Sustainable Design Accelerator: Infusing Entrepreneurship and Evidence-based Design into Architecture Pedagogy

OMAR AL-HASSAWI
Washington State University

DAVID DRAKE
Washington State University

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Development of systems-level thinking and an entrepreneurial mindset is invaluable to prepare architecture program graduates for challenges posed by the global climate crisis. This paper reports initial results from the Sustainable Design Accelerator, a funded project within our Master of Architecture program to advance student skill sets through entrepreneurship and evidence-based design. Prior to this project, our students valued entrepreneurship but lacked curricular opportunities despite recent faculty experience in the area. Additionally, existing courses on sustainability provided only a broad overview of sustainable design principles, with little opportunity for hand-on exploration.

By stacking a lab course and a studio course, a semester-long sequence was created, introducing and applying a comprehensive suite of digital and analog tools for entrepreneurship and evidence-based design. In the lab course, tool introduction and application occurred within the context of a design challenge to produce innovative and marketable passive cooling system prototypes, while in the concurrent studio course, students applied tools to calculate environmental impacts at a whole building scale for proposed designs of a multi-family housing community. Both courses featured workshops by national experts in entrepreneurial studies and product life cycle assessment, as well as reviews by practicing architects specializing in environmental stewardship. In addition to direct assessment of learning outcomes, exit surveys were used to assess student perceptions of knowledge depth and the value of newly acquired skills. Survey results and faculty observations resulted in modifications to a second iteration of the Sustainable Design Accelerator, to be delivered Spring 2022.

Also reported here is the impact on the sequence of the university's move to online-only education for the 2020-2021 academic year, due to the COVID-19 global pandemic. Return to in-person instruction for the 2021-2022 academic year provides for future comparison between online and in-person iterations.

INTRODUCTION

Climate change and the built environment. Buildings account for nearly 40% of global CO_2 emissions, and over a third of global energy consumption. [1] Similar patterns exist in the U.S. .[2, 3, 4] Architects, interior architects, and landscape architects therefore have a responsibility to develop effective, sustainable solutions that go beyond carbon neutrality, in line with the targets outlined in the Paris Climate Agreement and the Architecture 2030 Challenge. [5, 6] Given the complexity and scale of the problem, and the accelerating pace of urbanization, achieving carbon neutrality in the built environment will require systems-level thinking, alongside unprecedented invention and innovation. [7]

Gaps in education and practice. Prior to the launch of the Sustainable Design Accelerator course sequence described below, our curriculum lacked in-depth, higher-level courses focused on sustainable design. The primary investigator and co-PI observed that students in our school's design disciplines valued entrepreneurship, but lacked opportunities for entrepreneurial exploration within the existing curriculum, in spite of recent faculty experience in that area. This may be due to the traditional business model of design practice as work-for-hire, relying on clients to seek out practitioners and commision projects. [8] This is changing, with the emerging recognition that entrepreneurship and entrepreneurial mindset are critical tools for designers who seek to mitigate the climate crisis through development of commercially-viable solutions.[9, 10]

We hypothesized that our school was well positioned to close this curricular gap, and advance student skill sets in entrepreneurship and evidence-based design. The school's nationally-recognized, professional design degree programs incorporate cross-disciplinary, team-based learning and have recently become STEM-designated. Faculty members, including the primary investigator and the co-PI, have experience developing and commercializing innovative, sustainable building systems. Our students are trained in analog and digital fabrication, and have access to well-equipped prototyping facilities. In addition, the investigators had recently been awarded $10,000 in internal seed funding to design and fabricate a climatic test chamber for use in evidence-based design education and faculty research.

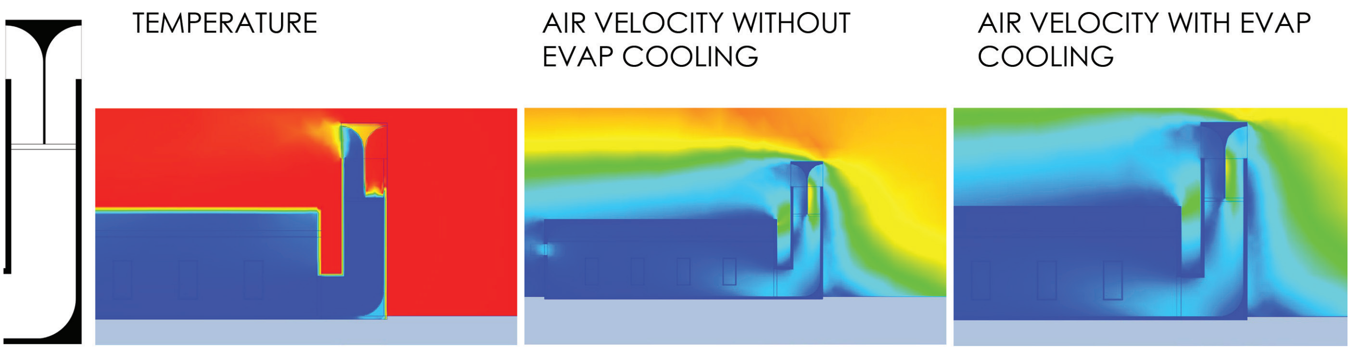


Figure 1. Example Computational Fluid Dynamics results from lab course, 2021. Image credit Nathan Albrecht, Colter Nubson, and Yu-Hsien Chou.

Existing courses were broad but not deep. Sophomore students in the four-year pre-professional architecture program are currently required to take an introductory sustainability course, which provides an overview of design issues and strategies to mitigate the negative environmental impacts of the built environment. In recent years, a design studio on the professional degree track (undergraduate + graduate) has had a sustainable design focus. Student teams submitted final projects to the American Institute of Architects Committee on the Environment Top Ten for Students Design Competition, and the award was won by one of the teams. Both courses are taught by the primary investigator, who also mentored the winning team. This success suggests opportunity for deeper exploration within the curriculum.

To provide students with hands-on experience and prepare them for changing fields of practice, we submitted a proposal for external funding to seed the new Sustainable Design Accelerator course sequence detailed below. The sequence as proposed combined a lab course and a design studio, and provided concurrent lean entrepreneurship training. During the intensive semester-long experience, student teams were to design, prototype, and test innovative systems for carbon neutral/restorative architecture, then integrate the systems into designs for a multi-family housing community emphasizing environmental, social, and economic sustainability. The funding proposal was successful, and the project launched Spring 2021. As a consequence of the COVID-19 global pandemic, our university moved to online-only education for the 2020-2021 academic year, and this required significant modification to the proposed course sequence, which we also detail below. With a return to in-person instruction for the 2021-2022 academic year, delivery of the Sustainable Design Accelerator as a sequence of in-person courses in Spring 2022 provides a valuable opportunity to compare outcomes between the two modes of instruction.

COURSE DESIGN AND METHODOLOGY

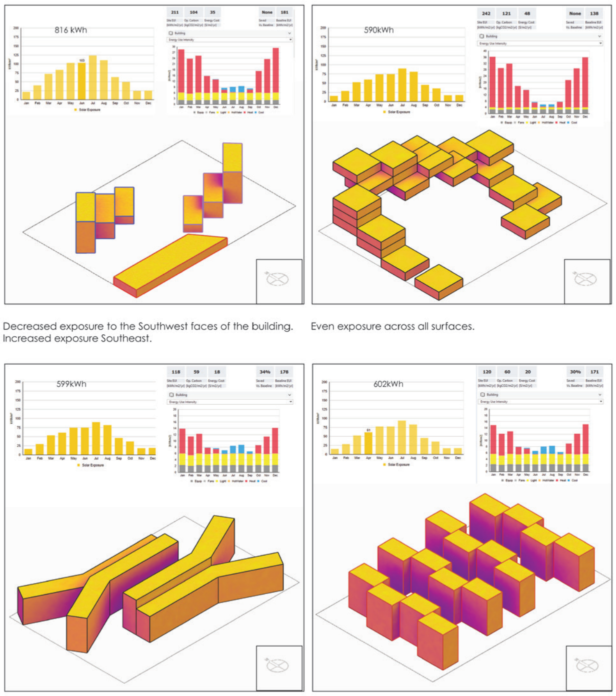
The Sustainable Design Accelerator sequence covers carbon neutral building design at multiple scales, from individual building systems, to implementation of these systems in the design of a complete multi-family housing community.

The sequence is offered to students in the first year of the Master of Architecture professional degree program, including students pursuing the two-year path, and students pursuing the accelerated one-year path. This is an optimal point in the curriculum, as it follows four-plus years of pre-professional coursework, thus ensuring student teams have sufficient technical competence and prior team-based experience to succeed.

Version 1.0 of the sequence was delivered Spring 2021, with enrollment of 23 students in the lab course, including seven students enrolled concurrently in the studio course. Students worked in teams in both courses. Due to the COVID-19 global pandemic, virtually all instruction was offered online via the Zoom platform. Instruction included design critique and workshops delivered synchronously, and available asynchronously through recording of the Zoom sessions.

The lab course: Students worked in teams of 3-4 members and met with faculty once a week. They were tasked with development of an innovative and marketable passive cooling system, including proof-of-concept physical prototype. The course was organized in four phases.

The studio course: Students worked in teams of 3-4 members and met with faculty twice a week. Teams were asked to develop a design for a mixed-use multi-family housing complex sited in a mid-sized city in the northwestern United States. Total built-up area for this project was between 125,000 and 150,000 square feet. The course was organized in five phases, with the incorporation of bi-weekly workshops targeted towards the objectives of the grant.



Decreased exposure to the Southwest faces of the building. Increased exposure Southeast.

Even exposure across all surfaces.

Same issue as the third building. Dark overshadowed areas in between buildings.

Even shadowed exposure in between buildings. Possible sun space in between?

Figure 2. Example surface radiation maps from studio course, 2021. Image credit Colter Nubson.

AREAS OF KNOWLEDGE

Systems Level Thinking. Rather than presenting building design and detailing as a series of disconnected choices from a 'menu' of off-the-shelf components, we introduced Whole System Mapping (WSM) using the Faludi four-step methodology. WSM is a qualitative method, conceptualizing individual building components as part of a complex system of interactions and energy inputs incorporating resource extraction, manufacturing, interaction with other components, user behavior, and end-of-life strategies, including disposal or reuse/recycling. By understanding the whole system, students learn strategies for systems-level sustainability, rather than a disconnected and piecemeal approach.

Life Cycle Assessment (LCA). In addition to qualitative WSM analysis, we introduced students to quantitative Life Cycle Assessment (LCA) tools for cradle-to-grave product analysis. Tools included the Equalizer Eco Design database, coupled with a Microsoft Excel calculator for evaluating environmental impacts of multiple product design alternatives throughout its entire lifetime. Estimating LCA for whole-building design alternatives was performed using the Athena Impact Estimator calculator.

Entrepreneurial Mindset/Entrepreneurship. Following common usage, we regard entrepreneurial mindset and entrepreneurship as two connected but distinct concepts. Entrepreneurial mindset refers to the set of skills and attitudes underlying entrepreneurship, such as opportunity recognition, comfort with risk, creativity and innovation, flexibility and adaptability, among other. Entrepreneurship is the application of entrepreneurial mindset to specific entrepreneurial activities, such as commercializing an innovation, starting a business, customer discovery, etc.. Of the two , entrepreneurial mindset has the broadest application for designers moving into professional practice. While we hope some student teams participating in the Sustainable Design Accelerator will be able to begin commercializing their innovative designs, for the inaugural cohort the focus was primarily to encourage development of entrepreneurial mindset. To this end, student teams used a Lean Canvas Model (LCM) to create business and marketing plans for designs developed in the lab course. This tool reinforced the need for commercially viable solutions to sustainability challenges in the built environment, and required students to clearly articulate value propositions, identify customers, strategic partners, and marketing strategies, while developing quantitative estimates of costs and revenue, as well as a path to profitability. While there are other simple business models that could have been used, the LCM is already incorporated into existing entrepreneurial programs at our university, including NSF I-Corp. This allowed us to easily include those resources with the Sustainable Design Accelerator.

Digital Tools for Initial Design Validation. Prior to constructing physical prototypes, students used digital modeling tools to test performance of multiple iterations and narrow designs to a single option. To model performance of passive cooling systems developed in the lab course, students used the Autodesk CFD tool for Computational Fluid Dynamics (CFD) analysis. This tool simulates air flow through the proposed system, temperature drop due to direct and indirect evaporative cooling, and distribution patterns of cooled air within building interiors. Fig. 1 illustrates work for one of the passive downdraft cooling iterations attached to a single family residential unit developed by Nathan Albrecht, Colter Nubson, and Yu-Hsien Chou.

To model the whole-building performance of designs developed in the studio course, students used Solemma ClimateStudio to simulate daylight availability, energy consumption, and external surfaces incident radiation levels. In first step of massing development, each student in each team was asked to propose six massing iterations for their assigned project and create them nearly identical in square footage to compare one to the other in terms of energy consumption and incident solar radiation. A team of three would then select three out of the 18 iterations for the following step informed by simulation results and then select one out of the three iterations in the final step. Fig. 2 illustrates work developed by Colter Nubson for step one of the massing phase.

Physical Prototype Fabrication and Validation. Following digital modeling to select designs for physical prototypes, scaled prototypes of the teams' designs were constructed in the school's

Figure 3. Functional prototypes of passive cooling systems design from the lab course, 2021. Image credit Nathan Albrecht, Colter Nubson, Yu-Hsien Chou (left), Brittney Bland, Lydia Hansen, Jovannie Laforga (middle), Maggie Cooper, Jacob Dunn, and Logan Brown (right).

fabrication labs. Fig. 3 illustrates photos of final built prototypes from the lab course. The prototype in the left photo combines a two-stage direct and indirect evaporative cooling system at the top of the tower shaft. The prototype in the middle photo uses ceramic pots as a unit capable of being stacked into a wall element that cools the air flowing through the gaps between the pots. And the prototype in the photo to the right utilizes light weight materials capable of creating a demountalbe cooling tower that can be attached to portable structures or deployed in disaster relief locations.

Fabrication methods and materials prioritized needs for testing and experimentation, and students learned rapid construction methods using readily available materials. Physical testing of prototypes performance is currently underway, using a recently constructed environmental test chamber capable of simulating a range of exterior climatic conditions, including air temperature, wind speeds, and humidity levels. When complete, results from physical testing will be compared with previous results from digital modeling and simulation.

LAB COURSE LEARNING OBJECTIVES AND TEACHING METHODOLOGIES:

Phase 01 (3 Weeks): Introduction to Whole System Mapping and Life Cycle Assessment. Learning objectives: Acquire working knowledge of Faludi four-step WSM method, Ecolizer Eco Design LCA Database, and Ecolizer Excel calculator. Methodology: Use of tools to investigate environmental impacts of example household systems and devices (e.g., window-mount AC unit, ceiling fan, etc).

Phase 02 (4 Weeks): Preliminary Design and Computer Validation. Learning objectives: Acquire working knowledge of Computational Fluid Dynamics (CFD) software (e.g., Autodesk CFD). Methodology: Use of CFD analysis, as well as tools learned in Phase 01, to make evidence-based design decisions while developing innovative passive cooling systems for single family residential units in a hot, dry climate. This included review of passive cooling system precedents, and comparison of student designs with baseline passive and active systems.

Phase 03 (4 Weeks): Lean Canvas Model and Design Development. Learning objectives: Working knowledge of Lean Canvas Model (LCM) business planning, and development of a business model for commercializing innovative cooling systems developed in Phase 02. Methodology: Teams were introduced to the LCM and presented their proposed business models in a workshop with the director of our college's entrepreneurial education institute.

Phase 04 (5 Weeks): Design Finalization and Fabrication Plan. Learning Objectives: Preparation of fabrication plans, including: detailed shop drawings; bill of materials (BOM); and budget. Methodology: As originally conceived, each student team would have fabricated their own prototypes during this phase, using our school's fabrication labs and training resources. Due to COVID-19 restrictions, this phase was modified and all physical prototyping was instead carried out by a three-person fabrication team of paid student employees. Following fabrication, teams presented final designs, including built prototypes, to outside reviewers with expertise in LCA and product design. This feedback was incorporated in final revisions of the deliverables package submitted at the end of the course.

STUDIO COURSE LEARNING OBJECTIVES AND TEACHING METHODOLOGIES:

Phase 01 (2 Weeks): Site Analysis. Learning Objectives: Ability to synthesize available data and present a quantitative profile of both macro and micro site conditions including climate, history, demographics, and regulatory environment. Methodology: Student teams analysed existing site conditions and presented findings for review.

Phase 02 (3 Weeks): Case Study Analysis. Learning Objectives: Acquire working knowledge of daylighting simulation software tools, i.e., Solemma ClimateStudio. Methodology: Teams applied software tools to analyze daylighting performance of national and international mixed-use project case studies and presented findings for review.

Phase 03 (3 Weeks): Preliminary Design. Learning Objectives: Application of tools learned in Phase 02 to drive preliminary design decisions for the project introduced in Phase 01. Methodology: Teams developed multiple massing iterations for the project, and used software tools to rank iterations based on energy use intensity and external surfaces incident radiation levels. From this initial ranking, a subset of three iterations per team were selected for detailed daylighting simulation analysis to investigate optimal fenestration patterns.

Phase 04 (3 Weeks): Design Development. Learning Objectives: Application of Phase 01 and 02 analysis and tools, as well as LCA analysis tools introduced in the lab course, as a means to further focus and refine project development. Methodology: Teams selected a single preferred iteration from Phase 03 for continued development. Design development proceeded through daylight, energy, and external surfaces incident radiation levels simulations, coupled with whole-building LCA analysis for baseline materials.

Phase 05 (4 Weeks): Final Design. Learning Objectives: Application of learning outcomes from previous phases (including relevant lab course phases) leading to a comprehensive presentation of a schematic design. Methodology: Teams finalized designs and developed all presentation materials. Whole System Mapping and whole-building LCA analysis was used to optimize systems-level performance, user experience, and sustainability of building materials and operations for the proposed design. Proposed designs were presented to external reviewers.

DIRECT ASSESSMENT METHODS AND DELIVERABLES

Lab course design proposals were assessed in four areas: reduction of environmental impact of proposed system versus baseline systems, as analysed using WSM and LCA tools; iterative improvements in performance of the proposed designs, evidenced through CFD-modeled temperature drops and air velocity levels in the attached space; economic viability of the proposed designs, based on market research and customer discovery and demonstrated through a Lean Canvas Model business plan; and constructability of the proposed designs, based on the fabrication plans submitted to the fabrication team. Deliverables included: cumulative presentations of design process and progress, with required weekly revisions and additional new material; and production of comprehensive drawing sets and BOMs, as well as responses to RFIs from the fabrication team, resulting in fabrication of physical prototypes of their designs.

Studio course projects were assessed based on iterative design development, and modeled performance improvement in daylight availability, reduced energy consumption, and reduced environmental impacts. Deliverables included: digital slides and presentation boards communicating the overall design through site analysis materials, drawing sets and perspective renders; and graphic presentation of performance simulation and LCA results.

COVID-19 impacts and course modifications. As a consequence of the COVID-19 global pandemic, our university moved to online-only education for the 2020-2021 academic year, and this required significant modification to the proposed course sequence. All instruction, included design critique and workshops, were delivered online synchronously via the Zoom platform, and available asynchronously through recording of the Zoom sessions.

Online teaching significantly impacted fabrication and experimental evaluation of scaled passive cooling system prototypes developed in the lab course, and delayed completion of the environmental test chamber. Instead of each team building their own scaled prototype, as originally planned, all prototypes were constructed by a student fabrication team, from shop drawings and bills of material (BOMs) supplied by the design teams. One unexpected benefit of this method was that teams learned the importance of preparing accurate shop drawings and BOMs, as well as learning how to respond to Requests For Information (RFIs) from the fabrication team. This also allowed for comparable fabrication results for all teams. For similar logistical reasons, we eliminated physical model requirements from the studio course in favor of more performance simulation results.

EXIT SURVEY OUTLINE

At the end of the course sequence, students were asked to complete a five-question exit survey, assessing learning outcomes using a five-point Likert scale:

- Level of awareness in the knowledge areas before the course sequence.

Figure 4. Results from exit survey: Change in students level of awareness in the knowledge area before and after taking the course sequence. image credit Omar Al-Hassawi and David Drake.

- Level of awareness in the knowledge areas after the course sequence.
- Level of understanding in the knowledge areas.
- Ability to apply the knowledge areas in their designs.
- Likeliness of integrating the knowledge areas in their future work.

We elected to have the survey focus on understanding outcomes from the lab course. This is because the overlap was minimal between the two courses, all students in the studio course were in the lab as well, and all areas of knowledge were covered in the lab course.

The survey included multiple choice questions asking students about their preference in the school continuing to offer this content and their preferred method of delivery (online, in person, hybrid). It also asked the students to give a score for this course on a scale from 1 to 10 and to rank the areas of knowledge from their most to their least favourite. It ends with an open ended question asking students to provide any modifications/suggestions they have that we could consider incorporating in version 2.0 of this sequence.

RESULTS

Student Response rate. All 23 students responded to the survey.

Self-reported knowledge increases. Results indicated significant improvement in students' knowledge of the tools covered in this sequence as illustrated in Fig. 4. On a five-point scale, an increase in knowledge of two or more points was reported by students after taking the sequence. This result was reported by 75% of the students for the Whole System Mapping (WSM) and Life Cycle Assessment (LCA) tools, 65% of the students for the Lean Canvas Model (LCM) tool, and 40% for the Computational Fluid Dynamics (CFD) tool, and prototype construction. Sixty-five percent of the students reported four or five point scores in their understanding and ability to apply WSM, LCA, CFD, and prototype construction tools to a design project, and 50% of the class reported four or five point scores in their understanding and ability to apply the LCM tool to a design project. Furthermore, for all questions, at least 50% of students reported they were 'likely' or 'extremely likely' to use tools introduced in the course in professional practice.

Course evaluation and format preferences. The average score students gave of the course was 7.2 out of 10. A plurality of students (47%) recommended a hybrid format for future course delivery, with software tool workshops and design stages delivered online, and in-person delivery of prototype construction and evaluation. Of the remaining 53%, 40% recommended in-person delivery for the entire course. Only 13% of the students expressed a preference for entirely online course delivery.

Written comment summary. Key recommendations included improving delivery of the LCM and the CFD tools. It was also suggested the example household systems and devices analysed in Phase 01, as an introduction to use of WSM and LCA, could have been better matched to the design problem introduced in the following phases. Selected comments from the survey are as follows (lightly edited for clarity):

> "More focus on applying tools such as CFD in the design process. Introduce Lean Canvas Model earlier in semester. The duration of WSM was too long by comparison."

> "Bringing in entrepreneurial influencers earlier in this semester would be very helpful."

> "The different phases of the course were effective, but the Lean Canvas Model introduction was brief and could use more explanation. It would also be helpful to provide one more tutorial on using the CFD software. Overall it was an informative experience."

> "Finding some correlation between the given object we had in the first project to what we are doing now."

DISCUSSION

Not surprisingly, given that this was the inaugural delivery of the sequence, and given the novel circumstances surrounding the delivery, some outcomes fell short of goals and expectations.

In addition to challenges due to COVID-19, expected integration of the lab and studio courses proved difficult. Not only was studio course enrollment much smaller (meaning most of the lab course students were disconnected from the studio course), it became apparent a few weeks into the semester the courses were progressing at different rates with respect to design development, with the studio course lagging behind the lab course. We attribute this to the much larger scale of the studio project (a mixed-use multifamily residential project on a 100,000 SF site). Accordingly, plans were dropped for overlapping major reviews at the end of each phase, wherein teams in one course would present their findings to teams in another. Significantly, the disconnect between courses made it impossible to incorporate innovative building systems designed in the lab course into the studio design, as originally envisioned. Moreover, entrepreneurial training introduced in the lab course played no role in the studio design project.

However, in spite of the need to pivot from planned in-person course delivery to online instruction, all lab course student teams were able to learn and apply a complex suite of software tools, and develop innovative passive cooling system prototypes, together with detailed plans for bringing the systems to market. Students who took the studio course concurrent with the lab course were able to apply tools learned in the lab course to a challenging design project, resulting in quantitative improvement in modeled design performance compared to initial design concepts. Reaction of external reviewers to final presentations of student team work in both courses was overwhelmingly positive.

CONCLUSIONS

Based on our observations as instructors, on insights shared by external reviewers, and on results of the student exit survey, we have identified three areas for improvement in future iterations of the Sustainable Design Accelerator:

- Increased integration of the lab course and studio course, as well as increased integration of individual phases within each course.
- Increased role for entrepreneurship and entrepreneurial mindset, especially in the studio course.
- Optimized introduction of software tools, including sufficient lead time for mastery of complex tools, and less time devoted to introduction of tools that have proved easier to grasp.

These areas will be addressed through the following revisions when Version 2.0 of the sequence is delivered Spring 2022:

Better integration between courses:

- Create more meaningful overlap between the lab and studio courses by assigning a smaller scale project and smaller site for the studio course. This will allow students to have a design in place by mid-term and to dedicate more time for estimating building performance and whole building environmental impacts.
- Use the same site (or at least sites with equivalent climatic conditions) for the lab and studio courses.
- Better distribution of students concurrently enrolled in studio and lab courses. Ideally, each lab course team will include at least one student in the studio course.

Increased role for entrepreneurship:

- Incorporate more experts in business innovation and product design earlier in the semester, along with simultaneous introduction of the LCM. This will encourage entrepreneurial thinking during formative stages of design, rather than superficial application later in the process.
- Encourage students to seek concurrent in-depth entrepreneurial training, through entrepreneurial programs offered by our college and university (including the NSF I-Corp Teams program), or by accessing entrepreneurial materials available through the external funding organization.
- Build entrepreneurial mindset into the studio course as well as the lab course, by using the concepts underlying the Lean Canvas Model as a tool for analysing the viability and sustainability of proposed projects in both courses.

Optimized introduction of concepts and software tools:

- Invite students who took Version 1.0 of the sequence to be peer-to-peer mentors, helping V. 2.0 teams grasp concepts and tools, and develop ideas.
- Continue to make software workshops and tutorials available online, even with the majority of course content returning to in-person delivery. This will continue to allow for asynchronous self-paced learning, better tailored to individual time commitments required for tool mastery.
- Choose case-study household systems and devices (Lab course, Phase 1) more clearly related to the design challenge introduced in subsequent phases.

The return to in-person instruction for the 2021-2022 academic year provides an opportunity to compare outcomes between the different modes of instruction in Versions 1.0 and 2.0. This is an area for future research.

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