hoped that Alternative Cementitious Materials (ACM) would reduce the impact of concrete, but found it difficult to demonstrate through quantitative analysis. Reflecting after the second phase, Alice shared an ambition to fix the numbers by improving materials, writing “Some research was done on…a less carbon intensive concrete…” adding that, “Actual data for these types of products proved challenging to find.” This example points to the range of possibilities when novices confront a frustrating lack of data: it may stem only from the limits of their knowledge and method of searching; sometimes it indicates a developing idea is possible although not yet matured to widespread documentation. However, the absence of evidence might also mean there is no evidence or support. Teasing out legitimate innovations from

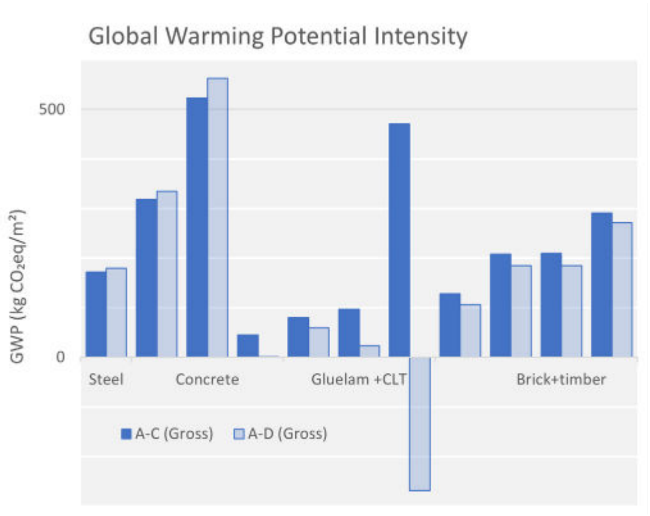


Figure 4 Chart of Global Warming Potential of students in one section. Students are grouped by by construction type. Dark solid bars on the left show the A-C life cycle stages while the light, translucent bars on the right show the effect of extending the accounting beyond building's life (stage D). Note Aaron's design fifth from right, which changes from the second largest at 470 to the the lowest at -268 CO_2e/m^2.

handwaving and vaporware demand significant effort for students with limited research skills and limited time in the context of the studio. Eventually architecture projects require the student to focus on multiple things, and this experience illustrates the challenge integrating novel materials and methods in an effort to "preserve" a particular design. Ultimately, Alice proposed that adding wood infill panels as enclosure would sequester enough emissions to offset the impacts from the concrete, but neglected to consider weathering, decomposition, and replacement, perhaps the relatively short-lived envelope will release any sequestered carbon again in a few short years. The lessons in this case emerged from inspiring questions, identifying conceptual directions that may move the performance of the project in the right direction.

Andrew also worked through multiple iterations of the design, dutifully performing the life cycle assessment of each revision and reporting the numeric results, but without affecting the next design in any discernible way. The early structure used cast-in-place concrete, but cycled through tilt-up, precast, steel, and eventually back to cast-in-place with some adjustments in structural pattern and building size. Without endorsing the approach of responding to each critique with wholesale revisions, Andrew's willingness to change the design presented a learning opportunity in which life cycle assessments become one metric to compare different approaches, a tool to ask and answer questions about design alternatives. Unfortunately, that learning depends on students using modeling to ask an answerable, meaningful question, rather than as a results-focused mechanical plug-and-chug. Incorporating simulation into part of iterative process requires open-mindedness, not mere willingness to change, but mental curiosity about why and how to change and what they mean: a process of thinking not merely doing. The LCA assignment offered an opportunity for learning, not a guarantee for everybody. It eventually became clear that the LCA was not helping Andrew advance course learning objectives of integration and synthesis, so the faculty prioritized developing other architectural knowledge and skills.

Anne struggled with the complexity of an integrated and comprehensive design; and rather than adding valuable insight and nuance to design decisions, the demand for life cycle impacts merely added complications, and a burden of extra work. At the time of the LCA assignment, Anne's design consisted of a Byzantine mixture of masonry, concrete and heavy timber ripe with possibilities to learn by resolving the structural, circulation, life safety, and enclosure challenges. Although Anne's subsequent work paid lip service to considerations of materials and impacts—writing at one point that "The reality of the carbon intensity of brick has been looming overhead the entire semester"—Anne only used quantitative LCA during that first day's workshop. Merely entering the labyrinthine design into the LCA tool required an intricate process of measuring the volume of various assemblies level by level, and yet that process elided the conceptual difficulty with modeling. Just as masses of brick can float in a digital model with no path the ground, the LCA model accepts any quantity of any material: the model is perfectly logical, an perfectly stupid. Unlike physical models, analytical models like LCA do not inherently constrain; they may enable nuanced consideration, but alone cannot resolve complications or impose limits like gravity or space. Unfortunately, Anne was unwilling to disentangle the design in response to analysis or critique and instead deployed ever greater effort in modeling, drawing, and writing to justify decisions after the fact, rather than inform them. The remainder of the semester necessitated frequent faculty intervention—what Anne described with some resentment as "divine interventions"—to cut these Gordian knots and ensure the complexity of synthetic architecture presented desirable rather than insurmountable difficulty.[27]

DISCUSSION

It is obviously impossible to extrapolate far from a handful of case studies or a single course, and certainly the COVID-19 Pandemic made this an unusual year, so one interpretation sees the LCA assignment simply reflecting and reinforcing each student's circumstances and trajectory. Xavier made mistakes and learned from them thanks to comparisons; constraints prompted Yvonne to reconsider design assumptions; Aaron's narrow focus dominated other concerns; Alice tried to resolve the LCA within the context of concrete by finding a miracle mixture; Andrew plugged away uncritically at requirements; and Anne was overwhelmed by additional complexity. Even these close examinations show that LCA foregrounded the synthesis of conflicting design requirements, for example the timber projects met the carbon benchmark, but required careful attention to satisfy code and life safety provisions, while for concrete structures the reverse was true. LCA was a means rather than end of the course so having every student arrive at the same place is not important, and perhaps the different outcomes show students taking from this assignment what they needed and were ready to learn.

That said, considering the experiences in aggregate reveals some common themes. First, students recognized the connection between their design decisions and the calculated emissions. While not every individual took responsibility for this connection or used it as a design tool, comparing multiple projects employing diverse structural systems helped students identify errors and grow familiar with relative scales of impacts. Furthermore, most students embraced, or at least accepted this agency and attempted intentional changes, perhaps because of the benchmark. Codes and benchmarks enforce changing societal values, and so can ossify into unthinking habits[28] but in this instance, the arbitrary inflexibility of 500 kg CO_2e/m^2 served as a budget, inspiring iterative testing, hybridization, and refinement of designs, and prompting some convergence across the studio as low embodied energy numbers offered design freedom to trade increased impacts for affordances elsewhere, while high numbers forced creative reductions. In at least some instances, the reciprocal understanding of standards and projects drove a process of sense-making that might be the path towards wisdom.

CONCLUSION AND FUTURE WORK

The teaching team found this pilot a qualified success: for many students, the LCA exercise expanded the array of criteria to synthesize and the quantitative analysis supported systematic integrated design. LCA becomes an undesirable difficulty when projects are insufficiently developed to model and when students are not prepared to interrogate their designs with data. To address this situation in the future we intend to try a low-stakes, highly-simplified shoe-box model exercise, although worry the lack or relevance to design. That said, the charette-like workshop helped overcome student concerns about learning new software and virtually every student produced a model in a single class period. Based on the data available, LCA tasks requiring collective effort like scope definition, baseline development, and the first day's comparison seemed to result in authentic learning. The subsequent design decisions and integration might benefit from similarly collaborative exercises in interpreting results and particularly modeling assumptions and data limitations, for example complicating the "wood is good" narrative with discussions about length of sequestration and sustainable forestry. Limitations in available data and tools can inhibit simulation of novel materials and techniques: perhaps access to an expert consultant could assist students in finding meaningful workarounds to support their synthesis. This experience leads us to believe that experience with quantitative and comparative methods can help students develop situated knowledge to support integrated design, and eager to continue exploring these opportunities together.

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