Embodied and Operational Carbon Analysis: A Grasshopper-Based Method for Visually Comparing Impacts of Material Choices

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This paper aims to describe and evaluate a parametric method for enabling embodied carbon analysis early in architectural design. The method utilizes Grasshopper, within Rhino, to convert volumes of modeled materials into equivalent volumes of carbon dioxide, providing a means to visualize and compare embodied carbon impacts. As described here, the parametric method is an extension of an earlier method developed within a graduate-level architecture design studio taught by authors Mike Christenson and Malini Srivastava, focused on renovating an existing building. The studio aimed to influence students' awareness and consideration of embodied carbon impacts in their design processes. Author Robert Gay, a student in the studio, proposed an extension to the original method, increasing its relevance to early design decisions informed by awareness of embodied carbon impacts. The paper provides details on the extended method and its implementation, identifies limitations, and proposes specific enhancements.

INTRODUCTION

This paper proposes a parametric method for embedding embodied carbon analysis into the early stages of architectural design. The method is an extended version of an earlier parametric method defined by Mike Christenson and Malini Srivastava, offered in a graduate-level design studio under their instruction. That earlier parametric method will be briefly described in this paper, as a basis for discussing the extensions made to that method by graduate student Robert Gay.

Christenson and Srivastava, faculty members in the School of Architecture at the University of Minnesota, instructed a professional graduate design studio in 2023 that introduced students to questions of embodied-carbon analysis.[1] In an effort to incentivize and enable the graduate students to consider embodied carbon and material issues early in the design process, Christenson and Srivastava introduced the students to a method for representing embodied carbon using Grasshopper, a graphical algorithm editor running within Rhino.[2] This parametric Studio Method was built upon comparative analysis of volumes within a Rhino model. The method was designed to estimate per-material "weights" for comparison, promoting early-stage awareness of embodied carbon.

Robert Gay, a graduate student enrolled in the studio, extended the studio method to compare embodied carbon directly using material embodied carbon data. In this paper, Robert's Method is described as enabling more detailed comparison than was possible with the original studio method. Robert's Method makes it possible for students to compare embodied carbon directly rather than through a potentially oblique series of equivalences. This maintains parity with the Rhino digital modeling environment while enabling embodied carbon analysis early in the design process.

BACKGROUND AND RELEVANT LITERATURE

IIn the context of the work described here, "embodied carbon" refers to the comprehensive measurement of carbon equivalent (CO2e) emissions associated with all stages of a building's life cycle. This includes the building's production, construction, operations (excluding utilities), and eventual demolition and disposal.[3] Notably, embodied carbon constitutes a significant proportion of the global carbon emissions stemming from existing buildings, estimated to vary from 25% to 75% of overall emissions.[4] Pursuing reductions in embodied carbon may involve, for example, innovative approaches to carbon sequestration or the repurposing of existing buildings as resources.[5]

It is well established that considering sustainable solutions like reducing embodied and operational carbon early in the design process improves design outcomes.[6] Students and practitioners benefit from having access to appropriate tools for implementing embodied-carbon analysis early.[7] Digital tools in particular have an important role to play in embodied carbon analysis, particularly in the early stages of design.[8] Parametric tools, including Grasshopper, can highlight the impact of relevant geometric and material variables, specifically embodied energy and operational costs, while increasing awareness of the potential effects of interacting design and material decisions.[9] Nevertheless, Grasshopper-based methods may be best suited for small-scale problems with less complex models.[10]

Yet, current mainstream digital tools for analyzing embodied carbon, such as Tally and OneClick LCA,[11] have significant limitations. While Tally integrates well within the Revit environment, recognizing specific building elements and materials, it is limited by its own material databases and somewhat lacking in flexibility.[12] Also, because Tally operates with Revit, it establishes a limitation for users, e. g., users who do not rely on Revit for early-stage design.[13] OneClick LCA allows a wider range of materials through international databases and EPDs, although its results can vary based on calculation methods.[14] OneClick LCA also allows a wider range of integrations, including both Revit and Rhino.[15]

The now deprecated tool Athena Impact Estimator[16] functioned by performing LCA analysis on buildings by defining building assemblies, potentially limiting its usefulness in early-stage design decisions. Athena Impact Estimator relied on an extensive North American material database for whole-building assessment, which could certainly be useful in a specific geographic context even as it constitutes a major limit on the tool.[17] BeOPT software identifies cost-effective efficiency measures to reach "zero net energy" homes.[18] The software evaluates both new and existing residential buildings and allows users to compare optimization solutions to reference buildings.[19] The software's major limitation concerns its design space and available objective functions, i. e., that it does not address larger commercial or institutional buildings.[20]

PEDAGOGICAL CONTEXT

The work described here began within a semester-long design studio in the professional Master of Architecture (M. Arch.) program at The University of Minnesota.[21] The studio project involved transforming Nolte Center, a 1936 three-story building on the University of Minnesota campus in Minneapolis, MN, with potential for a cold climate courtyard. Students could choose to retain the existing program of academic offices, classrooms, and study spaces, or they could propose alternatives.

Instructors Christenson and Srivastava organized the studio to satisfy two sets of learning goals aligned with relevant program-accreditation criteria. First, in their proposals to transform Nolte Center, students developed integrated design skills, gaining the ability to make architectural design decisions considering building systems, environmental controls, safety systems, and measurable performance outcomes. Second, students increased their understanding of built environments' impacts on human health, safety, and welfare, while learning relevant regulatory contexts.[22]

The studio was structured in two modules. In the first half of the semester, the "Net Positive Design" module focused on strategies for buildings to produce more energy than they consume, aided by iterative energy modeling. The Net Positive Design module, initially offered as an independent half-semester studio, was originally introduced at our institution by our colleagues Mary Guzowski and Richard Graves.[23] The module's approach was informed by prior research in the area,[24] and is compatible with strategies such as biophilic design in pursuit of overall positive impacts.[25] The second-half module, "Integrated Design," emphasized the coordination of building systems, envelope, structures, and performance factors. Students were expected to synthesize these technical elements in their architectural design proposals.

A major emphasis was placed on embodied carbon analysis throughout both of the semester's modules. In this overall context, the existing building was framed as a repository of embodied energy and material. Students were asked to position their proposals relative to one of three strategic approaches: reincarnation, which involved completely dismantling the current structure and reconstructing it using the same materials; reconfiguration, which involved adding new volume either within the existing building or on top of it; and as-is, which involved maintaining the physical fabric of the existing building while effecting transformations in its operation or in the behavior of occupants.

As part of the studio's emphasis on embodied carbon analysis, students were asked to assess the embodied carbon impacts of their design proposals. The instructors (Christenson and Srivastava) proposed a parametric method involving Grasshopper, making it possible for students to assess their design decisions on the basis of embodied-carbon equivalent.[26] For example, students pursuing a reincarnation strategy could assess the total embodied carbon represented in material volumes. Students exploring reconfiguration strategies could calculate the embodied carbon impacts of their proposed changes relative to the existing conditions. Alongside the use of the parametric method, students also engaged a physical model-making exercise in which they measured the physical weight of iterative design models.[27] Through these parallel exercises analyzing material volumes, students were able to assess and compare embodied carbon for different design approaches. The visualization enabled by the Studio Method allowed them to see the carbon impacts of their choices.

Both of the exercises (the parametric Grasshopper method and the physical model-making exercise) aimed to raise awareness about material decisions, rather than precisely calculate total carbon. Students prepared semester-long journals in which they wrote about their design decision-making processes, and these journals provided insight into the relevance of the embodied-carbon exercises, as we describe in our Conclusions section.

METHODS

As discussed above, Christenson and Srivastava introduced a Grasshopper-based method in the studio, for the purpose of estimating and comparing embodied carbon of modeled material volumes. The method enabled students to visualize carbon impacts of their design choices at various stages of design. Their method, described more fully elsewhere,[28] forms the basis for Robert's Method that is the focus of this paper (Figure 1). Rhino

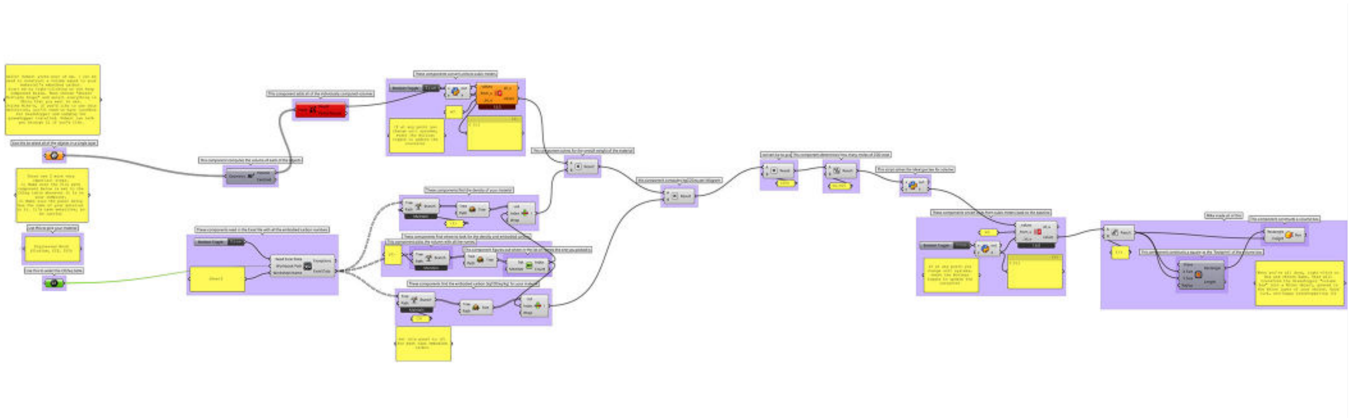

Figure 1. The Extended Method Grasshopper script. Image: Authors.

models for use with either method must be constructed with entities organized into layers representing building materials such as concrete, brick, stone, and glass. Two conditions necessarily apply to viable models: first, the modeled entities must consist of closed polysurfaces with computable volumes; second, each polysurface is assigned to a material layer representing a material with a known unit weight. Grasshopper considers a closed polysurface as a boundary representation (BREP), which may be considered a mathematical model of a solid object composed of joined surfaces. BREPs with non-zero volumes enable geometric queries such as (in this case) volume calculation. Applied to a Rhino model organized by material layers, the Studio Method calculates the total aggregated volume of the closed polysurfaces in each layer, constructs representative cubes as BREPs, and organizes the cubes for visual comparison

Development of Robert's Method began as a way to more easily conceptualize a quantity of material as its equivalent amount of embodied carbon. This was most useful when comparing functional equivalents like glass, floor materials, or insulation. This enabled additional and more detailed comparisons between materials within the scope of the student project (the renovation of Nolte Center). Developing the Grasshopper script required a method to convert a volume of material into a volume of embodied carbon, similar to the original script, which converts a series of BREPs into one BREP with an equivalent volume to the previous group.

To create the volume, the Grasshopper plugin Lunchbox was used to import embodied carbon data via Microsoft Excel and convert it into a data tree, from which the data can be extracted and used (Figure 2). After Lunchbox components read the Excel file as a data tree, the tree is split into three different streams, one containing the material names, one containing the corresponding densities in kilograms per cubic meter, and one containing the corresponding embodied carbon values per kilogram. The script uses Grasshopper tree management nodes to find the index of the proffered material, then find the corresponding density and embodied carbon values in the other two data streams, before the data is sent to the appropriate point in the embodied carbon calculation. Then, the script was set to sum the BREP volumes as before, use the aforementioned data to convert into an equivalent volume of embodied carbon in the form of carbon dioxide, and then create the appropriately sized BREP: a cube of equivalent volume.

To do this, the ideal gas law (pV=nRT) was utilized to create a volume of the calculated embodied carbon at room temperature and pressure (Figure 3). Namely, the number of moles of CO2 was substituted for the variable n, and the remaining constants (p, R, and T) were set to room temperature (in this case 20 ▯), the ideal gas constant (Boltzmann's constant * Avogadro's constant: equal to ~8.1345 joules per Kelvin per mole), and 1 atmosphere of pressure (101325 pascals). This equation was implemented using this simple Python script.

```
import rhinoscriptsyntax as rs

def gas_law(y):

    """

    (num) -> float

    Solve ideal gas law in terms of volume from the number of moles of CO2.          """

    r=8.3145

    #Ideal gas constant [Avogadro's number * Boltzmann's constant

    T=20

    #Room temperature in degrees Celsius

    P=101325
```

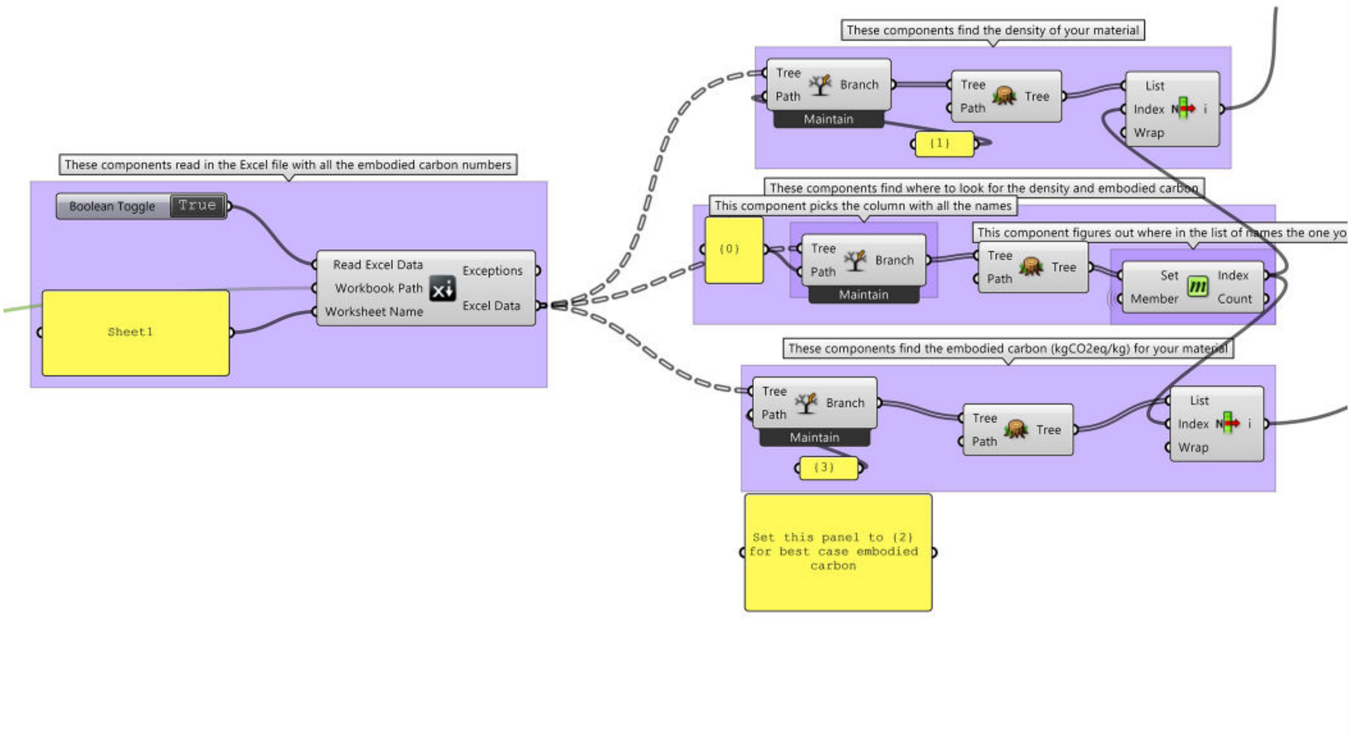

Figure 2. Detail of Extended Method Grasshopper script (data lookup). Image: Authors.

```
    #Atmospheric pressure in Pascals

    if x >= 0:

    return (y*r*T)/P

    else:

    return "invalid input"

    #Solve ideal gas law in terms of volume

a=gas_law(x)
```

One other consistent issue in this process required a custom solution: different students and instructors in the studio used different units for their 3D models. While this wasn't an issue for the original volume comparison, when converting from a volume to a mass and back again, unit consistency is crucial; otherwise a series of components would be required to convert density from kg/m3 to kg/ft3, etc. Converting the volume automatically to cubic meters was considered simpler and more computationally efficient. Using GhPython commands and the "Unit Convert" component from Ladybug Tools[29] a group of multiple Grasshopper nodes was assembled that automatically converted from the file's unit system, like feet, inches, or millimeters, to cubic meters, which was used for the mathematics within the script (Figure 3). The group is then run in reverse to convert the volume of CO2 back into the original unit system. The python code proceeds as follows:

```
import rhinoscriptsyntax as rs

supportedunits={2:'mm3', 4: 'm3', 5:'km3', 8:'in3', 9:'ft3', 10:'mi3'}

units=rs.UnitSystem()

if x == True:

    if units in supportedunits:

    a=supportedunits[units]

    else:

    a='unsupported unit. Please change to mm, m, km, in, ft, or mi; and then reset the Boolean toggle'
```

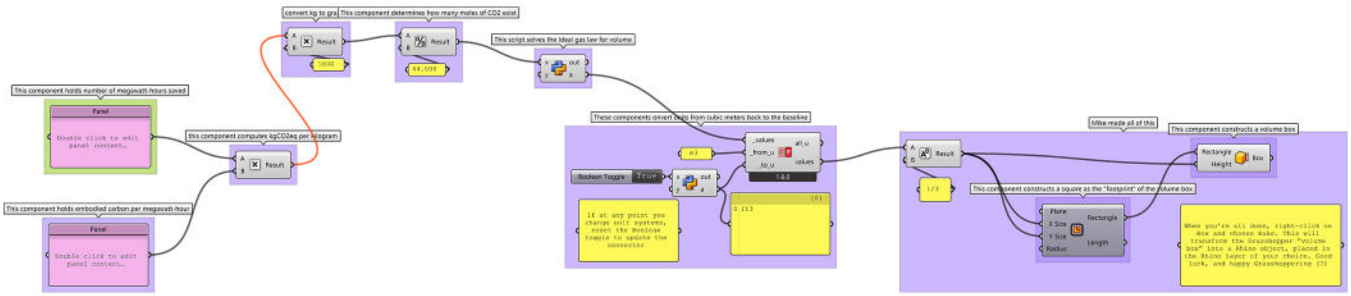

Figure 3. Detail of Extended Method Grasshopper script (unit conversion and implementation of Ideal Gas Law). Image: Authors.

```
    else:

        a='please turn the boolean toggle to True'
```

This code first checks if the Boolean toggle attached to it is set to 'True'. This is done to prevent the node from failing to update if the unit system is changed. Then, the rs.unitsystem() function checks the unit system. If the unit system is supported by the Ladybug node immediately following it, the script sets the output variable to a string that the Ladybug node can interpret to convert the volume into cubic meters for further analysis.

Later in the studio, a secondary use case for the script was discovered. During the studio process, tests were performed using Sefaira to measure the operational efficiency of the design projects as compared to the existing building. While designing the renovation to the building, a question emerged asking when/how the addition of additional material, and thus embodied carbon, was feasible, taking into account its design efficacy. For example, is there a point where replacing the windows with more energy efficient ones costs more carbon than it saves? The script was utilized to create a comparative visualization to test that hypothesis. To create the comparison, two equivalent tests were run in Sefaira: one with the null case, and one with the material change taken into account. For example, the case with the original windows was run, followed by the case run with the proposed window replacements; with all other variables left unchanged. The net change in EUI was converted to total energy use across the full square footage in units of megawatt-hours. The components of the script were then utilized with approximate data for carbon emissions associated with combined heat and power plants to convert the change in EUI to a volume of saved embodied carbon over an interval of time, typically a year. The number of megawatt-hours was linked into the script at the stage where total embodied carbon is calculated before converting it into a volume as before. This volume was used to compare the embodied carbon cost of the intervention to the operational carbon saved and gauge how appropriate it was in the context of the project.

RESULTS

The Grasshopper script and its use provided several useful outcomes. The existence of the script and the requirement for author Robert Gay to test their choices using the script influenced their design choices. For example, when their design proposed public underground space and a constructed wetland, they briefly considered using an acrylic wall to make a visual connection between the two interventions. While the script was not run on the acrylic wall, the concept was abandoned quickly. Robert's heightened awareness of embodied carbon influenced by the script triggered a discussion to remove the high embodied carbon solution prior to the script being run. The wall was replaced with a lower embodied carbon material with acrylic portholes.

The script also enabled the choice to explore multiple new insulation materials, like wood fiber, to run the script in multiple ways. The script also enabled Robert to justify the addition of significant amounts of embodied carbon using the comparison to saved embodied carbon from the script. This usage of the script required exiting the program and disconnecting nodes to make the specific calculation possible. Future work may enable the script to make these rough calculations of operational carbon easier and more intuitive. This script was also used on replacing windows to justify the use of new engineered glass units to replace the existing flat glass windows. Replacing windows makes the designer responsible for both the already committed embodied carbon of existing windows and the proposed embodied carbon of new windows, both of which must be compared against the saved embodied carbon. The initial visualizations from the script don't support this, and later work was necessary to enable this full comparison.

During final studio reviews, the analysis enabled by the script took the form of comparative visualizations (Figure 4). These visualizations prompted conversation about the impacts of embodied carbon on both the initial test project the visualizations were keyed to, as well as other nearby and related projects. The conversation was driven by the visualizations reproduced in

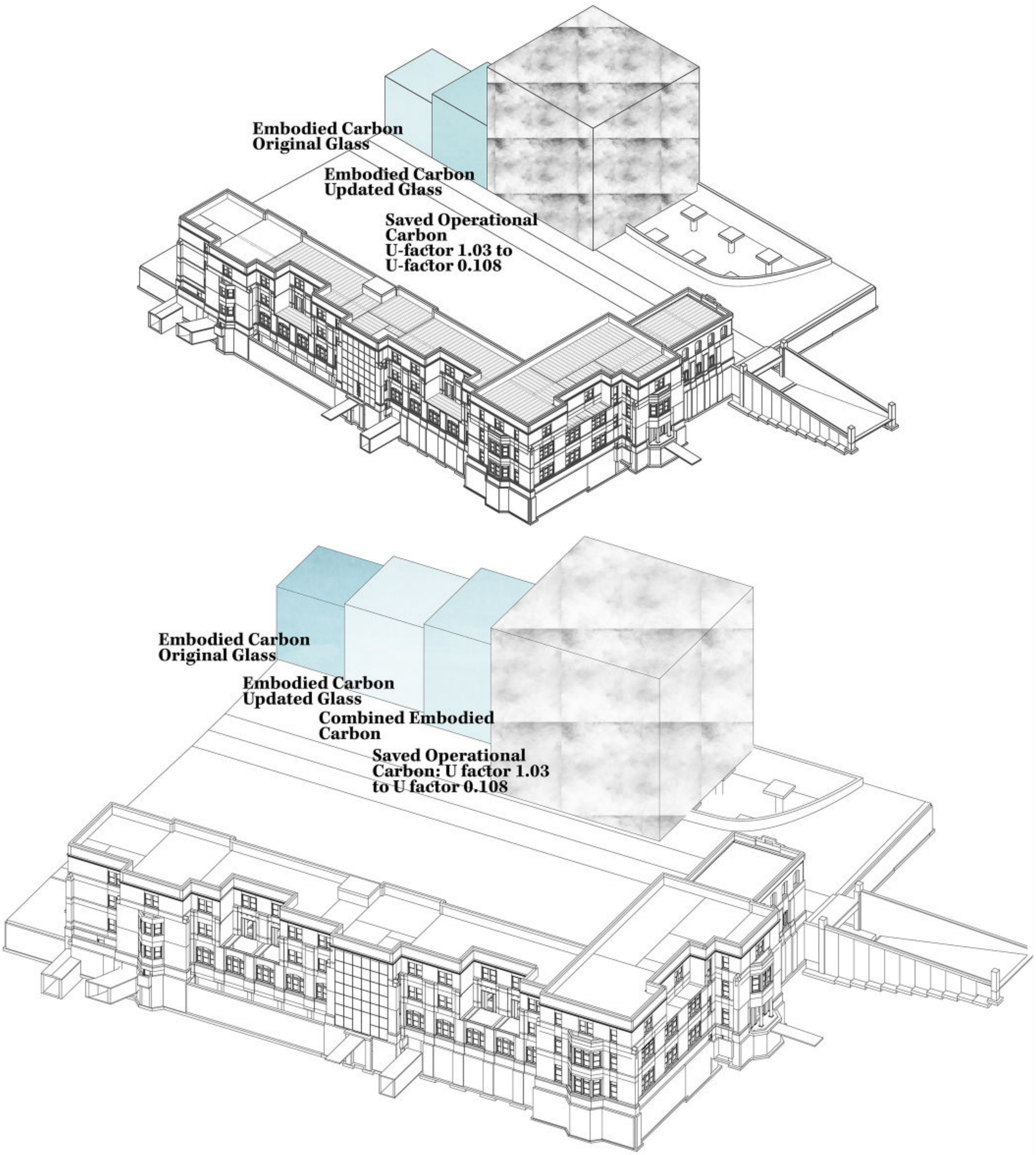

Figure 4. Top: Volume visualization of embodied carbon for Nolte Center glass options. Bottom: Volume visualization including sunk cost embodied carbon and replacement glass embodied carbon. Image: Authors.

Figure 5. Final review. Image: Authors.

Figure 4 to a degree more than anticipated. The final review involved participation from students and invited experts (Figure 5).

CONCLUSIONS AND LIMITATIONS

TRobert's Method, as described in this paper, is a useful approach for conceptualizing embodied carbon in early studio design. This parametric method provides useful visualization that can create real impacts on design processes, since students are prompted to consider embodied carbon early and often. The visualizations may impact material choices as well as discussions of material quantity for materials like glazing. For adaptive reuse projects in specific, the script may influence student choices about the degree to include or exclude existing materials from new designs due to discussions of embodied carbon. For one project, timber was specified over new masonry due to the embodied carbon cost of new masonry, despite material consistency being a desired outcome.

While the described method has performed well conceptualizing material quantities in terms of embodied carbon, the simplicity of the method comes with a necessary loss of accuracy. When comparing different insulation materials for the purpose of functional equivalencies, a point exists when the difference in R-value between different materials becomes significant. For the purpose of this method in early design stages (e. g., Schematic Design), this difference is unlikely to significantly impact the method's usefulness, but this limitation does affect how late the method remains useful into later phases (e. g., Design Development).

The script could have handled comparison with existing materials better. Future work could clarify the workflow in such a case by building in a comparison and sum function into the script. This could add the ability to run the script on multiple materials in parallel, before summing the embodied carbon at the end to demonstrate the net embodied carbon (embodied carbon sunk into the original material, plus the carbon added by each potential replacement). The script also requires external tools in order to make an effective comparison between embodied carbon and saved operational carbon. This is a similarly significant issue as the previous one, where the script is capable of modeling carefully. This enhancement would require significant work to clarify without reliance on an external tool for some time. Future work may enable parallel computation via an open-source energy simulation engine like OpenStudio/EnergyPlus[30] via a tool like Honeybee.[31] In this update to the tool, the external calculation of energy savings from the added material would be calculated by the tool itself using a Honeybee energy model constructed of the building. The model would be run in parallel on the pre-material case and post-material case before making the comparison between energy savings and operational carbon as before. This could be either compared directly or via a net difference to create a more integrated look at embodied carbon within the building. This update to the tool would require significant time and appropriate hardware to run the simulation appropriately, likely making it infeasible for the early-stage design decisions targeted in this research.

In evaluating the studio from the perspective of possible pedagogical improvements, several limitations and constructive critiques were identified. First, assessment provides opportunities in one or more of three distinct pathways. As discussed above, assessment of embodied carbon is a critical component of the studio pedagogy, and is expected to gain in importance. Second, in a traditional sense, instructors have an established need to assess student work relative to various standards and expectations, and we expect that future iterations of the studio will incorporate a stronger grading rubric relative to embodied carbon measurements. Also, student assessment of instruction should be more actively incorporated into the pedagogy, throughout the length of the semester, to enable the instructors to identify opportunities to shift rapidly in response to student needs.

From a research results perspective, future iterations of the studio could engage a more systematic study of Grasshopper's use as a customizable mechanism for assessing embodied carbon impacts. The pedagogy could evolve to challenge future students to assume a greater role in designing their own extensions to a provided script. In this way, the pedagogy could expand beyond the circumstances of the studio described here, where only a single student took on the challenge of developing the Grasshopper script as a way of understanding implications for embodied carbon. Moreover, future iterations of the studio could involve a systematic comparison among tools, such as Tally and OneClick LCA, alongside a Grasshopper-based approach. By comparing results and student experiences across different tools, a richer understanding of their respective strengths, weaknesses, and conceptual capabilities could be realized.

In summary, the work described here represents a promising approach to a developing pedagogy. We expect that future iterations of the studio, by strengthening assessment, engaging a comparative approach among different tools, and providing a thorough analysis across multiple projects, will build on the example of Robert's Method to strengthen the pedagogy and expand its reach and relevance.

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