

METHODS

Cooperative learning in design studios: a pedagogy for net-positive performance

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Abstract

Students of architecture are often inadequately prepared to address the consequences of climate change. Among the factors contributing to this, traditional design studio pedagogies tend to privilege individual ownership of projects instead of promoting cooperation and collaboration. This traditional focus on individual projects has the effect of minimizing the cognitive diversity that can be brought to bear within the development of projects, and that new knowledge is created through interactive processes based on the sharing and integration of previously unshared knowledge. A new studio pedagogy is presented in which cognitive diversity is foregrounded by means of shifting away from individual ownership of work and towards groupings of works and students. Periodic discussions focus on works grouped by thematic commonalities and re-assigned ownership based on interest, self-identified strengths (skills they can contribute or teach), or deficits (skills they need to learn), rather than authorship. Evidence from implementation reveals this process supports the creation of new knowledge in a short period of time (a 6.5-week studio) and students learn skills related to quantification of performance measures and develop capabilities to transform existing buildings to be net-positive contributors to their communities.

Practice relevance

The presented pedagogical method, entitled 'Shifting Allegiances,' is easy to replicate and flexible for customization. It does not require larger curricular or program changes and is not bound to specific content. It can be implemented by an individual instructor in a single studio section. An emphasis on shared student authorship, cooperative structures, and collaboration led to a learning process based on productive comparisons of student work. Comparisons in students' energy modeling results due to in-depth knowledge of, and participation in, their colleagues' work became second nature to the students. This led to the acquisition of new capabilities enabling students to use a variety of strategies to achieve a 70% reduction in energy demand over the current baseline; this was augmented further with the use of photovoltaics. Other aspects (water, waste, resources), selected by the students are also actively reduced to meet net-zero goals.

Keywords: architects; climate change; design studio; education; energy; pedagogy; retrofit; zero carbon

1. Introduction

As carbon emissions increase (United States Global Change Research Program 2018) and climate change continues to accelerate, professional degree programs in architecture face an increasingly urgent need to educate students in relevant content and design strategies. In attempts to meet this need, existing architectural pedagogies are often constrained by a range of traditionally grounded assumptions, for example: distinctions between studio and non-studio courses (Stevenson *et al.* 2009); complex and crowded professional curricula with little room to supply the necessary breadth of coverage (Altomonte *et al.* 2014); the failure of existing accreditation and qualification criteria to contribute to the systematic promotion of environmental sustainability (Altomonte 2009); and the lack of teaching tools for positioning integrated practice as a necessary component of sustainable curricula (Vassigh & Spiegelhalter 2014). Moreover, the work of the studio is often conditioned by asymmetrical power relations (Dutton 1987), a lack of diversity in both demographic and substantive forms (Groat & Ahrentzen 1996), particularly with respect to the composition of the faculty (Anthony 2002), and by the potentially problematic yet promising approaches to collaboration, community participation, and approaches to group work (Horner *et al.* 2016; Dunster 1990). As overall context, Groat & Wang

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(2001) discuss the complex relationships between research and design, and Kwok & Grondzik (2018) provide an essential compendium of strategies and approaches relevant to design judgment in the studio.

Specifically contributing to a failure to prepare architecture students adequately to address climate change, traditional studio pedagogies tend to focus on the design of new buildings rather than on the possibilities inherent in existing buildings (Christenson 2017). From the point of view of carbon emissions, existing buildings constitute a unique problem insofar as they are large energy consumers and carbon emitters while simultaneously being repositories of embodied carbon (Pomponi & Moncaster 2016). In this context, operational energy (OE) is defined as 'the energy consumed during the lifetime of a building after the building is occupied,' while embodied energy (EE) is 'the energy consumed in order to produce and transport building materials and install them in buildings' (Dilsiz *et al.* 2019: 1). The relationship between these broadly characterized sources of carbon emissions is far from settled, and while research strongly suggests the primary contributory effect of OE as distinct from EE (Dilsiz *et al.* 2019), precise determinations remain elusive due, in part, to methodological differences affecting comparison (Yung *et al.* 2013) and to variations in indicators, data sources, and the determination of temporal and physical boundaries (Rasmussen *et al.* 2018). Yet, despite acknowledged methodological inconsistencies, the contributory effect of EE is by no means negligible (Giordano *et al.* 2017). Elefante (2018) identifies the retrofit of existing buildings as the most effective strategy for reducing carbon emissions, and in projecting that over the next 30 years more than twice as many buildings will be renovated than newly constructed, he suggests the growing criticality of the problem. While Stein (2008) acknowledges the additional knowledge required of designers addressing existing buildings, in comparison with designing new buildings, for Lapadula and Quiroga (2012) the pedagogical value of existing buildings implicates designers' ability to transform existing conditions productively while simultaneously addressing architecture's symbolic dimension (*i.e.* the need to assign new value to existing buildings while building new meanings).

Decades of study have suggested the value of cooperative work structures in architectural pedagogy (Cuff 1989; Anthony 1991: 161; McPeck & Morthland 2010; Emam *et al.* 2019) and the detrimental effects of competition between individual students (Dutton 1987: 18–19). However, architecture studio pedagogies continue to promote a culture of individualism, manifest through individual student ownership of projects, leaving little opportunity for students to develop fluid, cooperative work structures (Vowles *et al.* 2012: 29; Koch *et al.* 2002). Traditional pedagogies grounded in sole ownership persist despite the obvious need to bring collaborative efforts to bear on the solution of complex issues such as climate change, and their impacts on processes and products of architectural design.

A key question arises: How can the pedagogy of the architecture studio productively incorporate group work to address a net-positive agenda? A case study approach was adopted for implementation and testing, allowing for several assumptions. First, the author assumed that the studio pedagogy could be developed without requiring changes to the existing professional degree curriculum as a whole. Thus, for example, relationships between the studio pedagogy and related non-studio courses (*e.g.* technology courses) were not considered as part of the pedagogical case study. Instead, pedagogical development focused on the studio's internal structure, in particular on challenging traditional assumptions of student ownership of projects, and the development of cooperative work structures. This approach builds on the author's earlier work emphasizing a cycle of individual authorship and cooperative readership/ownership (Srivastava & Christenson 2018; Srivastava 2019a, 2019b; Srivastava *et al.* 2019).

Second, as a means of introducing students to performance issues in actual buildings, and particularly carbon emissions, the studio pedagogy assigned students to analyze and retrofit an existing building. While the specific conditions of any given existing building and site are unique, drastically better performance results for existing buildings may depend on whether the project is strictly a retrofit for performance, or if functional and programmatic shifts such as typology and related occupancy are also changing simultaneously, requiring small or substantive additions.

In the studio pedagogy described here, students were required to examine passive performance variables such as existing orientation, massing, form, and the surface area-to-volume ratio with respect to prevailing light and wind conditions. Large-scale factors such as building orientation and massing were largely treated as given (*i.e.* not subject to meaningful change) in the constrained urban site. Although minor changes to building massing were permitted, these did not have a significant effect on the existing building's surface area-to-volume ratio due to physical site constraints. Given the pivotal contribution that the building skin has with respect to energy efficiency (Sadineni *et al.* 2011), and acknowledging the potential of significant performance gains due to building skin retrofit (LaFrance 2013; Balaras *et al.* 2000), the *skin* was positioned at the center of the studio pedagogy. For example, building orientation was changeable only to the extent that it involved rethinking skin configurations or transparency–opacity ratios on different surfaces. Therefore, in order to drastically reduce the size of systems in existing buildings (and therefore the OE use), the building skin as the *interface* between the controlled and uncontrolled environments was examined for its potential to achieve net-positive and resiliency goals.

Taken together, these assumptions informed a studio pedagogy, titled here 'Shifting Allegiances,' which encouraged knowledge-building based on valuing cognitive diversity (Miller *et al.* 1998) or larger numbers of differing perspectives and experiences within the studio, in order to explore more fully the solution space with greater creativity and independence (Menold & Jablokow 2019; Hastie 2019; Godwin 2017; Kress & Schar 2011). Mitchell and Nicholas (2006) establish that cognitive diversity is significantly related to the emergence of creative new knowledge in groups and is positively correlated to high levels of transactive memory and open-mindedness. Cognitive diversity is defined as the differences in knowledge, perspectives, belief, and preferences of group members. Transactive memory is the

understanding of the knowledge and skill of the various members, and open-mindedness holds that group members are free to express their perspectives and that individual, differing perspectives have value which leads to debate, cognitive confrontation, information-sharing, and enhanced understanding. Overall, the empirical findings indicate that new knowledge is created through interactive processes based on the sharing and integration of previously unshared knowledge by the integration of diverse perspectives where cognitive diversity, transactive memory, and open-mindedness are likely to impact the creativity of outcomes (Mitchell & Nicholas 2006).

2. The Net Positive Design Studio

The Net Positive Design Studio is offered in the penultimate year of a three-year professional Master of Architecture degree program at the School of Architecture, College of Design, University of Minnesota. The spring semester of the second year in the program is divided into two approximately seven-week-long modules. In the first of the two modules, the studio focuses on the integration of architectural design, environmental technology, and high-performance regenerative practice. The studio is organized into three instructor-led sections of nine to 12 students each, with each studio section addressing a unique project, but sharing an overall alignment in schedule for all-studio lectures, consultant workshops, and energy modeling training. The shared brief developed by professors Mary Guzowski and Richard Graves reads:

In [T]he Net Positive [S]tudio, architectural design integrates design excellence, beauty, and theories of architecture with the achievement of performance standards. Historically, these standards have been checklist based and focused on the built environment as being less bad rather than having positive effects. The goal of the studio is to evolve high performance design strategies, apply processes and techniques to improve performance, and redefine architectural beauty from a socioecological perspective.

Using the guiding principles of Architecture 2030¹—that achieving zero emissions from the existing building stock will require accelerating the rate and depth of energy retrofits—the two steps to achieve the goals were outlined as improvements in the energy efficiency of building operations and the generation and/or procurement of carbon-free renewable energy. The performance standard for the studio was established by Chris Wingate (MSR Design) and Pat Smith (Center for Sustainable Building Research, University of Minnesota) during two energy modeling workshops using Sefaira² software (during weeks 2 and 5), to meet a fossil fuel, greenhouse gas (GHG)-emitting, energy consumption performance standard of 70% below the regional (or country) average/median for that building type for 2019. The instructions were to achieve as low an energy-use intensity (EUI) as possible using the following strategies in the order introduced through several iterative studies:

- Applying passive strategies such as orientation, massing, size, location, proportions of building form and locations, orientation, and sizes of transparency (windows, skylights, glazed doorways, *etc.*) and opacities (walls, roofs), shading systems, and natural ventilation systems.
- Thermal properties of building envelope (*R*-values), glazing, and heating, ventilation and air-conditioning (HVAC) systems selections.
- Any deficit in reaching the target goals was met by calculating the size of a solar array system required to reach the 70% reduction.

Mang & Reed's (2015) definition of net positive (*i.e.* as buildings that add value to ecological systems that they exist within) was central to the studio's pedagogical framing. Although students were free to design for surpluses of typically quantified measures such as energy production to achieve zero energy use or positive energy production, this was not how net positive was approached in the original studio brief. Net positive was defined as having a variety of approaches in addition to OE-efficiency and energy production. For example, one of the three studio sections defined net-positive contributions in terms of biophilic approaches to wellness in addition to OE, while a second studio section focused on net-zero water systems in addition to OE.

3. Studio section

In the author's section of this studio, net positive was defined as a method of working in cooperative structures with work held in shared authorship, leading to solutions providing positive socioeconomic impacts through (1) passive strategies meeting performance goals, (2) adaptive strategies for addressing resilient solutions to climate conditions, and (3) renewable energy strategies reaching beyond the Architecture 2030 goals for 2019 (70% reduction) towards the net-zero OE performance for existing buildings.

Positioning the EE benefits of existing buildings and the complexities of making them efficient, this studio section asked students to redesign and transform an existing urban ice-cream manufacturing and retail facility by proposing (1) minor changes in massing that addressed the existing building's orientation, volume-to-surface area ratio, and opacity-to-transparency ratio for greater passive efficiency; (2) changes or modifications in the program and occupancy for net-positive impact, especially in the realm of socioeconomic net-positive benefits that supported equity and resiliency; (3) the addition of active or passive means of energy production; and (4) the development of two building

Table 1: Performance goals for passive massing and envelope strategies.

Results	Baseline	Target
EUI (%) reduction from baseline	0%	70%
Site EUI, kBtu/ft ² /yr (kWh/m ² /yr)	51 (160.9)	16 (50.5)

Note: EUI = energy-use intensity.

envelope strategies: (i) a passive boundary condition meeting the Architecture 2030 goals; and (ii) an adaptive building skin that can change its functions in response to changing temperatures and climate conditions.

For the passive boundary condition, students could selectively modify or completely replace the building's existing boundary condition in order to create a passive, high-performing, deep boundary condition to meet the Architecture 2030 performance goals. Using the Zero Tool,³ two of these metrics (for the purposes of this article) are shown in **Table 1**.

Lstiburek (2007), describing the 'perfect wall' concept, was the reference reading for the passive boundary condition and required students to develop an understanding of various building envelope layers and their properties. Students developed their strategies through wall sections, in which they detailed, examined, compared, and critiqued the layerings of high-performance envelopes. Simultaneously, the Sefaira energy modeling workshops positioned the building envelope as one of the variables in overall building performance goals.

When considered as adaptive skins, building facades are capable of dynamically improving a building's energy performance and/or its interior comfort in response to varying weather and climate conditions (Attia *et al.* 2020; Wigginton & Harris 2000). In this context, the studio pedagogy aimed to design climate-adaptive building shells, which for Loonen *et al.* (2013: 485) have:

the ability to repeatedly and reversibly change some of [their] functions, features or behavior over time in response to changing performance requirements and variable boundary conditions [...] with the aim of improving overall building performance.

Thus, for the adaptive building envelope strategy, students were asked to newly imagine and design an envelope for the existing building that responds to changing conditions (*i.e.* a cloak or a shield) creating a modulated exterior environment. For the research and design of the adaptive layer or cloak, students were provided with reference materials about Loonen's taxonomy (Loonen *et al.* 2013) and related examples. Loonen's taxonomy includes thermal, optical, airflow, and electrical responses in the adaptive skin. For the adaptive strategy students were not required to complete energy-modeling studies, although some students attempted to use Sefaira and other tools such as Ladybug⁴ and Honeybee⁵ for Grasshopper⁶ to assess the performance of these strategies in multiple static conditions.

4. Studio learning methods

While the instructor designed the overall structure of the studio including schedules, goals, and evaluation criteria, the day-to-day and week-to-week studio structures were developed in partnership by the students and instructor through large- and small-group discussions. With few exceptions, the studio day began and ended with a large group meeting involving the instructor and students. Key issues of discussion were the problems encountered, thematic concepts being observed and articulated, work plan, and announcements. The discussions focused on (1) observing, reading, discussing, debating, and articulating the thematic concepts emerging in the studio, and combining work generated by various students to strengthen emerging themes; and (2) what was next, in other words what was being made, researched, or tested in order to advance concepts and by whom (Srivastava & Christenson 2018; Srivastava *et al.* 2019).

At regular intervals during the semester (**Table 2**), the whole studio or small groups would gather for a substantive amount of time to bring all the work together. The instructor was mostly an observer, participating for purposes of minimal feedback. During the gatherings, students would display and discuss the work of the studio, where the work produced by the participants was considered to be in shared authorship, where no one student needed to defend their work, but the differences and variety of perspectives, backgrounds, knowledge, and practices of the various students were considered to be of value. As an example, during the second week, each student responded to several variables by producing at least four artifacts, each of which proposed changes to the existing building's massing to achieve better performance. The following variables were explored:

- Artifacts that iterated passive massing and form change strategies to test the performance results of various volume-to-surface area ratio and/or opacity-to-transparency ratios for building envelopes.
- Artifacts that iterated *adaptive* strategies (able to change in response to changing environmental conditions).
- Net-positive *energy-production* strategy and addressing one other criterion (waste, air pollution, green jobs, biophilia, *etc.*) so the building can make a net-positive contribution to the surrounding built environment and living community (Mang & Reed 2015).

The process of grouping students' works together based on agreed-upon and evolving definitions of emerging thematic ideas followed a three-step process: (1) setting the table; (2) conflation; and (3) reassignment of ownership, which are described and illustrated in **Figures 1–3**.

5. Performance results and collaborative structures

The impacts of the Shifting Allegiances pedagogy are discussed with four different observed outcomes in the following sections.

5.1 Baseline models

The students began to notice that the energy modeling software they were using was not producing consistent results. Several reasons contributed to this important observation, including their engagement with each other's works. Variations in baseline EUI ranged from 88% to 118%. Students experimenting with the same or similar design concepts for modification encountered varying results in EUI as well. In order to investigate this further, the students initiated a systematic group review of the software. The whole studio decided to use the same baseline model of the existing building, developed by a volunteer student, and they all tested the same series of design iterations. They all recorded their results in a shared spreadsheet. It was quickly evident they were all getting different results. They went through this cycle a few times, checking settings in the energy modeler to make sure everyone was starting with a consistent baseline. Accuracy in modeling form including walls, windows, doors, ceilings, roofs, choosing systems, outlining occupancy patterns, and variables that defined envelope, were all examined to achieve consistency with the as-built drawings and specifications. The students requested existing building occupancy patterns, systems information, and utility bills from the current owner. They were then able to individually model the same parameters in the energy

Table 2: Weeks 1–7: studio schedule and process.

	Weekly topic (or activity)	Testing method or reference	Sharing	Gathering and discussion format
W1	Passive and adaptive building envelopes	Joe Lstiburek's Perfect Wall and Loonen's Climate Adaptive Building Shells (CABS) taxonomy	Wall sections	Whole studio: Steps 1 and 2
W2	Passive strategies (massing, form, location, orientation, glazing) iterations	Sefaira Energy modeling (Workshop 1—Passive) and climate consultant site analysis to create the baseline performance	Site analysis with climate consultant or Ladybug, massing thematic ideation through models	Whole studio: Steps 1–3
W3	Iterative development of passive massing strategies	Testing each massing strategy for Architecture 2030 performance measures with Sefaira	Baseline models, Sefaira test performance results for massing iterations: energy-use intensity (EUI), CO ₂ , daylighting metrics, renewable energy needs	Whole studio: Steps 1 and 2
W4	Passive and adaptive envelope strategies	Testing net positive (different calculations and metrics dependent on strategies)	Energy production strategies, wall sections and massings of passive and adaptive envelopes	Within small groups: Steps: 1–3
W5	Active systems (heating, ventilation and air-conditioning—HVAC)	Sefaira Energy modeling (Workshop 2—Systems and Envelopes)	Wall sections, Sefaira passive strategy results, adaptive or net-positive ideation	Within small groups: Steps 1 and 2
W6	Taking stock: passive massive and envelope Architecture 2030 performance; net-positive and adaptive envelope strategies	Check Architecture 2030 the goal requirement with Sefaira	Sefaira test performance results of passive envelope and HVAC selections: EUI, CO ₂ emissions; identifying issues and questions for final discussion	Whole studio: Steps 1 and 3 (regrouping for final discussion, roster preparation only)
W7	Final versions of all artifacts for passive, adaptive and net-positive strategies	Energy modeling results for passive strategies	Second iteration of issues and questions for discussions	Whole studio: Step 1 (for discussion only)

Note: Step 1: Setting the table: displaying and sharing all work; Step 2: Conflation: discussing all work, finding groupings of multiple works based on emerging thematic commonalities without regards for individual authorship; and Step 3: Self re-assignment of ownership: student(s) take responsibility for forwarding work groupings based on interest, strengths (skills they can contribute or teach) or deficits (skills they need to learn) rather than ownership.



Figure 1: Step 1: Setting the table.

Note: Each student contributes multiple artifacts to the studio for discussion. Here, an individual student (S) is shown to contribute four artifacts (circles). It is understood that a student's artifacts embody their attempts to give form to their ideas, perspectives, or questions about the architectural problem.

modeler, producing more accurate baseline models, a closer understanding of input and output variables, software platforms, and common performance goals from the Zero Tool (**Table 3**).

This became a cycle of consistent and systematic testing where the students worked cooperatively to develop not just familiarity with the modeling process but a deeper understanding of input variables and the results that the software produced as a result. Helping each other by testing shared iterations together and comparing redesign strategies and modeling methods allowed them to learn from differences in approaches. They quickly started to realize that concinnity between variables such as form, occupancy, building envelope layers, transparency and opacity ratios, massing, orientation, function, and environmental factors led to determining performance. They also concluded that the software release year, differences in platforms being used, and the order in which strategies were introduced by various students can make a difference to the modeling outputs. If they had worked in the traditional studio format where each person had their own model, and no structure or basis for comparison, or peer-learning support, they would not have deepened their understanding of energy modeling in the same way. In the end they submitted all their comparative result spreadsheets to the local representative of Safeira to get an expert's explanation of the anomalies and variations they had discovered.

5.2 Results: dialogue between design and data

The Shifting Allegiances approach was essential in addressing the cycle between energy modeling and design. As part of the evidence-driven process, the students were required to demonstrate individually mastery of the energy-modeling software. To do this, two Friday studios were dedicated to Safeira workshops, followed by a related weekend charrette and a Monday review of the findings with the workshop instructors. The first workshop (in the second week) included fundamental passive design variables such as orientation, massing, opacity and transparency ratios, and surface area-to-volume ratios. The second workshop (in the fourth week) introduced mechanical, electrical, and lighting systems and passive strategies for building envelope performance based on varying *R*-values and glazing parameters such as solar heat gain coefficient (SHGC). After the workshops, design processes were expected to follow

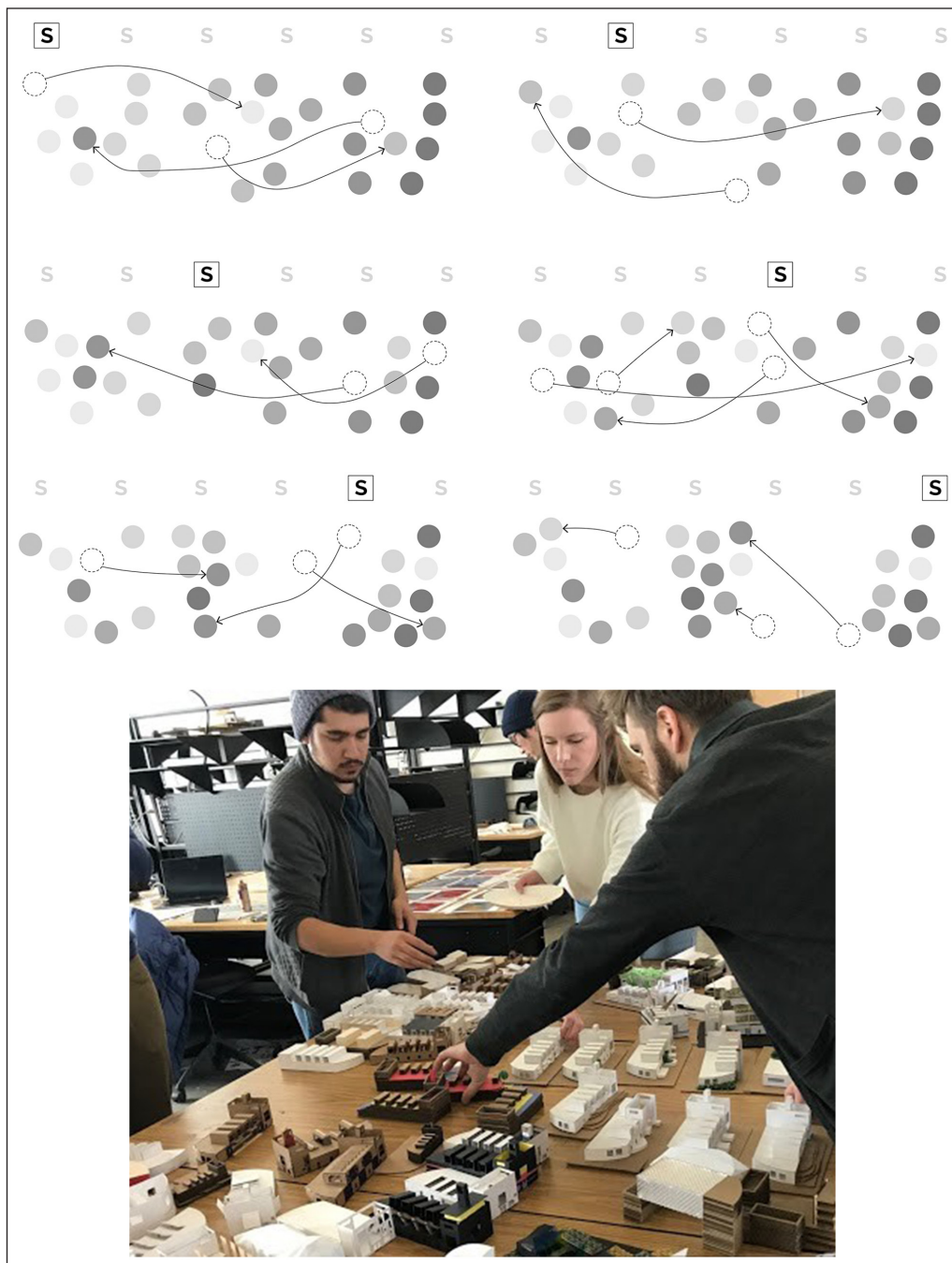


Figure 2: Step 2: Conflation.

Note: In this step, sets of artifacts contributed by individual students are discussed and provisionally combined into groups, based on the students' collective assessment of the artifacts' thematic affinity. Each student gets a turn to lead the discussion sharing their perspectives with the group, moving artifacts around to illustrate alternative groupings, readings, and generating potential design strategies for the studio to test. As a provisional step, conflation proceeds in an experimental and iterative manner: the students work collectively to test and discuss possible affinities among artifacts and future directions. Here, students (S) are shown to contribute various artifacts (circles). There is no expectation that all the artifacts produced by an individual student will 'travel as a set'—instead, the artifacts produced by any one student may themselves be widely distributed across many different groups. Single artifacts may be determined to have thematic affinity with more than one group.

a cyclical, iterative process of making and testing (**Figure 4**). Any drawings or models made to develop design ideas alternated with energy modeling for performance to test at first the passive strategies, before iterating active systems. In the second workshop, students were introduced to active strategies (those requiring to be powered, such as HVAC), to test parametrically multiple strategies while developing an understanding of the active factors such as heating, cooling, ventilation, lighting, equipment, and dehumidification on OE consumption.

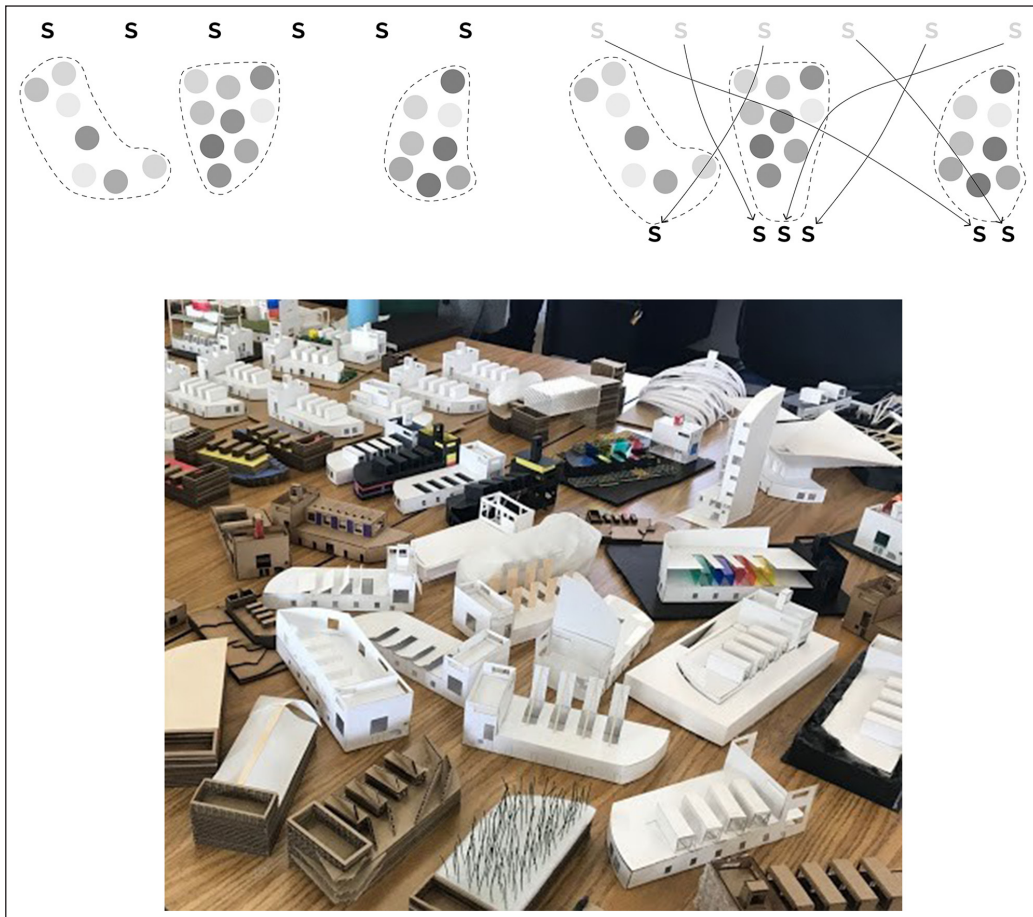


Figure 3: Step 3: Re-assignment of ownership.

Note: In this step, the testing of possible combinations is ended and the new groupings of artifacts are unambiguously defined and agreed upon. Through discussion, students (S) then develop a high level of transactive memory and assign themselves, based on self-identified strengths (skills they can contribute or teach) or deficits (skills they need to learn), to the responsibility of one or more groups of artifacts. The consequence of the re-assignment of ownership is that a student or group of students takes on responsibility for artifacts they did not themselves create, but for which they had agency in defining their thematic focus. In this way, students take on ownership of new combinations of ideas or questions that are understood to be embodied in the artifacts, learning from the perspective of their peers, while testing the thematic ideas through tools such as energy modeling in preparation for the next setting of the table where they can teach what they learned to the rest of the group.

The EUI, measured in kBtu/ft²/yr, became a common discussion metric to assess performance goals. After the first workshop (weeks 2 and 3), students generated between four and 14 iterations of passive strategies (**Table 4**). Based on the student output files from Sefaira, EUI ranged from 39 to 106 kBtu/ft²/yr (from 123.0 to 334.4 kWh/m²/yr) (not considering an outlier reading of 345 (1088.4) EUI). As students became more confident of their testing skills, more iterations were completed. After Workshop 2 (weeks 4–6), numbers of iterations ranged from nine to 49. These iterations tested further parameters for building envelope efficiency and systems efficiency. EUI values improved, ranging from 10 to 54 kBtu/ft²/yr (from 31.5 to 157.7 kWh/m²/yr). Of the 12 students, the energy analysis data for two students were not available. Of the remaining 10 students, seven had 70.5–80.0% reductions in OE use over the baseline, meeting the Architecture 2030 goals outlined in the studio brief. The remaining three students' reductions ranged from 47% to 52%. Students further quantified the area of photovoltaics (PV) panels that would be needed for all the design iterations to achieve net-zero OE use. These ranged from none needed to 3999 ft² (371.5 m²). Yet, not all student groups pursued PV as their renewable energy source.

5.3 Adaptive strategies results: proposed expansion of Loonen's taxonomy

In addition to passive strategies that met Architecture 2030 goals, the students developed adaptive building envelope strategies with Loonen's taxonomy (Loonen *et al.* 2013) as a reference including thermal, optical, airflow, and electrical responses to changing conditions. Although the students were not required to test the OE performance of the adaptive skins, they were required to reference and place their work within Loonen's taxonomy (**Table 5**). Within the Shifting Allegiances methods, students debated and discussed the variables contained in various adaptive envelope strategies and

Table 3: Comparisons of the student energy modeling result using the same baseline model and design iteration after several attempts to align the results by examining several design variables.

Student code	First attempt to establish baseline energy models <i>before</i> cooperative peer-teaching and group work		Final effort to establish baseline energy models <i>after</i> cooperative peer-teaching and group work			
	Sefaira area output, ft ² (m ²)	Baseline site EUI = plug-in or web app, kBTU/ft ² /yr (kWh/m ² /yr)	Sefaira area output, ft ² (m ²)	Baseline site EUI Sefaira plug in, kBTU/ft ² /yr (kWh/m ² /yr)	Baseline site EUI Sefaira web app, kBTU/ft ² /yr (kWh/m ² /yr)	Sketch-up versions used to input massing into Sefaira
S1	4970 (461.7)	60.2 (189.9)	8429 (783)	51 (160.9)	51 (160.9)	Make—2017
S2	4970 (461.7)	57 (179.8)	8429 (783)	51 (160.9)	49 (154.6)	Make—2017
S3	10,653 (989.7)	45 (142)	8429 (783)	51 (160.9)	51 (160.9)	Make—2017
S4	4970 (461.7)	48 (151.4)	8429 (783)	51 (160.9)	49 (154.6)	Make—2015
S5	4971 (461.8)	59 (186.1)	8429 (783)	51 (160.9)	49 (154.6)	Make—2017
S6	7670 (712.5)	59 (186.1)	8429 (783)	51 (160.9)	51 (160.9)	Make—2017
S7	4970 (461.7)	60 (189.3)	8429 (783)	51 (160.9)	51 (160.9)	Make—2017
S8	4970 (461.7)	60 (189.3)	8429 (783)	51 (160.9)	51 (160.9)	Pro—2018
S9	4970 (461.7)	60 (189.3)	8429 (783)	51 (160.9)	49 (154.6)	Make—2017
S10	4970 (461.7)	60 (189.3)	8429 (783)	51 (160.9)	48 (151.4)	Make—2017
S11	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
S12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Note: EUI = energy-use intensity; n.a. = not available.

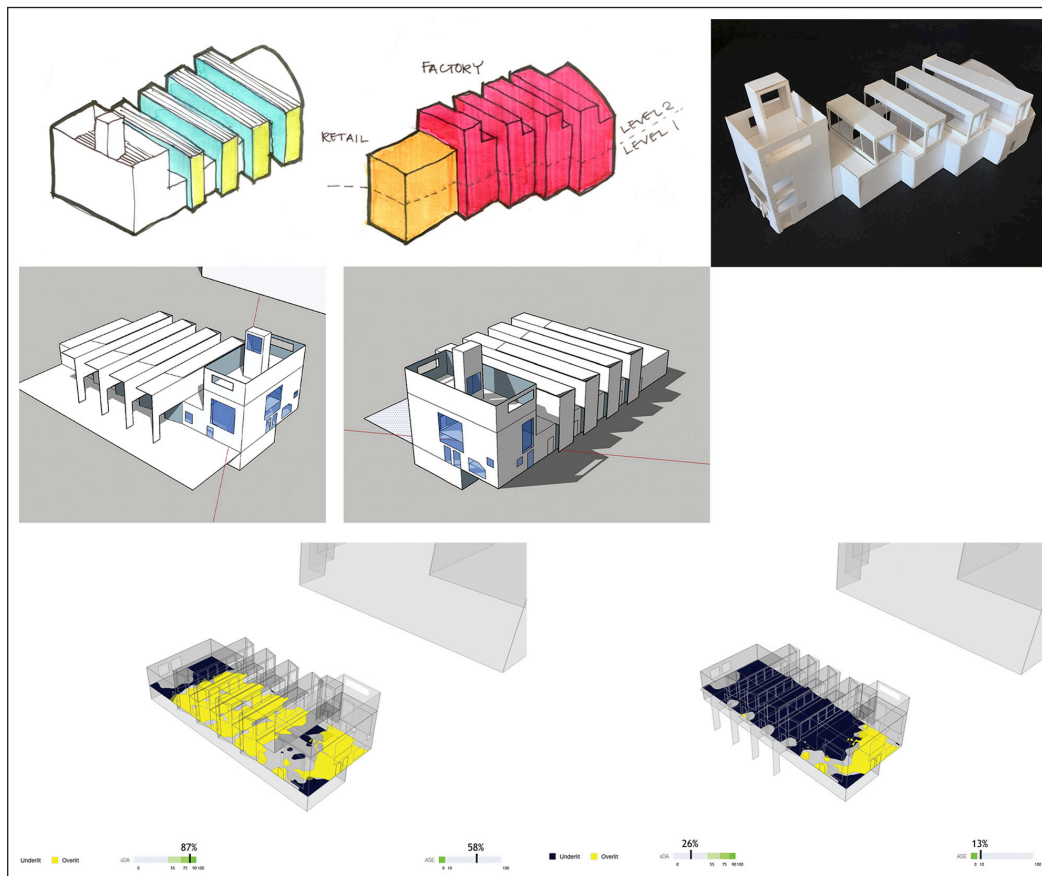


Figure 4: Cyclical process between ideation and testing.

Source: Drawings and models by Mackenzie Kusler.

Table 4: Comparisons of student energy modeling results, design and data cycle iterations to achieve Architecture 2030 targets (renewables for net-positive target).

Student code	Weeks 2 and 3: passive strategies only			Weeks 4–6: passive strategies + R-values + HVAC systems			Type of renewable energy researched, designed and estimated for the net-positive contribution	
	Iterations	Week 3 EUI range of iterations, kBtu/ft ² /yr (kWh/m ² /yr)	Iterations tried by student	Weeks 4–6 EUI range of iterations, kBtu/ft ² /yr (kWh/m ² /yr)	Final percentage reduction (%)	PV needed to achieve the 2030 target, ft ² (m ²)		PV needed to achieve net positive, ft ² (m ²)
S1	6	57–82 (179.8–258.7)	18	54.0–24.5 (170.4–77.3)	52%	n.c.	n.c.	Algae as fuel
S2	10	54–106 (170.4–334.4)	24	36–11 (113.6–34.7)	78%	None	2834 (263.3)	Compost waste energy generation
S3	12	43–67 (135.7–211.4)	49	71–27 (224.0–85.2)	47%	2794 (260)	3999 (371.5)	PV
S4	9	39–70 (123.0–220.8)	36	32–10 (101.0–31.5)	80%	None	1300 (120.8)	PV
S5	14	40–88 (126.2–277.6)	35	44.0–13.5 (138.8–42.6)	74%	None	2860 (265.7)	Compost waste energy generation
S6	10	48–65 (151.4–2015.1)	17	51–26 (160.9–82.0)	49%	1268 (117.8)	3380 (314)	PV
S7	8	47–61 (148.3–192.4)	Several	47–14 (148.3–44.2)	72%	None	n.c.	PV
S8	7	50–65 (157.7–205.1)	9	50.0–14.5 (157.7–45.7)	71.5%	None	n.c.	PV
S9	4	45–60 (142.0–189.3)	25	50–15 (157.7–47.3)	70.5%	None	n.c.	Algae as fuel
S10	6	60–345 (1889.3–1088.4)	19	47.0–11.5 (148.3–36.3)	77%	None	1725 (160.3)	Algae as fuel
S11	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Compost waste energy generation
S12	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	PV

Note: EUI = energy-use intensity; HVAC = heating, ventilation and air-conditioning; n.a. = not available; n.c. = not calculated; PV = photovoltaics.

Table 5: Expansions to Loonen's taxonomy for Climate Adaptive Building Shells (CABS).

Loonen's original categories based on primary function	Studio proposal 1: Power source that allows the adaptive envelope to respond to changing conditions	Studio proposal 2: Frequency of responsiveness of the adaptive envelope to changing conditions
Optical	Active power (renewable)	Continuous
Thermal	Active power (fossil fuel)	Seasonal
Airflow	Physical material properties for spontaneous response (<i>e.g.</i> composite laminates)	
Electrical	Human-powered (manual)	

realized that the various projects in the studio needed more definition, and consequently they proposed an expansion of Loonen's taxonomy. Specifically, their concern was the time-scale frequency of dynamic, adaptive, and active skin transformations. The frequency of transformations in the strategies proposed and studies ranged from the spontaneously continuous in response to temperature shifts, to deliberately seasonal in response, to larger changes in temperature, humidity, and daylight hours. To this they added the question of agency (*i.e.* what provides the power for dynamic skin transformations). First, active skins may be powered by an energy source (fossil fueled or renewable). Second, the skin's material may respond to changing temperature conditions by predictable movements, such as the laminated metal skins investigated by Sung (2009, 2016) and the bio-laminates investigated by Braaksma *et al.* (2018). Third, skin transformations may be human-powered and controlled by manual manipulations. For example, an insulated panel layer that can be manually added to the building envelope, but which is used as site furniture in warmer months when the building is not cooled. A three-person group of students led a discussion of the potential for seasonal human-powered transformations of this kind to affect the potential for green economy jobs, even as they make buildings highly efficient.

6. Conclusions

The cooperative structures created in the studio led to a learning process based on productive comparisons based on student successes as well as their failures. When considered as learning opportunities, early failures to achieve performance (**Tables 1 and 2**) were considered to be just as relevant as successes on the path to a majority of the students achieving and exceeding performance measures. High transactional memory (generating and retaining the knowledge and skills of the various students) allowed strength- and deficit-based shifts in groupings to allow for peer-learning and teaching. Comparisons of students' energy modeling results due to in-depth knowledge of, and participation in, their colleagues' work became second nature to the students. The studio structure also resulted in a cooperative and comparative examination of input and output variables (**Tables 1 and 2**). Finally, this enabled the students, in a student-led, discussion-based review, to situate their projects for thematic overlap, encouraging comparison-based learning habits that valued various perspectives and diverse proposals to meet performance goals. Most importantly, due to an in-depth knowledge of the studio work, students were able to display independence and develop a review structure of the work in a way that was educational and relevant to them. This knowledge of the studio work also led to proposed expansions of Loonen's taxonomy (**Table 5**).

6.1 Potential for replication

The Shifting Allegiances approach is easy to replicate and flexible for customization for individual needs. It is a meta-framework in the sense that it is content independent. It may be implemented at different levels (undergraduate or graduate) within studios addressing a range of subjects and topical material. It is a micro-framework in the sense that it does not require larger curricular or program changes and is not bound to specific content, and therefore can be implemented by an individual instructor in a single-studio section. Lastly, studio instructors may be restrictive or open in their implementation of the framework. For example, if studio instructors want students to focus on individual skill development rather than cooperative or group work, they may ask each individual student to become responsible for separate thematic work groupings that combine work from multiple students.

6.2 Student-defined net-positive contributions in cooperative structures

Various thematic groupings of work and people that evolved ranged from three-person groups to one-person efforts (see Table S1 and further examples in the supplemental data online). While allegiances to ideas being tested were emerging in the first three weeks, student groups coalesced around thematic groupings of artifacts and ideas by week 4. From weeks 4 to 6, debates and discussions within the small group further refined and focused the ideas, using energy modeling as a means to eliminate strategies that were not achieving the desired performance measures and focusing on developing strategies that were.

The structure and organization of the course encouraged students to be peer-teachers for each other. They shared an interest in minimal external change in the existing building, creating most of their interventions and layering on the interior of the current envelope.

6.3 Redefining review formats

As the end of the semester neared, the instructor and students agreed to continue the studio's discussion-based format (**Table 2**) to the final review. The cooperative structures had created investment in the individual and collective work of the studio to various degrees and heightened the opportunities for peer learning.

In the studio's penultimate week, the 12 students gathered with an external reviewer and practiced a discussion-based review, where the students presented the work in quick succession (five to seven minutes each), outlining an issue or question and asking for response from each other and from the external reviewer. After these quick presentations, the entire studio discussed all the work, pointing out thematic similarities and overlaps in the work (week 6 in **Table 2**). Nine of the 12 students spontaneously diagrammed the work of the studio on a three-dimensional spectrum where the x -, y -, and z -axes represented common themes in the projects (**Figure 5**). The criteria for the axes determined by the students were the frequency of responsiveness in the adaptive skins, sources of energy to achieve responsiveness in the adaptive skins (manual, active, or a combination), and types and quantity of energy sources to achieve operational net-zero energy target. The discussion and diagramming took approximately two hours to complete and the diagram shown in **Figure 5** is one of the iterations.

Based on this experience, the studio decided to create a shared Google spreadsheet (see Table S2 in the supplemental data online) outlining what they had learned from the practice review. Several students modified or changed the discussion question or issue they chose to address in their work. Generally, students decided to take broad, open-ended questions and make them more specific, targeted, and succinct. This question definition activity took approximately 45 minutes of studio time.

Learning from the practice review, the students also proposed a new format where all the work of the studio was simultaneously displayed and available for reference for the three-hour review. Half the studio presented work in quick succession for a little over 30 minutes, grouped by thematic overlap, followed by a 60-minute group discussion where 12 students and seven external reviewers arranged themselves in a circle (**Figure 6**). Both the penultimate and the final reviews were moderated by two student volunteers. During the final review, the volunteer moderators also added two rules to the group discussion at the halfway point in order to ensure the discussion stayed related to and referenced the studio's work while also forwarding larger issues of climate change provoked by the work. The two rules were that the reviewers would reference as much as possible the displayed work of the studio in the feedback they were providing before discussing more generalized principles or references. Second, the reviewers were asked to point to multiple specific work examples while providing feedback such that the discussion was focused on broad emerging themes rather than feedback on any individual project at any given time. The discussion-based practice review and final review placed the students in a leadership role, empowering them to design the review structure based on the content of the work and the format and type of feedback they considered valuable.

7. Outlook and future work

The cooperative and comparative structures together with the peer-learning and teaching that permeated The Net Positive Studio led to an understanding of passive and adaptive transformations of an existing building, leading to individuals and groups defining the net-positive contributions of their projects. However, several factors need to be examined in future that may fall into three categories: tools, student experience, and course content.

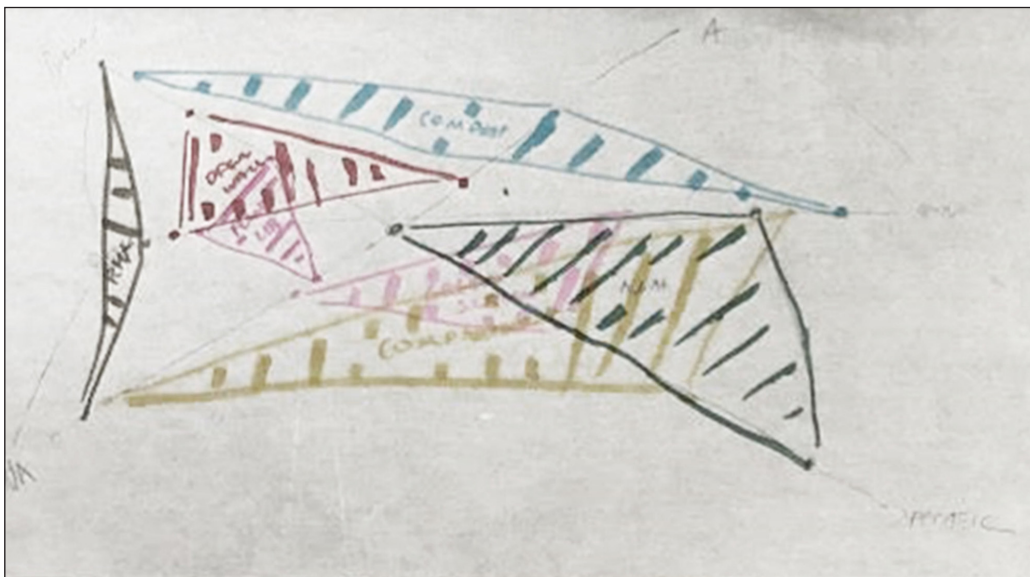


Figure 5: Practice review with spontaneous diagramming of thematic similarities and overlaps.

Source: Drawing by students in the Net Positive Studio.

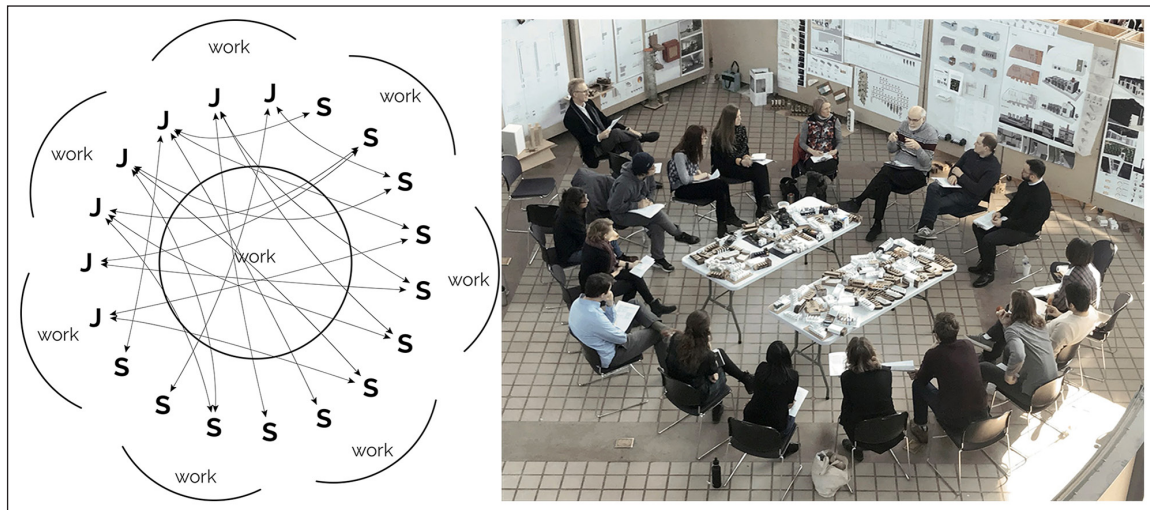


Figure 6: Discussion-based arrangement of the final review.

Note: J = jurors; S = students.

Source: Photo by Mike Christenson.

7.1 Tools

- There is a need to implement and test tools for assessing the EE expended in order to reach high-performance OE goals per Architecture 2030.
- There is a need to implement and test tools suitable for assessing the performance of adaptive building envelopes in terms of EUI, carbon emissions, and the need for on- or off-site renewable energy generation.
- There is a need for a continuously evolving examination of the content matter emerging from previous student work (e.g. expansions of established taxonomies) and quickly advancing problems that need to be addressed. Such problems include climate change, the carbon footprint, resiliency needs of areas such as coastal cities, climate-related migrations, as well as the implications of high operational performance such as the greater percentage of EE expended to reach high-performance OE goals and the influence of occupant behavior and policies on OE outcomes.

7.2 Student experience

- There is a need to examine student experience outcomes focused on the role of cooperative structures in their learning: Did cooperative structures help or hamper them in their individual work, collaboration, cooperation, and time intensity?
- There is a need to examine the student experience from a point of view of equity and inclusion due to peer-learning and teaching and the ability to make contributions to design, representation, and dialogue in group structures. Learning outcomes would examine the learning objectives and perception of learning in terms of whether the cooperative structures model allowed individual students to understand the core concepts and achieve the learning objectives.
- Currently, the pedagogical framework does not specifically outline how many times or at what times shifting allegiances should occur in a studio. This needs to be tested.
- Currently, the pedagogical framework allows students to determine group sizes according to self-identified interests, affinities, strengths, and deficits. There is a need to examine the impacts of group sizes based on previous pedagogical research, and to test the effect of negotiations between the instructor and students concerning group composition.

7.3 Course content

- The workload quantity relative to the short term (seven weeks) needs to be examined, while accounting for the need to develop multiple solutions examining passive, adaptive, and renewable energy strategies.
- There is a need to examine specific methods for quantifying net-positive performance specifically related to the balance between EE, OE, and systemic evaluations (emergy as defined by Odum 2007; and Srinivasan & Moe 2015) that the existing buildings are constituent in.

As development of the pedagogy continues in future iterations of the studio, there is a clear need for critical assessment of the learning outcomes. On the one hand, traditional modes of assessment focus on individual awareness and ability in support of professional degree program accreditation criteria. On the other, assessment criteria have the potential to broaden and encompass the fluid, collaborative work structures essential to addressing the complex issues inherent in climate change.

Notes

- ¹ See https://architecture2030.org/2030_challenges/2030-challenge/.
- ² See <https://sefaira.com/>.
- ³ See <http://www.zerotool.org/zerotool/>.
- ⁴ See <https://www.ladybug.tools/>.
- ⁵ See <https://www.ladybug.tools/honeybee.html>.
- ⁶ See <https://www.rhino3d.com/>.

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Competing interests

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Supplemental data

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