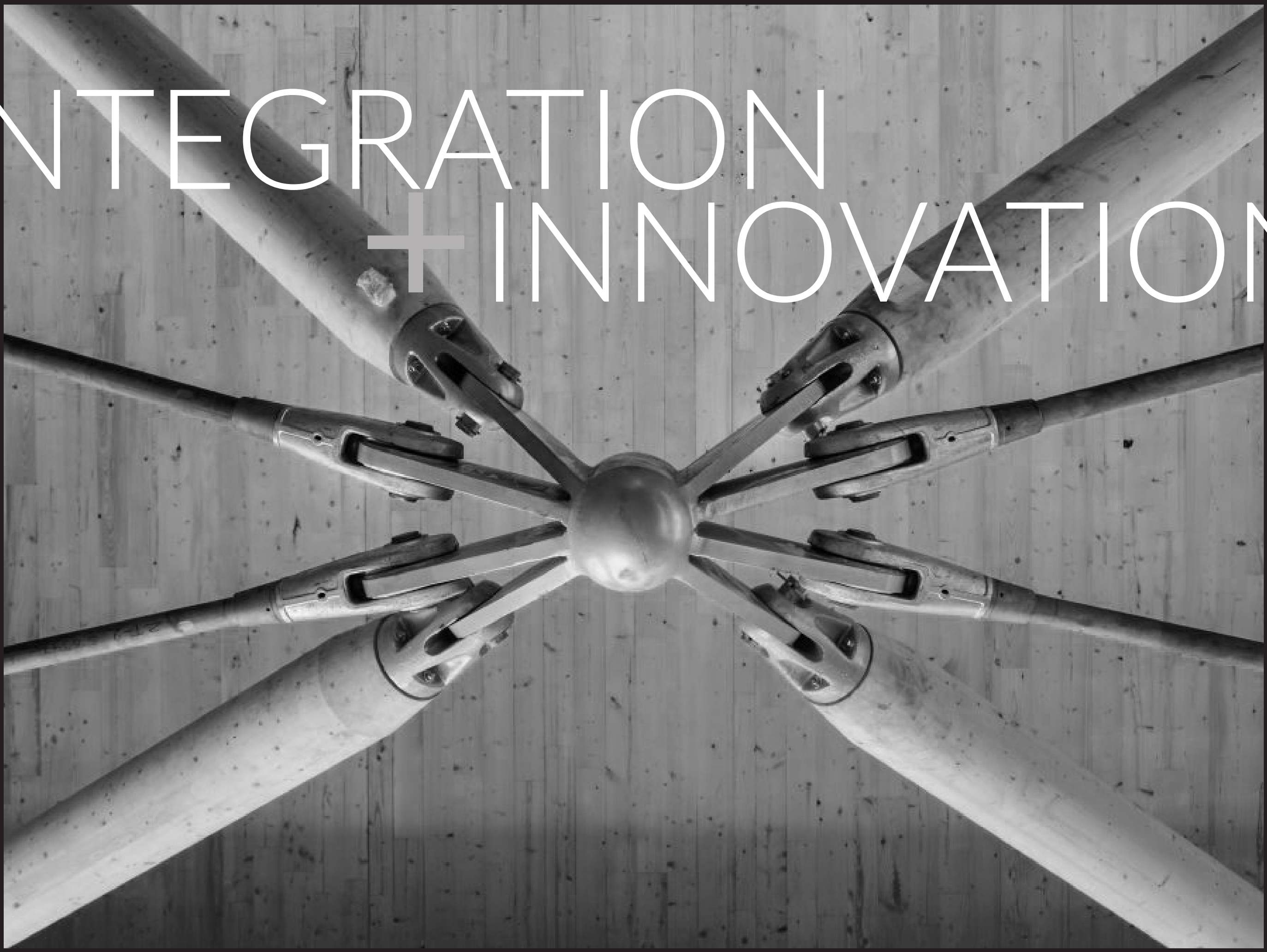
INTEGRATION + INNOVATION



PROCEEDINGS OF THE 2019
BUILDING TECHNOLOGY EDUCATORS' SOCIETY CONFERENCE
UNIVERSITY OF MASSACHUSETTS AMHERST

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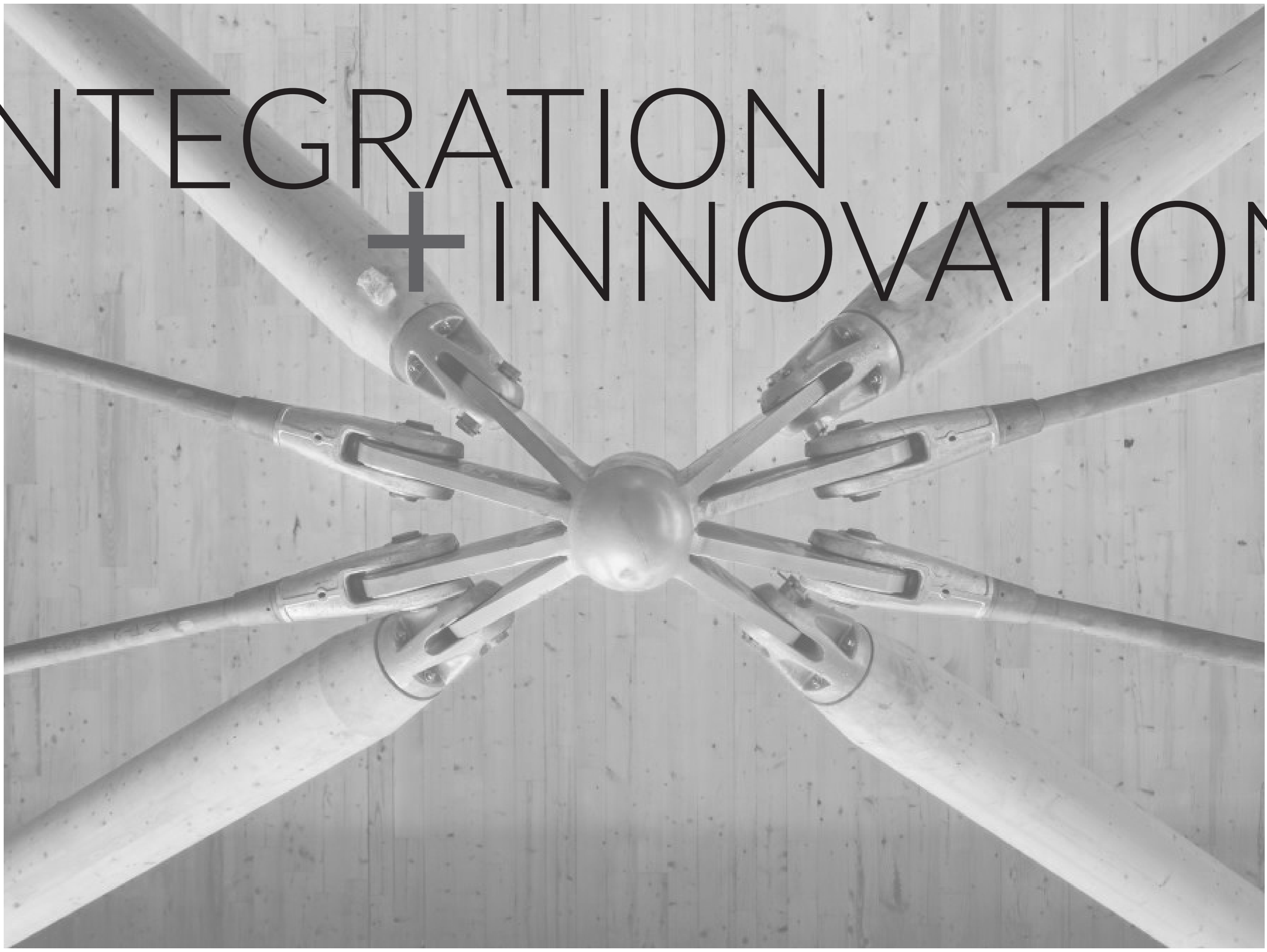

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BTES
BUILDING TECHNOLOGY EDUCATORS' SOCIETY

Edited by

Caryn Brause
UMass Amherst

Peggi L. Clouston
UMass Amherst

Naomi Darling
Mount Holyoke College // UMass Amherst

INTEGRATION + INNOVATION

Proceedings of the 2019 Building Technology Educators' Society Conference
June 19-22, 2019, University of Massachusetts Amherst

2019 Conference Co-Chairs

Caryn Brause Associate Professor, UMass Amherst
Peggi L. Clouston Associate Professor, UMass Amherst
Naomi Darling Assistant Professor, Mount Holyoke College // UMass Amherst

BTES Officers

BTES Board of Directors

BTES Mission Statement

The mission of BTES is to promote and publish the best pedagogic practices, relevant research, scholarship, and other creative activity to facilitate student learning, advance innovation, and enhance the status of building technology disciplines in the profession at large.

The Building Technology Educators' Society:

- shares the best architectural technology teaching practices
- hosts critical discourse in focused research areas
- enhances the mentoring process among faculty, students, and practitioners
- hosts discussions among building technology researchers and professionals
- facilitates connections and between researchers, professionals, industry, and associated regulatory agencies

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INTEGRATION + INNOVATION

ABOUT THE THEME

Following on the alliterative themes of recent BTES conferences, we have selected Integration and Innovation as the theme for the 2019 gathering. Innovation can begin with conjecture, with a searching for more effective solutions, or with an application to currently unknown or unarticulated needs. Innovation scholarship examines the personal intellectual habits that support new ideas, such as openness and exploratory behavior, as well as the circumstances behind the places in which creativity flourishes, such as support for cross-disciplinary fertilization and access to resources. The 2019 BTES conference will explore the role of technology education and curriculum in cultivating these intellectual habits in our students (and ourselves) and in creating the organizational spaces in which the future of practice will be shaped. Sessions will seek exemplary proposals of research and pedagogical applications that explore innovative practices and integrative thinking in the academy and profession.

These intertwined themes of innovation and integration are deeply embodied in the host site, the award-winning John W. Olver Design Building at the University of Massachusetts. Named one of the Best Buildings of 2017 by the Wall Street Journal, the 87,000 square foot building counted a number of superlatives at its opening, among them, the most technologically advanced cross-laminated timber building in the country. However, while we are delighted by these accolades and the building's warm appeal, it is the organizational potential that the site embodies that makes it a fitting site for the 2019 BTES Conference.

THE VENUE

Housing the university's architecture, building and construction technology, landscape architecture, and regional planning programs, the collective effort to realize the Design Building was launched to "represent the thoughtful integration of human creativity and ecological sensitivity that is the foundation of our professions."

The Design Building is a fitting backdrop for the sharing of BTES members' own innovative research and pedagogies. The structure is a testament to faculty ingenuity, political acumen, and creative collaboration: some of the building technologies employed, such as the layered composite floor system of concrete, timber, and steel mesh, were researched and developed by faculty right on campus. Moving from invention to application involved garnering the political support of a former congressman and the MA State Legislature, who ultimately activated the shift from the status quo steel frame to a demonstration project for new and innovative wood construction technologies through an Environmental Bond Bill. To deploy these innovations spatially, the architects and engineers collaborated closely with code officials to shape new codes while creating a building that is now a primary teaching tool for our students—from its exposed glulam and cross-laminated timber (CLT) frame, to its visible mechanicals and interdisciplinary teaching spaces.

The bulk of the conference's educational events will be taking place in the John W. Olver Design Building on the UMass Amherst Campus. The John W. Olver Design Building is the shared home of the Department of Architecture, the Building and Construction Technology program, and the Department of Landscape Architecture and Regional Planning. At its core, the Design Building has a contemporary, heavy-timber ("mass timber") wood structure, consisting of an exposed glulam frame (columns, beams, braces), cross-laminated timber (CLT) and concrete composite floors, and CLT shaft walls (for stairs, elevator, and mechanical shafts). It also features a three-story, folded, grand CLT stair in the atrium.

Caryn Brause
Peggi L. Clouston
Naomi Darling

OPENING PLENARY SESSION:
From Innovation to Implementation: Bio-Based Building Technologies from UMass Amherst

Plenary Description

In early 2017, the University of Massachusetts Amherst opened the John W. Olver Design Building – a 4 story structure that demonstrates leading-edge mass timber technologies. The building features an exposed glued-laminated timber column-and-beam frame, mass timber lateral force-resisting systems, and hybrid cross-laminated timber concrete floor systems informed, in part, by the presenters' own wood mechanics research group. This presentation will highlight the innovative structural use of wood in the building and discuss recent and ongoing research projects within the Building and Construction Technology (BCT) program at UMass on developing novel bio-based composites through numerical and experimental techniques.

PLENARY SPEAKERS

Peggi Clouston, PEng, MASc, PhD
Associate Professor of Wood Mechanics and Timber Engineering, UMass Amherst

Dr. Clouston has been working in the field of timber engineering for almost 30 years. As a Professor at the University of Massachusetts Amherst, she teaches structural timber design and material mechanics to students of architecture, engineering, and construction technology. Author of more than 80 publications, she conducts research on the structural behavior and efficient use of mass timber and bio-based composite materials. Current research topics include: cross laminated timber (CLT) panels from low-value eastern wood species, wood-concrete composite floor systems, computational modeling of structural composite lumber, and laminated veneer bamboo connections. Dr. Clouston has been a registered professional engineer (EGBC) since 1992. She is Associate Editor of the ASCE Journal of Materials in Civil Engineering and serves on numerous federal peer review panels and committees.

Alexander Schreyer, MASc, Dipl.Ing
Program Director of Building and Construction Technology, UMass Amherst

As Director of the Building and Construction Technology program and faculty in ECO and Architecture at the University of Massachusetts Amherst, Mr. Schreyer has been teaching classes in digital design, Building Information Modeling (BIM), and building materials and systems for over 15 years to a varied audience of students and professionals coming from construction, engineering and architecture backgrounds. He is the author of "Architectural Design with SketchUp," co-author of "Fundamentals of Residential Design," and he has published various extensions for SketchUp. In addition, Mr. Schreyer's background encompasses structural engineering, wood science and heavy-timber construction. He teaches and conducts research in structural wood systems and regularly speaks at national and international conferences.

OPENING KEYNOTE: Timber

Yugon Kim

Founding Partner, IKD, Cambridge, MA

Yugon Kim is a founding partner of IKD– a cross-disciplinary design studio in Cambridge, MA specializing in exhibition design – and director of TSKP Architects Boston. Prior to establishing IKD, he worked with the Renzo Piano Building Workshop in Genova, Italy and in Boston, where he oversaw the recently completed addition at the Isabella Stewart Gardner Museum. He has also worked at Carlos Zapata Studio in New York City, and he chairs the Boston Society of Architects Museum and Exhibition Design Committee and co-chairs the Harvard Asian Alumni Alliance in Boston. In addition to teaching at RISD, he has taught design studios at Wentworth Institute of Technology and Northeastern University. Before studying architecture, Kim was a sculptor and also worked as a custom furniture fabricator, where he discovered his love of materials and craftsmanship. He earned a master's

Keynote Description

With its smaller carbon footprint, timber construction should be considered alongside steel and concrete to build both low and mid-rise projects. With buildings in the U. S. accounting for 38% of all carbon emissions and with population growth on the rise, we must reconsider how we construct our buildings. Climate change can be combated in two ways –by reducing carbon emissions and by removing carbon from the atmosphere – and timber is unique in that it is the only building material that can do both. Recent innovations in timber technology is paving the way for timber once again to become integral to the fabric of cities, at this pivotal moment in time." Yugon Kim will introduce recent innovations in timber technology, and through his own research demonstrate the wide range of benefits for timber-based construction. He will focus primarily on his ongoing research of the material development of the first commercially pressed Hardwood CLT that lead to the construction of the first hardwood CLT project in the United States using grade 3 common mix species hardwoods.

CLOSING KEYNOTE: Critical Questions for the Future of Sustainability

Michelle Addington

Dean, School of Architecture
University of Texas at Austin

Michelle Addington is dean of The University of Texas at Austin School of Architecture, where she holds the Henry M. Rockwell Chair in Architecture. Formerly, she served as Gerald Hines Chair in Sustainable Architectural Design at the Yale University School of Architecture and was jointly appointed as a Professor at the Yale University School of Forestry and Environmental Studies. Originally educated as a mechanical/nuclear engineer, Addington worked for several years as an engineer at NASA/Goddard Space Flight Center and for E.I DuPont de Nemours before she studied architecture. Her books, chapters, essays, journal papers, and articles address topics ranging from fluid mechanics to the History of Technology to smart materials, and she has consulted on projects as diverse as the Sistine Chapel and Amazon rain forest.

Keynote Description:

As we stand by while we speed past climate change's warming limit of 2° C, after having already passed the 400 ppm CO_2 threshold a few years ago, we must step back to question the value and ultimate effectiveness of the strategies our discipline has been so wedded to over the last three decades. Unquestionably, there have been enormous strides in analysis and simulation, in the development of new technologies and materials, and in the collective commitment to bring sustainability to the design of the built environment. As much as these strides have advanced our field, they have not only been unable to reduce emissions, they have not even been capable of stemming the continuing rise in emissions. This presentation will look back at the questions and frameworks that may have led us astray, and pose alternatives that may help us right our course in the future.

CALL FOR PAPERS

To foster discussion on Integration and Innovation, the BTES 2019 Conference Committee seeks papers and projects on a broad range of topics that address the external forces advancing our work, as well as the internal inventiveness driving our research and our pedagogies. How can our spaces, organizational structures, and pedagogical platforms create new interdisciplinary approaches to problem framing and solving? How might experiencing physical construction cultivate new collaborative understandings and stimulate new forms of design knowledge? And how might new visualization and analysis technologies provide a platform for emergent forms of communication to better facilitate this integration? Papers and projects that address the interaction, collision, and synthesis of diverse knowledge stocks are particularly welcome, but we look forward to a broad mix of approaches that will encourage interaction and inspiration, argument and debate.

Paper and project submissions are intended to explore projects, pedagogies, methodologies, research, and best practices in building technology education. Papers and projects across all thematic categories will be reviewed by subject matter experts to provide content-specific peer review. All submitted papers and projects should refer to and build on relevant scholarly literature within their respective fields including practice, research, education, and design.

CONFERENCE KEYWORDS:

- Materials + Construction Techniques
- Structures
- Energy + Systems
- Landscape Technologies
- Computational Design + Analysis
- Design/Build
- Professional Practice
- Pedagogy

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CONFERENCE PAPERS

Integrative Design and the Problem of Fragmented Knowledge

Dustin Albright, Ufuk Ersoy, David Franco and Ulrike Heine
Clemson University

Abstract

During its 2017 NAAB accreditation, the School of Architecture at Clemson University received high marks for *Integrative Design*, having met this criterion "with distinction." The report stated: "*There was ample evidence… from the comprehensive design studios that students possessed the necessary abilities and skills to synthesize a broad range of contextual, design, and technical considerations into an integrated design solution…. The quality of the projects is high, which is in large part due to collaborative teamwork*." Undergirding the effective collaboration of the students, the Comprehensive Studio thrives on a careful schedule plus measured team-teaching from the faculty.

The Studio comprises 30-40 M.Arch students, working in pairs. The projects typically range from 30,000 to 60,000ft^2, and feature complex programs. The site and building design phases fill the first half of the semester, with the remainder focusing on technical development.

Overseeing this is a versatile team of instructors possessing professional experience and diverse expertise – from history/theory, to zero-energy design, to structural systems. This addresses, in a critical way, the notion of integration. Too often, the design studio is set up to recognize alpha designers, under the tutelage of the sage instructor. This leads to fragmented knowledge. Our approach instead emphasizes distributed knowledge while embracing ambiguity when it arises. On the one hand, the instructors' expertise is complementary, promoting robust, integrated design solutions. On the other hand, our critiques sometimes conflict, presenting a purposeful challenge and demanding that students carefully consider each position and chart a path forward. The projects are tested and refined by the process. This methodology has been honed over six years with decidedly positive outcomes and supportive student feedback.

This paper presents these methods and considers both the successes and challenges of directing integrative design studios in this manner. This analysis is supported with student samples and course feedback.

Introduction

The Graduate Comprehensive Studio at Clemson University is the concluding studio course in the M.Arch curriculum. It is required in lieu of a thesis.[1] The studio generally comprises 30–40 M.Arch students in their final semester, typically equating to three sections for the course. It is our practice to blend these sections and co-teach across the entire group. There is a single project spanning the entirety of the semester, and students work in pairs from start to finish.

The course's catalog description reads: "Architectural design studies addressing comprehensive building projects. Topics include site design, programming, building systems design and materials selection. Final product is a complete building design with detailed drawings and models." The broader objective stated in the syllabus is "to balance the extensive and complex technical, functional, and theoretical aspects of architecture with the creative and humane qualities of architecture."

Within our program, the specific NAAB student performance requirements (SPC's) assigned to the Comprehensive Studio are as follows:

> **B.3 Codes and Regulations:** Ability to design sites, facilities and systems that are responsive to relevant codes and regulations, and include the principles of life-safety and accessibility standards.
>
> **C.2 Integrated Evaluations and Design-Making Design Process:** Ability to demonstrate the skills associated with making integrated decisions across multiple systems and variables in the completion of a design project. This demonstration includes problem identification, setting evaluative criteria, analyzing solutions, and predicting the effectiveness of implementation.
>
> **C.3 Integrative Design:** Ability to make design decisions within a complex architectural project while demonstrating broad integration and consideration of environmental stewardship, technical documentation, accessibility, site conditions, life safety, environmental systems, structural systems, and building envelope systems and assemblies.

There are two corequisite courses, Professional Practice 2 and a course titled "Building Processes: Technical Resolution." These courses and the ways in which they dovetail with the Comprehensive Studio will be discussed later. A fourth course, Architectural History and Theory 4, is also completed at the same time, though it is not as explicitly linked to work of the studio.

History of the Comprehensive Studio at Clemson

The M.Arch program at Clemson University consists of a 6-semester track and a 4-semester advanced placement track. These two streams join in semester 3, with both cohorts being blended from that point forward. Semester 3 is highly structured, featuring a team-taught studio, Professional Practice 1, Research Methods, and Materials and Assemblies. Semesters 4 and 5 are considered "fluid" and invite students to study in one of our three off-campus programs. Students electing to stay at the main campus would take part in elective studios during that time. All students regroup on campus for semester 6 to complete the Comprehensive Studio and the other required courses mentioned above.

The evolution from a required thesis to the current Comprehensive Studio model involved multiple steps. Prior to 2005, all M.Arch students completed a thesis project over the course of their final year in the program. At that time, the "fluid" semesters, described above, occurred in semesters 3 and 4, leaving 5 and 6 for the thesis. During the 2005-06 academic year, an early version of the Comprehensive Studio was introduced as an alternative path to completion. The thesis technically remained an option in the graduate catalog (until 2010-11), but few, if any students elected to go that route. For the next couple of years, the Comprehensive Studio was held in semester 5, leaving semester 6 for a "Research Studio" in which course projects were linked to ongoing faculty research. The results of the Research Studio were uneven and it generally proved to be a disappointing way to end the M.Arch program. Eventually the Comprehensive Studio was moved to semester 6, where it remains today, and the Research Studio was later dropped.

Regarding the Comprehensive Studio itself, there was a series of structural improvements that led to the current format. Up until 2008, students worked individually on their Comprehensive projects. In the Fall of that year, they were instead teamed in pairs. This tended to lead to stronger work, primarily because it required internal collaboration. Beyond the questions and critiques of contributing faculty, each student now faced a steady stream of alternative ideas from their design partners.

This led to more vetting, reworking and, ultimately, refinement.

A form of co-teaching began in 2009, first with two faculty, and later with three in the years that followed. The instructors had each come from professional practice and were guided by their experiences of distributed expertise, modeled within their firms and across their relationships with project consultants. Thus, each took on the responsibility of contributing from her/his complementary knowledge base - from material exploration and methods of construction to passive energy strategies to structural systems. The quality of student work at this time (2010-2012) was notably strong, including numerous successes in student design competitions.

Fig. 1. Professors Heine and Ersoy, Spring 2018

However, significant operational challenges stemmed from the fact that there were still three distinct sections working on three different projects. At the time, the instructors (each in a tenure track) were encouraged to steer their sections' projects toward their individual research interests – perhaps as a holdover from the Research Studio. This approach, however, made it difficult for the instructors who, desiring to work together, had to keep up with each other's projects and evaluate students with consistency across a range of programs and scales. Beginning in 2013, the Comprehensive Studio moved to a true team-taught model, with blended sections and a common project. This general approach has remained consistent since that time.

Comprehensive Studio Faculty

Since 2013, there has been a steady cast of instructors for the Comprehensive Studio. Together, they draw from a diverse range of professional experiences and academic knowledge bases. For context, the expertise of each instructor is described below.

Ulrike Heine hails from Berlin, where she first specialized in highly technical, net-zero-energy design. Among other things, she contributes knowledge in balancing passive design strategies with well-tuned mechanical systems. Professor Heine served as coordinator for the Comprehensive Studio until 2015, when she assumed the role of Assistant Director in the School. Dustin Albright, from the U.S., possesses a dual background in structural engineering and architecture. A licensed architect, Professor Albright has worked professionally on a wide array of project types, with particular interests in structural systems and building tectonics. He has served as Comprehensive Studio coordinator since 2015. Ufuk Ersoy, hails from Izmir, Turkey, and practiced and taught internationally prior to arriving at Clemson. He teaches in the area of architectural history and theory, with a particular interest in metaphorical thinking and the role of memory in architectural imagination. David Franco comes from Madrid, where he practiced for many years. In addition to teaching materials and methods courses in the School, he teaches in the area of history/theory. His scholarship revolves around the social and political aspects of modern and contemporary architecture. Professors Ersoy and Franco have tended to teach the studio in alternating years, with Professors Heine and Albright teaching every year.

Supportive Courses

The first of the co-requisite courses, Professional Practice 2, covers NAAB SPCs B.3 (Codes and

Regulations), B.10 (Financial Considerations), D.1 (Stakeholder Roles in Architecture), and D.4 (Legal Responsibilities). It is structured around the topics of zoning regulations, building codes and cost analysis. These lessons are applied throughout to each student's Comprehensive Studio project. Products include a site and zoning plan, a life-safety plan, and a detailed estimation of project costs.

The second co-requisite course, "Building Processes," operates as a technical support seminar to the Comprehensive Studio. It addresses SPCs B.4 (Life Safety), B.5 (Technical Documentation), B.6 (Environmental Systems), B.7 (Structural Systems), B.8 (Building Envelope Systems), and B.9 (Building Service Systems). Lectures on these topics and their integration within architectural projects are presented during the first half of the course. The second half involves application to the Comprehensive Studio projects, during which time the "Building Processes" instructors act as technical consultants to the design teams. This coincides with the technical resolution phase of the comprehensive projects, described in the next section.

The Comprehensive Project

The projects selected for the Comprehensive Studio tend to fall in the range of 30,000 to 60,000ft^2. They feature complex programs with multiple uses. Some examples from past years include: a live/work development, a performing arts center, a university student center, and, most recently, an urban high school (in 2017), and mixed-use graduate student housing (in 2018). In each case, a base program is provided as a starting point. Students are also invited to propose program additions, provided that they are well-conceived and defended. In the case of the high school, for example, students were challenged to think of programming that could double as after-hours community amenities – such as maker spaces, gym spaces, cafés, etc.

Project locations are almost always within a 3-hour driving distance from our campus, providing the class with opportunities to visit and get to know the context. Typically, students are given choices of specific sites within the larger location. For example, in the case of the high school, students were provided four potential sites within the fabric of downtown Anderson, South Carolina. These sites were preselected by the faculty according to considerations for access, available footprint, and the potential for the new school to complement and/or reshape the spatial and programmatic structure of its setting. Students then begin with a detailed analysis and selection of site. Wild card sites are sometimes permitted if the students make a compelling case.

Project Sequence

The sequencing and pacing of the project, along with the timing and manner of critical feedback from the faculty, have proven to be decisive forces for project success. Broadly speaking, the semester is divided into two predominant phases: initial project design and technical development. In order for students to achieve the level of technical depth required by the course and its associated SPCs, the instructors have found it essential to allocate a third of the course schedule for the resolution of technical systems (structural, environmental and envelope), prior to final documentation. This means that the earlier design sequence (site analysis, programming, building planning and design) must be entirely completed during the first half of the course.

This pace can be jarring for students, who are generally unaccustomed to making resolute design decisions so early in a project. The structure of the course deliberately accelerates analysis, ideation and response, preventing participants from languishing uncommittedly between concepts. The decision to have students work in pairs is particularly helpful at this juncture. Whereas the extra set of hands makes practical sense for increasing productivity in the later documentation stages, the partnership serves to generate internal discussion and fruitful criticism in the early design stages.

Within this overarching framework, there are numerous intermediate stages and deadlines, set to motivate intensity of focus, and to keep the projects on track. Each of the stages is described in detail in the following section. For clarity, the urban high school project from 2017 will serve as a reference point throughout.

Stage 1: Site Selection, Analysis and Concept Forming (2-3 weeks)

Upon introducing the project, the Studio jumps into detailed analyses of the available sites and comparisons of their challenges and opportunities. In the case of the 2017 project, students tackled this first step in larger teams of five or six, traveling together on the first afternoon to the city of Anderson, less than 20 miles from our campus. In this case, site studies addressed topics of adjacent uses and vacancies, parking and parking utilization rates, established pedestrian routes, traffic and noise, etc. The student teams shared their analyses and their preferred site (from among the four suggestions) during a presentation the following studio period.

Fig. 2. Analysis of existing parking (by Kaylan Betten and Amelia Brackmann, 2017)

It is also within these first couple of meetings that the Studio is introduced to any external project partners, who often serve as advisors and critics throughout the process. In this case, we welcomed an arts teacher and an administrator from an innovative local high school[2] who described their unique project-based learning model and its implications for their facilities and operations.

In the following week, the Studio works through initial programming and spatial design concepts, working now in pairs. As a base program for the 2017 project, students were given a list of required program elements (classrooms/labs, media center, dining, assembly hall, health clinic, administration, and support) and provided a reference program (including space allocations) from an existing high school in the area. As mentioned above, students are given license to propose program additions and/or hybridizations, as may benefit the project.

It is customary for studio faculty to divide up at this stage and meet individually with the student pairs. This ensures that every group receives ample time with instructors during each studio session at this early juncture. Instructors then rotate from session to session, seeing different projects on successive days. This introduces each instructor to the whole range of projects while also providing each design team with multiple perspectives on their foundational concepts and actions. Often, the comments of the faculty align and reinforce each other. Sometimes, the comments are in conflict. This possibility is embraced by the instructors (though it sometimes frustrates the students) because it requires a process of critical thought and interpretation, wherein teams must adopt one path or the other, or perhaps chart a third way. In any case, their response tends to be well-considered, and projects are generally improved through this tension.

Fig. 3. Conceptual program organization (by Kaylan Betten and Amelia Brackmann, 2017)

The initial project concepts are presented in a first formal pin-up during the third week. Students are often encouraged to present multiple schemes at this stage and lead a discussion of each scheme's merits relative to programmatic objectives and site parameters.

Stage 2: Massing and Building Planning (2-3 weeks)

The second stage picks up with site design, building planning and massing studies. Students negotiate topographic conditions, issues of scale, orientation and circulation through iterative massing models. These are performed in parallel with initial plan and section drawings. Student teams explore precedent projects, often receiving particular guidance from Professors Ersoy or Franco in areas ranging from typological studies to urban design theory.

The course faculty continue to meet individually with students, rotating from session to session, as with the earlier stage. Occasionally, they will team up to meet with any students who are falling behind or struggling with some aspect of the project. In these cases, the instructors are able to efficiently gauge the project's status, and together recommend next steps to take and a schedule by which to take them. This way, each instructor is on the same page and knows what, specifically, to be expecting in subsequent meetings with these particular teams. The work from this second stage is again presented in a formal pin-up.

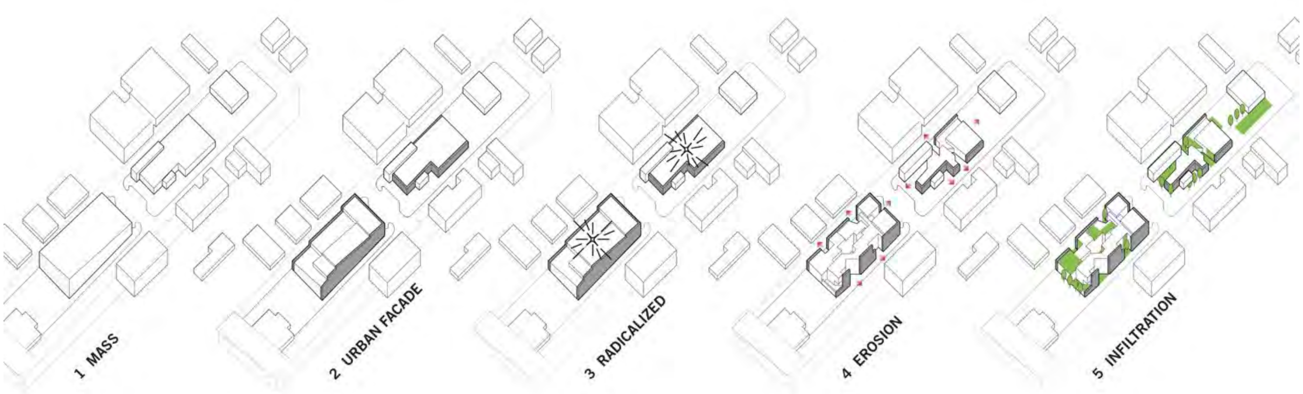

Fig. 4. Building massing diagrams (by Kaylan Betten and Amelia Brackmann, 2017)

Stage 3: Final Schematic Design (2 weeks)

Next, students are allotted a couple of weeks to refine their site and building designs. The floor plans and associated sections are closely evaluated at this stage. They are appraised for efficiency (in circulation, in the stacking of wet functions, etc.), and for issues of life safety and accessibility. It is at this time that the projects undergo a detailed plan review with a building code official in the accompanying Professional Practice course.

The designs are examined broadly for load path continuity, bay size, improbable overhangs, and other early structural issues that may have immediate implications for the plans. Professor Albright tends to advise in these discussions. The projects are likewise evaluated, at a schematic level, for adequate daylighting and appropriate shading. Professor Heine takes a leading role with passive design strategies and helps teams premeditate synergies with their eventual mechanical and lighting systems.

Stage 3 concludes with a formal pin-up. Outside critics are welcomed in at this point, including any project partners. Colleagues from Landscape Architecture are often included for their input on site design. Importantly, this review marks the cut-off point for the overarching "design" phase. Students are given the remainder of the week and weekend to respond to critics' remarks and make any necessary revisions to their projects. Beyond that point, the Studio moves into its extended period for technical development and resolution.

Stage 4: Technical Resolution – Structure (1 week)

The first of the technical resolution stages focuses on structural systems. One intensive week and weekend is allotted for this work, and, under the direction of Professor Albright, students are required to produce three coordinated deliverables. The first is a scaled physical model of the entire structural frame. This forces students to visualize the systems in three dimensions, identifying primary, secondary and, sometimes, tertiary components. They evaluate direction of flooring/roofing systems and lay out appropriately spaced supporting members. The model quickly exposes any discontinuities in their planning. It also provides an excellent vehicle for discussions of lateral force design. Finally, it forces students to tackle any unique challenges presented by the massing. It is stressed that these models are working models, intended to be modified with each successive consultation.

Stemming from the model, the second deliverable is a set of structural framing plans for each level, plus ground floor foundation plans. Students are not asked to calculate member sizes. Instead, the course's required reference text helps with general estimations of slab thicknesses, beam depths, and column dimensions, while also providing a good overview of the material systems at work.[3]

The third deliverable is a set of structural diagrams articulating load path and system hierarchy. Building upon the physical model, this last requirement ensures that students understand the system at a deep level, to the point that they can illustrate how it is really working.

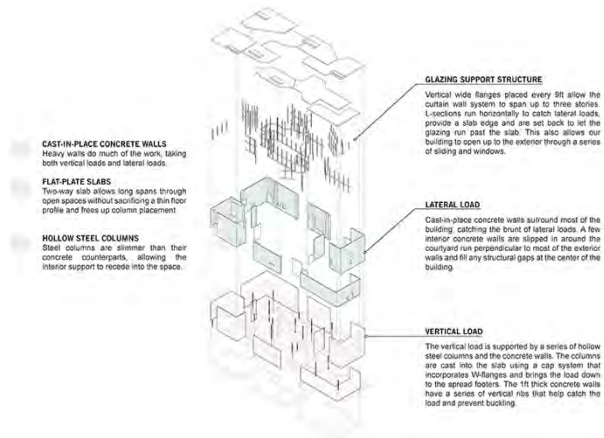

Fig. 5. Structural hierarchy diagram (by Kaylan Betten and Amelia Brackmann, 2017)

The rigor of the structural resolution stage is particularly critical in light of the fact that many of our 2-year M.Arch students will not take dedicated Structures courses in our program. Instead, they bring with them the equivalent courses from their undergraduate institutions, which often vary in quality. Moreover, it may have been many years since a given student completed these undergraduate courses. Such differences in comfort and proficiency are discernable each year, and the structural stage of the project provides the chance to iron out some of the wrinkles.

Unlike the earlier stages, Studio faculty tend to visit with student teams together at this point and for the remainder of the technical resolution work. This ensures that students are receiving coordinated advice on the finer points of the projects. Some discrepancies can arise at these stages from the consulting instructor(s) of the "Building Processes" corequisite, whose consultation times fall outside of the studio sessions. It is incumbent upon both course's faculty to maintain good communication throughout, and that students learn the pros and cons of any competing technical solutions.

Stage 5: Technical Resolution – Environmental (1 week)

Following structure, the next stage focuses on environmental systems. Here, students are required to select and lay out appropriate HVAC solutions. Again, they use the course text to help with selection and approximate sizing of mechanical equipment and ducting. Professor Heine works with students to integrate their earlier notions of passive ventilation, where appropriate, and each team is required to produce mechanical plans plus detailed spatial diagrams communicating the circulation of air, or water, in the case of radiant systems. Students are required to confirm that ductwork is not in conflict with the structural systems laid out in the previous stage. In some cases, this requires reevaluation of one or both systems. Importantly, all M.Arch students complete a required environmental systems course in the preceding academic year, and so are prepared with a fundamental knowledge. That being said, the comprehensive project provides the first real design application of this knowledge.

Fig. 6. Mechanical system diagram (by Kaylan Betten and Amelia Brackmann, 2017)

Stage 6: Technical Resolution – Envelope (2 weeks)

The development of the building envelope occupies the final two weeks of technical resolution. At this stage, the collective professional experiences of all the studio faculty come into play, and all are equally involved in advising students. Student teams are generally required to produce at least three annotated wall sections, typically ¾" = 1ft in scale. Each section must extend from the foundation to the roof, and any window or door openings should be emphasized. Additional sections at a larger scale are often required to capture the finer details.

Design teams will go through multiple iterations of the wall sections, printed out and marked up during each studio session. Customarily, each team member will be required to author at least one of the drawings, ensuring that both partners have mastered the content. This is one measure taken to prevent partnerships from devolving into siloed work under the pressure of producing within a tight schedule.

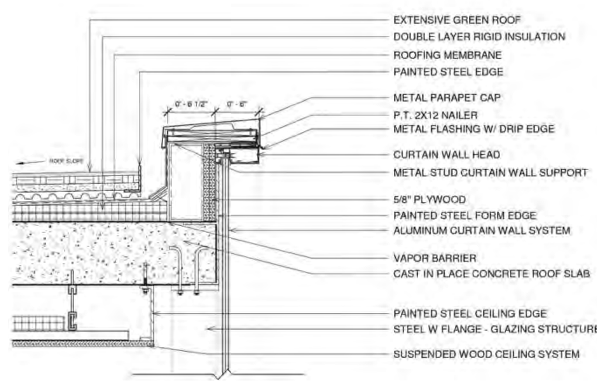

Fig. 7. Section detail drawing (by Kaylan Betten and Amelia Brackmann, 2017)

The section drawings, as one might expect, end up being potent demonstrations of integrated design. Structural and mechanical systems are depicted in concert with the envelope solutions. Daylighting strategies come into focus, as do considerations for acoustical treatments and other finishes. The degree to which building systems are displayed or concealed must be considered. With every element depicted comes a web of connected decision-making.

Stage 7: Comprehensive Examination (1 week)

On the heels of the technical resolution stages, and as a way of demonstrating a deep and cohesive knowledge of the lessons learned, students are required to pass an oral examination. This takes the form of a closed presentation made by each project team to a faculty panel, including the studio instructors and, often, the instructors of the corequisite courses. The points of emphasis for this presentation align directly with those outlined in NAAB SPC C.3: "environmental stewardship, technical documentation, accessibility, site conditions, life safety, environmental systems, structural systems, and building envelope systems and assemblies." Each of the models, diagrams and drawings prepared in the technical resolution stages, along with the site and building plans themselves, takes a prominent place in the examination process, and students are required to speak with clarity and accuracy about their choices. In lieu of a thesis, this serves as a sort of defense of the work, and the process acts as a formal gateway for graduation.

Student teams are advised in advance that each member should be conversant about all aspects of the project, and may be called upon at different points to speak on their own. Naturally, students will divide and conquer on project tasks – such is the nature of working efficiently toward design goals. However, the course, and the degree, requires that every student develop and demonstrate comprehensive and integrated knowledge. The manner in which the faculty administers the oral examination, therefore, requires careful attentiveness to team dynamics and provides another check against specialization and siloed knowledge within the project.

Stage 8: Refinement & Final Documentation (2-3 weeks)

Following the successful completion of the Comprehensive Exam, students are allotted an extended period for any final revisions and for final, polished documentation of the project. This is in preparation for the final project review. Distinct from the exam presentation, the final review is open to classmates, external critics, and any project partners. An emphasis is placed on presentation drawings and rendered images, as well as final site models and a detailed wall section model. This latter model, often scaled at ½" = 1ft, serves to cement for the students the interoperability and the tectonic qualities of the various systems at work. Students must reach back and recall the guiding premises from the project's early stages, and recognize their imprints on the resolved, constructed solutions. Is the project self-consistent intellectually and technically? This is, after all, the ultimate litmus test for integrative design thinking.

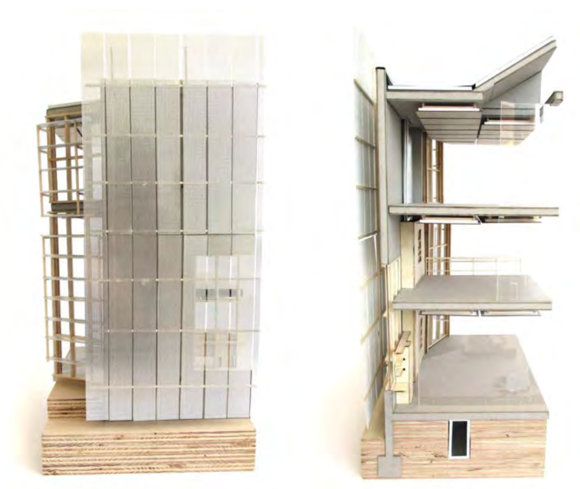

Fig. 8. Wall section model (by Kaylan Betten and Amelia Brackmann, 2017)

Student Assessment

Beyond the anecdotal pride in their accomplishments and appreciation for the substance of the work, students' formal assessments of the course have been remarkably positive. Specific to the course structure, 93% of respondents in 2017 and 92% in 2017 rated the course as very-well organized.[4] The average ratings were, respectively, 4.93 and 4.92 (out of 5). This compared to averages of 4.30 and 4.02 among other classes within the discipline and at the same level.

Regarding the co-teaching of the course, students routinely offered comments such as: *"I firmly believe all three professors are strong assets…. Each one brings a unique background and a wealth of information to the course. Without their personal and professional insight, I know my work wouldn't [have] reached the level it was able to."* And, *"Very well organized, [the instructors] each bring a different perspective and different strengths to the course."*

Noting the challenge of receiving conflicting feedback, some students expressed frustration: *"Desk Crits when all three would be together would be most helpful. When they would split up, sometimes the three different directions given would be conflicting."* Others saw the value, affirming the underlying intentions of the faculty: *"Contradicting ideas sometimes can get confusing but it's the responsibility of the student to choose where to take the different ideas."* And, *"All three professors worked very well together. At times, they would give different opinions that would help to give a broad spectrum of feedback, which created a better project in the end."*

Students were generally positive about the pace of work, recognizing the rigorous demands of the course. In conjunction, some expressed a desire for greater cohesion between the studio projects and the corequisite courses: *"I really enjoyed the notion of the [Studio] course working with the 2 other courses... It made the workload a lot easier... But I believe there is some refinement that still needs to be worked out. At the start of the semester it just seemed like studio was a week ahead in comparison to the other classes that were linked to the project."*

Conclusions

The methodologies of the graduate Comprehensive Studio at Clemson University have been important contributors to strong student work that consistently demonstrates excellence in integrative design. By placing the technical stages on equal footing with the earlier design stages, a clear message is sent regarding the limitations of ideation without deep development and execution. Furthermore, through its structured commitment to collaboration, among student partners and among the instructors, the course recognizes distributed knowledge as a necessary foundation for integration (and deterrent to fragmentation).

Reflecting on the strengths of the current approach, the course faculty point to their own diverse backgrounds which lead to open and honest conversation, in which the technical aspects of the project become questions to debate rather than certainties to be transmitted to the students. This process, and the length of time afforded for technical resolution, makes it possible to develop the technical aspects creatively, not as a mere problem-solving process, and it also contributes to great diversity in the architectural outcomes. The faculty report greater personal satisfaction from working together in a dialogue, though they recognize that co-teaching demands more front-end preparation and organization.

Relative to the pairing of students, one underdiscussed benefit is the flexibility for individuals to dig into whichever aspects (formal, material, etc.) or skills (model making, technical drawings, etc.) they are most interested, without diminishing the scope of the project. However, this positive can become a challenge, if unchecked and students are allowed to disentangle themselves from the integrative work. The teamwork can likewise present a challenge to employers who, while recognizing the inherent value of collaboration, report difficulty in discerning the specific contributions of individual students.

Reflecting on other downsides to the current approach, faculty note that the rigors of the schedule do somewhat limit the scope and depth of conceptual questions in the early stages. The faculty also agree that greater coordination needs to take place across the schedules of the corequisite courses. While these courses undoubtedly contribute to the successes of the Comprehensive Studio, their potential has not been fully tapped.

Notes:

1 There is still a thesis option within the healthcare design specialty in the School of Architecture, though most students in that program also opt for the comprehensive project.

2 The NEXT High School is a public charter school in Greenville, South Carolina. It offers an alternative, project-based curriculum that has drawn praise in education circles. A project-based learning (PBL) approach was required for the 2017 design proposals.

3 Allen, Edward and Iano, Joseph. *The Architect's Studio Companion: Rules of Thumb for Preliminary Design.* Wiley: Hoboken, NJ. 2017.

4 These figures are based upon a 64% survey participation rate in 2017, and a 79% rate in 2018.

Teaching Structures Online: Finding Opportunities for Tangible Engagement

Dustin Albright
Clemson University

Abstract

Faced with increasing demand but limited flexibility within the academic year, the School of Architecture at Clemson University developed and delivered an online version of its undergraduate Structures 2 course during the summer of 2018. This shift in timing and format presented a range of challenges, most significantly the compressed schedule (six weeks to deliver fifteen weeks of content), and the desire to maintain engaged, experiential learning despite the detachment and asynchronicity introduced by the online setup.

With respect to this remoteness, it proved fruitful to turn the challenge on its head and instead identify opportunities afforded by the geographic distribution of the students. This resulted in a unique case study project devised to capitalize on diverse summer experiences and dovetail with student internships. The project aimed to develop a clearer understanding of the collaborative relationship between practicing architects and structural engineers through shadowing and interviewing both parties. In conjunction, students identified a current project in the office of these professionals as a reference point for the interactions being described. This provided a foundation for discussions of scope, contracts, design stages, workflows, and special coordination. The case study also provided a vehicle for integrating basic course content relating to material systems, hierarchy, load path, and connections, all while developing other key competencies ranging from interpreting construction drawings to synthesizing architectural and structural information.

This paper details the first offering of the online Structures 2 course at Clemson University – its organization, its content, and the unique project devised as a thread tying everything together. The paper considers the scope of our students' unfamiliarity with the architect / engineer relationship, and how a project like the one described can address this need. It is punctuated throughout by examples of student work, and includes detailed student feedback concerning the course and its methods.

Keywords: Structures, Online Instruction, Pedagogy, Professional Practice

Introduction

The undergraduate Architecture program at Clemson University consists of a four-year Bachelor of Arts degree, in which students are required to complete a minimum of 122 credit hours. This number is comparable to other B.A. programs across the United States, and it has been in place at Clemson since the 2005-'06 academic year, prior to which the program required 141 credits. The most significant cuts were made in the area of requisite building technology courses, which were reduced from five to two.[1] Within this number, Structures 1 is required for all students, and a second technology course must be completed from among a list of options, including Structures 2. Almost all of the students complete their second technology requirement in the form of field studies or maker courses offered during a compulsory off-campus-study semester. This effectively relegates the Structures 2 course, then, to being an extra elective rather than required material. As such, it has been traditionally offered once per academic year, in a single section.

This changed in 2018, when a second section was offered over the summer to keep up with growing demand among students. While it was always recommended as a valuable course, the urgency with which our academic advisors have promoted it recently increased in response to the growing number of M.Arch programs requiring the equivalent of Structures 2 for admission. The summer offering was seen as both a pressure relief valve, managing the enrollment in the normal Spring semester section, and as a unique opportunity for students desiring more flexibility in their course schedules.

One significant constraint to a viable summer section, however, comes with the fact that many students pursue professional internships and other opportunities during these windows. It was determined, therefore, that an online version of the course would be necessary to allow for wide participation, and that an asynchronous format would best accommodate varying schedules.

Contents, Setting and Participants

The Structures 1 course at Clemson focuses primarily on the related topics of load path and statics. As a compliment to the quantitative dimension of basic statics, students are challenged to develop an intuitive sense of structural behavior through numerous tactile modeling exercises. Along the way, a variety of overarching structural typologies are introduced in service of highlighting the range of systematic approaches and their distinctions. Structural materials are discussed lightly and mostly in the context of presenting these typologies. The topic of Strength of Materials may be introduced, but is increasingly relegated to Structures 2.

Structures 2 delves into internal stresses and deformations and the impacts of material and cross-sectional properties. Beam theory is a central topic for the demonstration of these lessons, and students go in-depth through the analysis and design of steel, timber and reinforced concrete systems. The topical outline for the standard 15-week course (two periods per week, each 1.25 hours) is as follows: Review of fundamental principles, including equilibrium, load path, and reaction forces (3 weeks); strength of materials (1 week); beam theory (3 weeks); structural steel (1 week); structural timber (1 week); reinforced concrete (2 weeks); lateral forces (1 week); column design and stability (1 week); foundation systems (1 week).

Summer courses at Clemson are generally organized into 6-week terms. While it is possible to create longer-running summer courses, as needed, the decision was made to stick with the 6-week format for the inaugural summer version of Structures 2, allowing students and the instructor more flexibility with the rest of their summer schedules. The course was positioned in the second half of the summer (June 27 – August 7), allowing students time beforehand to gain their footing with any internships or other opportunities.

Eight students enrolled in the course, exceeding the university's required summer minimum of six. Of the eight, four were rising 3rd-year students, three were rising 4th-years, and one was an outgoing 4th-year, set to graduate upon completion of the course. Two of the rising 3rd-years and all three of the rising 4th-years were engaged in professional summer internships. Only one student was spending the summer in Clemson, as she was simultaneously enrolled in a summer Studio course. The others were spread across six different cities and two time zones.

Challenges and Opportunities

Given the condensed, 6-week time frame for the course, the organization and scheduling of content delivery was one central concern at the outset. A second challenge involved finding a way to promote active learning in a course taught online. It is evident from previous experiences teaching Structures at all levels, that students benefit greatly from project-based applications of the lecture topics. In addition to cementing the lessons of the lectures, such projects are avenues for new knowledge and synthesis across concepts. So, while physical, model-based approaches would be infeasible in this case, some other form of central project would be essential for providing tangible engagement with the course material. Moreover, a well-devised project could turn a constraint into an opportunity by taking advantage of the fact that students were living and working in a wide variety of different settings.

Course Organization and Delivery

The summer course kept the same topical outline described above, but featured up to five lectures per week, rather than two, in order to fit the 6-week timeframe. This equated to 25 core lectures in the following sequence: review of loads, spanning strategies and statics (5 lectures); strength of materials (2 lectures); beam bending and shear (6 lectures); structural steel properties and methods (1 lecture); beam deflections (1 lecture); timber design (2 lectures); reinforced concrete design (3 lectures); column buckling and stability (2 lectures); lateral forces (1 lecture); retaining and foundation systems (2 lectures). As with the normal 15-week course, the opening period for review is included with the 4th-year students in mind, as it may have been two years since they completed Structures 1. It is also important to mention that the various subjects are not as discretely separated as they may appear from the outline. Lateral stability, for example, is discussed throughout the entirety of the course, though it is only the principle topic of a single lecture.

In addition to the core content, one additional mini-lecture was provided in the first week, addressing the topic of structural documentation and coordination between architectural and structural drawings. In the traditional course format, this important topic would be informally covered in discussions surrounding class projects, such as those in which students are asked to work from as-built drawings to model and analyze structural systems of existing buildings. However, without such face-to-face interactions for the online course, this content was instead packaged as a pre-recorded add-on lecture.

Lecture Delivery

Each of the lectures has the format of a slideshow with audio narration, and each was simply recorded in PowerPoint and delivered as a pptx file, as PowerPoint is a program that is freely available to all students at the university. The lectures averaged 61 minutes in duration, but were broken up into shorter modules to better hold students' attention and allow more flexibility in the way they consume the content. The modules varied in duration, depending on content. One may contain an entire subtopic, while another may contain a complete design problem. The average module duration was 10 minutes. This is somewhat longer than examples gathered from colleagues[2], or even recommendations from Clemson's own online education department, each of which favor five-minutes or less. However, in this case, longer modules resulted from an effort to err on the side of subject continuity rather than breaking at places that could disrupt a theme or idea. That said, some selective editing in future iterations could break up certain longer modules, such as those featuring example problems that are divisible into discreet steps.

The course was administered through two cloud-based tools. Canvas, a learning management system, was used for course communications and for posting grades, while Box, the university's cloud storage service of choice, was used for uploading and sharing the lecture modules because of its ample space. Most lectures were recorded in advance of the course, allowing for batch uploads. In an earlier interest meeting, prospective students indicated that posting multiple lectures at once, at the beginning of the week, for example, would afford more flexibility for their schedules.

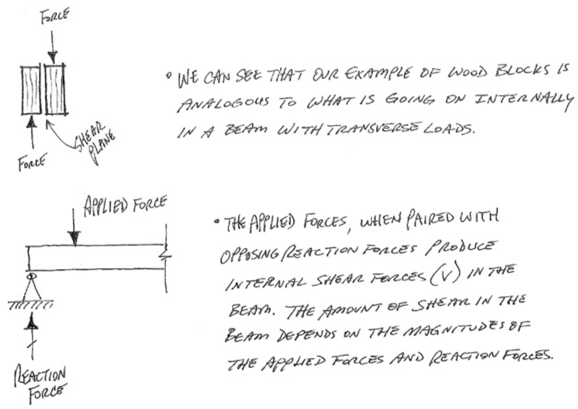

Fig. 1. Lecture slide example

The lectures generally fell into two categories. Some were image-based, such as discussions of structural materials and their applications, which tended to involve illustrated case-studies. Others, in particular those featuring more quantitative content, were heavier on written notes, diagrams and calculations. In these cases, the decision was made to stick with handwritten notes and sketches (see Figure 1 above). This method followed examples gleaned from a colleague who has found that handwritten content provides a better “sense of connection” with a remote instructor.[3]

Graded Assignments

The course contained three types of graded assignments. The first were homework problem sets, in which students could leverage lecture notes, the textbook[4], or even each other’s help to solve a range of structural analysis and design problems. There were two total problem sets, scanned and submitted by students via email. Each was followed within a few days by an exam, one at the midterm and one at the end of the course.

The exams were designed to cover the same quantitative content as the problem sets, but also address the more qualitative matters of the course. This might include making comparisons between structural materials and systems, or even sketching illustrations of key concepts, such as different types of retaining walls. For these reasons, both exams were written exams, presenting challenges for coordination and administration. Computer-based remote proctoring programs were considered as a measure for exam security, but the unique, paper-based aspects of the tests, led to a different solution.

In the weeks leading up to the course, students were contacted and asked to identify a suitable setting and proctor. Suggestions included testing centers, public libraries under staff supervision, or at their summer firms under a senior mentor. Once identified, these proctors were contacted, provided with guidelines for administering the exams, and asked to sign off on their willingness to serve in the role. On the mornings of each exam date, the tests were simply emailed to the proctors, along with any approved reference tables, and instructions regarding time limits and permitted materials. The proctors printed and administered the exams and scanned and emailed them back to the instructor, once completed. The physical copies were also mailed back via stamped envelopes provided by each student.

The third type of graded assignment, the course project, is described in the following section.

The Project

A multifaceted project was devised as a thread to knit together and apply the course’s central lessons. The project took the form of a building case study, but with a twist. Taking advantage of their various summer situations and locations, each student was to perform their case study while shadowing an architectural professional and consulting structural engineer. This wrinkle was aimed at addressing a knowledge deficit concerning the practical relationship between these parties.

Knowledge Deficit

A survey of 4th-year architecture students at Clemson University was recently conducted to gauge the level of familiarity with the working interactions between architects and structural engineers.[5] At the time of the survey, these students were in their final academic semester, twelve weeks from graduation. Of the 42 respondents, 37 reported that they intend to pursue architecture as a career. 31 reported having some prior experience interning in an architectural office, and the average length of experience among those that had any was 6.4 months. Interestingly, 40.5% of all respondents indicated that they had observed a coordination meeting between architects and structural engineers.

However, when asked to rate their level of "familiarity with the typical working interactions" shared between these parties, the majority of respondents reported little or no familiarity (see Figure 2). Additionally, only 23.8% reported that they could say with confidence how the content of these interactions changes over the course of a typical project.

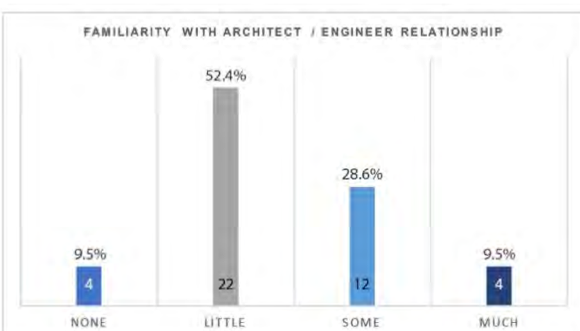

Fig. 2. Student familiarity with architect / engineer interactions

Taken together, these results indicate a clear knowledge deficit among students, and even among those who have had exposure to professional practice. One is left to conclude that summer internships and related experiences, while helpful for offering some awareness, are not consistently providing lasting insights into the architect / structural engineer relationship. One is likewise left to conclude that students have not learned about this topic in their academic coursework.

Project Setup

Aimed at tackling this blind spot, the course project required that students identify a partnering architect and engineer and invite them into conversation about their working relationship. Likewise, students were asked to select a particular case study building as a vehicle for mapping out the collaboration, and, if possible, try to attend a project coordination meeting between both parties. Given the short, 6-week duration of the course, there was no time to waste in selecting professionals and a building. Therefore, a draft description of the project was sent to each student five weeks before the course began to get them started on planning these connections. Students engaged in professional internships were invited to work within their own firms for the project, and all five ultimately took this route. The remaining three students were encouraged to find architects and engineers close to where they were spending their summers.

Once the course did begin, and within its first few days, all students were required to make an initial progress report to the instructor (via phone call), during which they confirmed that they had found willing professionals and had access to a promising case study project, including the project drawings. It was at this stage that two students reported challenges in finding a participating architect. The instructor was able to step in in both cases and help make the necessary arrangements through personal contacts. This worked out easily enough, as both of these students were somewhat local, but it could have proven more challenging in other circumstances. In addition to verifying access to professionals and case study resources, the early progress report also provided a good opportunity to confirm that students understood the project goals and requirements, and that they had a well-defined path for completion. A second progress report was required at the midterm to verify that students were still on the right track.

Project Goals and Parameters

Through conversations with professional architects and their partnering engineers, students were asked to construct a detailed picture of their interactions and what they look like at the various stages of a project. The selection of the accompanying case study project was, therefore, a critical decision, as this would serve as the lens for understanding the working relationship. As a guide to beginning fruitful conversations, and as a measure to ensure quality control in these engagements, the students were given the following questions as starting points. Additionally, they were encouraged to add their own questions to this mix.

- Where is each of the professional firms located? What are their histories?
- How are the contracts between architects and engineers structured?
- What are the various stages of a design project, and how do the architects and engineers practically interact at each stage? Can this be mapped out as an illustration?
- What tools (software or otherwise) assist in coordination between these parties? What opportunities or limitations are imposed by these tools?
- What tools are the structural engineers using to make the necessary calculations to size the structural elements? What does this workflow look like?
- Does each party feel that the typical measure of interaction on a project is adequate? Are there opportunities for operational improvements to be made?
- What attributes are architects looking for in an ideal structural engineer?
- What attributes are structural engineers looking for in an ideal architect?
- With respect to the selected case study project, are there any specific areas in the design that require special attention and coordination? If so, what do these interactions look like and what was the result?

More than just a reference point for mapping professional interactions, the case study project was also intended to be a tool for developing three key competencies among the students. First, they would practice reading and understanding construction drawings, including coordinating between the architectural and structural sets. Second, through drawing and diagramming, students would gain a greater appreciation for the hierarchy and interdependency among structural members. Third, through close study and re-representation, students would better understand the structural materials at work and, in particular, the details of their assembly and connection.

Project Deliverables

The final submission of the project took the form of a comprehensive report addressing the architect / engineer relationship and the accompanying case study project. Students were advised that the report should be more than a perfunctory listing of facts. It was each individual’s responsibility to be curious and creative in order to elicit compelling information that effectively told the story of these professional collaborations. Students were asked to include dates and times of conversations, as well as the names and roles of the individuals interviewed and observed. Photos and other images, such as example drawings of the case-study projects themselves, were to be included, as were any photos from in-person visits or diagrams made to illustrate the collaborative process.

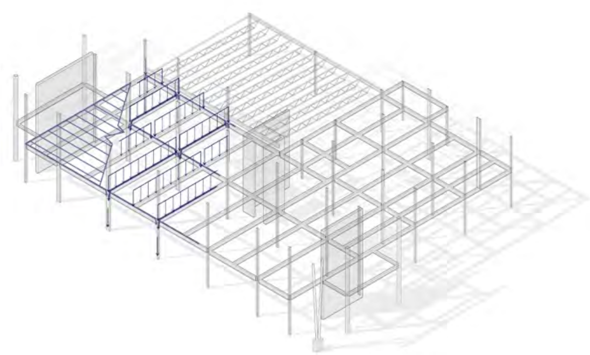

Fig. 3. Load tracing diagram (by Harrison Novak).

Students were required to make and include a series of analytical drawings, each pertaining to the selected case study project. The first was an axonometric diagram illustrating the load path at work in a given portion of the building (see Figure 3 above). For reference, the selected portion of the building was to be highlighted in the accompanying set of plan and section drawings.

Each student was also required to produce axonometric drawings articulating the assembly of at least three distinct structural joints. If a given case study project was not far enough along in its development for defined connection details, then students were asked to make drawings of representative joints from a similar project. The drawings were to be annotated so as to identify all of the key elements and their dimensions (see Figure 4). Students were informed that all drawings would be evaluated on thoroughness, accuracy, clarity, and graphic quality.

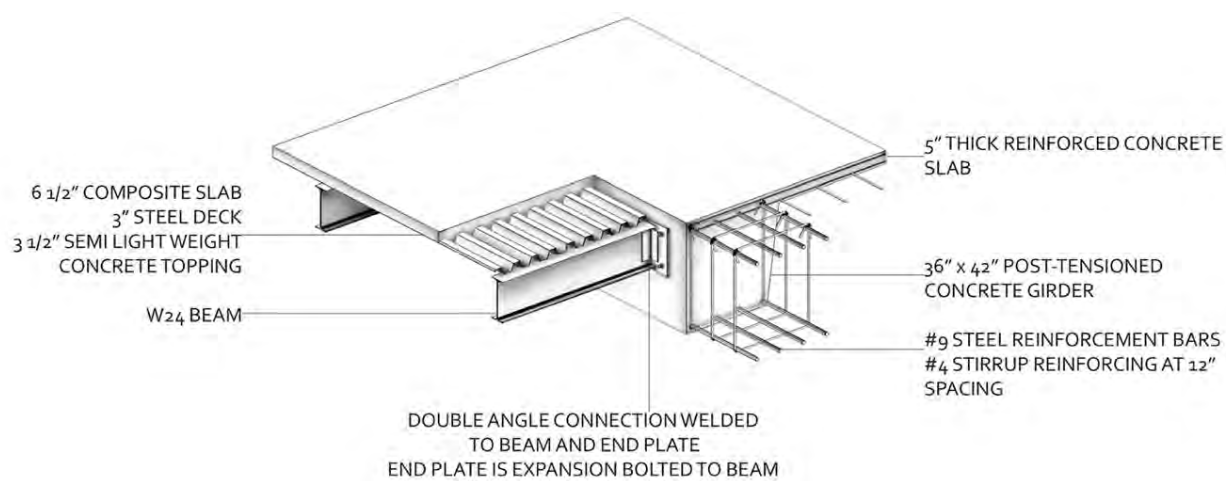

Fig. 4. Structural detail drawing (by McKenna Tiley).

Project Outcomes and Observations

As a set, the projects covered a lot of ground, owing to the diversity of the professional mentors, their practices, and their work. From the metropolitan offices of large, international firms, to a three-person practice a mile from our campus, each student had unique experiences to report. The case study buildings, by extension, ranged in scale and scope, from a small commercial renovation to a new 45,000ft^2 (13,700m^2) office building to a 370,000ft^2 (112,800m^2) conference center expansion. They also ranged in their states of completion, from the design stages to buildings under construction (see Figure 5). Relative to the questions posed by the project, this diversity presented a welcomed breadth of lessons. On the other hand, certain common threads were present, cutting across scale, location and complexity.

Fig. 5. Bracing detail during construction (by Kevin Crumley)

As expected, one of the more interesting topics to surface was the contractual variations and hierarchies associated with differing project delivery methods. Based on her interviews and case study, one student reported matter-of-factly that "typically, an architectural firm and a structural engineering firm work together in conjunction with a contractor with whom they both enter into a contract for the project." [6] Others described the engineers as consultants hired by the architect, and, in some cases, through competitive bid scenarios. These varying takeaways, fragmented as they were, led to productive teaching moments, in this case concerning design/build versus design/bid/build arrangements and their impacts on the architect / engineer relationship.

The diverse case studies also proved successful at highlighting the sorts of situations that may require special coordination. One student reported:

"I had the opportunity to discuss specific areas of the project that required special attention and coordination with [The Engineer] during our meeting…. Due to the building's location… along the river, there has been a lot of coordination and discussions, between structural, civil, and geotechnical about the poor soil. Due to the ballroom's large size, they have to account for a large amount of people in that area. There is coordination with a vibration consultant, who will help design the structure to limit the impact of all of the movement." [7]

Some of the lessons common to all the students included an appreciation for project workflows and the various levels and tools of collaborative engagement that are typical at different stages. In fact, a basic awareness of customary project phases was new knowledge for some of the younger students. Insights such as the following statement were common:

"[The Engineer] mentioned that, (from) the end of DD's all the way through CD's, the architect is in communication with an engineer several times a week. Usually there is a consultant meeting once a week ... During the CD phase, structural will send their updates on Tuesday while [The Architect] will send their updates and changes to the Revit model on Friday. This allows for quick and organized workflow." [8]

Another universal takeaway from the interviews was an appreciation for the "soft" skills that are most desirable across both parties – namely, the critical importance of good communication. Comments like the following were common:

"Good structural engineers are good communicators; they keep their partnering architect up to date on the progress and value an architect's project no matter the size. Good architects are also good communicators; they have the ability to convey their design clearly and have the understanding that structure is important and can aid with the organization of their building." [9]

Beyond the interviews, the project's required diagrams and drawings (see Figure 6) were shown to be a beneficial addition, in particular in their value for making tangible connections to the course's lectures on subjects such as load path, and material systems and their joints. The task of reading, interpreting and applying construction drawings was instrumental in these lessons. Even among students that had previous experience, the project provided a new and helpful lens. In feedback gathered after the course, one student reflected: "I got accustomed to going through CD's at my first summer internship, however I hardly ever looked through the structural drawings. I would fix and edit architectural drawings and that was the extent of my experience."

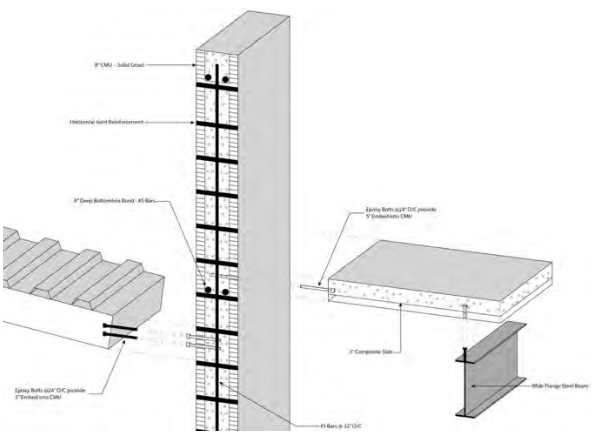

Fig. 6. Structural detail drawing (by Kaleb Mercer)

The quality and insight of the drawing studies varied among the students, with the older, more experienced students generally outperforming their counterparts. This was not unexpected. Beyond simply having a more developed skillset, these advanced students tended to have higher-level responsibilities in their summer internships, leading to more sophisticated approaches to the course project. That being said, it was evident that the project held much value for all students, in that it was broad enough to offer points of engagement across all skill and experience levels.

Student Feedback

Student course evaluations were helpful for assessing the strengths of the course, as well as possible areas for improvement.[10] Students felt that the course was "well organized" (4.43 rating out of 5), and were satisfied with the "availability of the instructor outside the class room" (3.86 rating out of 4). Students offered more modest assessments when asked to rate the "effectiveness of the instructor's teaching methods" for helping them "understand the course material." Their rating of 3.86 (out of 5) is consistent with the mean across courses in the discipline (3.89), but lower than the instructor's typical evaluations in comparable courses. By way of comparison, this same question garnered a rating of 4.78 in the graduate version of the course, offered in-person during the previous Spring. The content of these two courses was nearly identical, with the recorded lectures being prepared directly from the notes for the live course. The lower mean for the online course may stem, in part, from the smaller number of respondents (7 versus 18), which increases the impact of a single low rating. It may also underscore that student performance in the online setting is even more dependent on each individual's self-discipline and their ability to work independently and stay on schedule with the content, which can be challenging with a compressed schedule.

The intensity of the schedule was a common thread in the student comments. One respondent stated: "It was hard to have a full-time internship and make sure that I was keeping up with the lectures every night. It made for a long, tiring day. There were a couple of days where I missed the lectures and that made it hard for me to catch back up." Another suggested stretching the course out over a "slightly longer span during the summer."

Relative to the course project, students again mentioned the timeframe, stating: "Due to architects' and structural engineers' working schedules it can be hard to get ahold of people quickly and it would be good to have more of the summer to work on the project." Another critique came from a student who felt the project favored intern experiences with larger offices. There is some validity to this, in that a small, residential practice may feature limited and distinctly different interactions with structural engineers. This was acknowledged at the outset by the instructor, and students were presented the option of approaching an architect outside their firm, if necessary.

Otherwise, the projects were very well received. One respondent noted: "Prior to this class, I had never spoken to a structural engineer before about what they do," and "I believe I am now able to read structural drawings, and my understanding of the consultant process is much better than before." And, commenting on the building case-study: "It helped narrow the focus on one building that allows you to dive into details that you might miss with an expanded scope. Especially when it came to looking at connections." Commenting on the "greatest strength" of the project, a respondent noted: "I think the fact that it uses our summer internships as an access point into the communication of the architect and structural consultant is very strong."

Conclusions

Based on student evaluations and the instructor's own observations, it appears that the inaugural online Structures 2 course at Clemson University was largely successful. Student learning objectives were met, and exam averages were on par with comparable courses taught in-person by the same instructor. Based on student feedback, future versions of the course and its project may be stretched out over a longer period – perhaps eight weeks instead of six.

The course project proved to be an effective vehicle for synthesizing and cementing the lecture content, including specific material systems and the hierarchies and load paths among their respective components. Additionally, while different than the model-based approaches employed in an in-person setting, the course project successfully fostered new and applied knowledge through its own form of active learning. By incorporating the diverse locations and summer experiences of its participants, it resulted in a wide variety of practical lessons among the students. This demands a healthy measure of flexibility on the part of the instructor when it comes to managing and evaluating the project. It is important to embrace the variety and encourage the specific opportunities afforded by each unique experience. For example, the differing timelines of the case study buildings may result in early design meetings in one case and on-site construction visits in another. This should be viewed as a strength of the project, and future versions of the course will explore the best ways that each student's research can be disseminated to the whole class.

Notes:

1 A more detailed history of this credit hour reduction and its impact on required building technology courses can be found in an earlier paper: Albright, D. "*Action and Reaction: Balancing the Dual Challenges of Breadth and Depth in Undergraduate Structures Instruction.*" In Proceedings of the 2015 Building Technology Educators' Society Conference. Salt Lake City, UT. 2015. p 233-239.

2 Sprague, Tyler S. "Watch/ Respond/ Act/ Solve: A Hybrid Approach to Architectural Structures Education." In Proceedings of the 2015 Building Technology Educators' Society Conference. Salt Lake City, UT. 2015. p 223-229.

3 Ibid.

4 Onouye, Barry and Kane, Kevin. "Statics and Strength of Materials for Architecture and Building Construction." Fourth Edition. Prentice Hall, 2011.

5 This survey was conducted in January 2019, five months after the completion of the summer Structures 2 course. The survey results confirmed the author's suspicion that students generally lack knowledge of the typical architect / structural engineer relationship. The questions and results of the survey were as

follows: (1) *Including any past or current internships, how many months (total) have you worked in a professional architectural office?* Average duration = 4.675 months. This number included 11 participants that reported zero experience. (2) *How much familiarity do you have with the typical working interactions shared between architects and structural engineers over the course of a project?* None = 9.5%, Little = 52.4%, Some = 28.6%, Much = 9.5% (3) *Could you say with confidence how the content of interactions between architects and engineers changes over the course of a typical project?* 23.8% Yes, 76.2% No (4) *Have you ever observed or participated in a project coordination meeting between an architect and a structural engineering consultant?* 40.5% Yes, 59.5% No (5) *Do you intend to pursue architecture as your profession?* 88.1% Yes, 11.9% No.

6 Quoted from final report by student, Rachael Jackson.

7 Quoted from final report by student, McKenna Tiley.

8 Quoted from final report by student, Kevin Crumley.

9 Quoted from final report by student, Harrison Novak.

10 Course evaluation data was based on a survey participation rate of 87.5% (7 out of 8 students).

Transdisciplinarity & Innovation: Smart Materials in Landscape Architecture Education

Carolina Aragón
University of Massachusetts Amherst

Abstract

Designed landscapes are physical manifestations of natural, cultural, and technological forces. As such, they can physically embody technologies that support sustainable practices, and provide experiences that foster their cultural acceptance. However, the current focus of sustainable design in the landscape architecture profession has centered on ecological performance, largely ignoring the role of aesthetics and new material practices. In particular, the incorporation of energy-generating materials, such as smart materials, has remained largely unexplored. As a result, new methods for expanding engagement with materials and technologies are needed.

The need to address technological innovation while providing meaningful aesthetic experiences points to the importance of transdisciplinarity as part of the design pedagogy focused on sustainability. Transdisciplinarity challenges the conception of knowledge silos, the distinction between the objective and subjective, and embraces different ways of knowing that relate to different levels of reality.[1] In doing so, it presents opportunities for the integration of artful doing as part of technological innovation by simultaneously embracing the analytical, the emotional and the sensorial.[2]

This paper presents student work developed at the University of Massachusetts Amherst that explores the incorporation of smart materials for design applications. Landscape installations and prototypes developed in two courses: *Material Experiments in Landscape Architecture* and *Step and Flash: Creating a Piezoelectric Walkway*, will illustrate how transdisciplinary explorations led to technological innovations that reduce energy consumption while appealing to the senses. Based on this experience, an initial set of guidelines for introducing transdisciplinary practices in design pedagogy is presented. This paper calls attention to the value of transdisciplinarity as a way to engage technology and further engage students with a more holistic approach to sustainable design.

Keywords: Pedagogy, Landscape Technologies, Smart Materials

Landscape Architecture & Sustainability

Current practice and research in sustainability in landscape architecture, has largely focused on technologies based on living systems, such as stormwater gardens, to improve ecological performance. Analytical and science-based methods of understanding and exploration dominate the discourse. While more than a decade has passed since Elizabeth Meyer wrote about the "performance" of beauty in sustainable design as a way to contribute to the cultural acceptance of this type of work,[3] much remains to be explored in the way that aesthetics can support sustainability and resilience. The concept of beauty and aesthetic engagement as part of the design of sustainable landscapes, remains elusive. Furthermore, the problematic of aesthetics, which falls outside the realm of the science-based framework, runs parallel to the timid engagement with creative material explorations as part of the landscape architecture pedagogy. As a result, the profession may largely be missing opportunities for fully exploring its potential contribution to sustainable design.

While current discourse has brought attention to material exploration as a means to expand the profession's ability to address issues of sustainability and resilience, much remains to be explored. [4,5,6] In particular, design explorations that focus on the aesthetic and perceptual qualities of energy-generating materials and technologies are largely missing from the conversation. While exceptions—such as the work of artists like Dan Roosegaarde, and design proposals generated by competitions sponsored by organizations such as the Lands Art Generator Initiative—demonstrate the potential for artistic practices in engaging the public with renewable energy, much remains to be investigated in the profession and the classroom.

Smart Materials in the Landscape

Smart materials provide a unique opportunity for exploring issues of aesthetics and technical performance in the design of sustainable landscapes. Their ability to engage environmental phenomena—through their responsiveness— and to contribute to sustainable practices—through their capacity to generate electricity or reduce its consumption—uniquely positions them as a source for creating productive environments capable of creating meaningful aesthetic experiences. Addington and Schodek describe smart materials as those with the capacity to transform their physical characteristic as a response to surrounding energy fields. Their major distinguishing characteristics: transiency, selectivity, immediacy, self-actuation and directness, allow them to sense and respond to environmental events. Smart materials can be categorized into two major groups: *property-changing* and *energy exchanging*. Property-changing materials demonstrate a change in their chemical, thermal, mechanical, magnetic, optical or electrical properties, in response to a change in the environment in which the material is found. These changes can be caused through direct input, such as current or voltage, or through ambient conditions, such as temperature or light.[7] Examples of property-changing materials include photochromic and thermochromic materials, which change color in response to light or heat input. Energy-exchanging materials have the intrinsic capacity to transform input energy into a different form of output energy. Examples of energy-exchanging materials include photovoltaic, photoluminescent, and piezoelectric, among others. These materials are often used as sources of renewable energy, such as photovoltaic panels, but also—as is the case for piezoelectrics—for energy harvesting, normally referred to the conversion of ambient energy into electricity.[8]

Landscapes—with their ever-present dynamic conditions of light, wind, and temperature—can provide a rich environment in which to deploy smart materials and harness their intrinsic technological capacity for productive and experiential design purposes. Smart materials can be responsive, productive, help read environmental change, and directly respond to human presence. As such, they can be implemented in the design of landscapes to create interactive spaces that can provide unique experiences through their indexical relationship with dynamic environmental forces and/or human interaction.

Transdisciplinarity in Design Pedagogy

Integrating new materials and technologies in landscape architecture pedagogy can be challenging. This in part due to the unprecedented nature of the work and also the potential lack of expertise in the technical aspects of the materials. This may call into question whether designers, as non-experts, may be able to contribute to technological innovation—and if so, how? Understanding this new role and finding significant ways for students to begin to explore new material practices—often requiring knowledge outside of the field—invites new methods of thinking about design pedagogy. Transdiscipinary pedagogical approaches may provide such a model by promoting and valuing multiple ways of understanding and knowing.

Transdisciplinarity embraces multiple views of the world, diverse ways of knowing, blurring distinctions between objective and subjective, and challenging traditional notions of knowledge silos.[9] It can be understood as the final step in which disciplines can relate to each other: *multidisciplinary* collaborations involve fields studying a problem independently from each other, *interdisciplinary* work shares methods to arrive at a mutual understanding of a problem, while *transdisciplinary* collaborations transcend the boundaries of disciplinary fields to bring multiple ways of knowing and relating to the world in ways that include and go beyond disciplinary knowledge.[10] This transcendence of disciplinary knowledge implies being sensitive in non-cognitive ways and linking analytical intelligence, with feelings intelligence and body intelligence.[11] Often times, transdisciplinary knowledge also embraces the contributions and understanding brought forth by non-experts.[12]

Transdisciplinary pedagogical practices are recognized as highly important for 21st century education as they are recognized to be essential in addressing “wicked-problems.” A characteristic of these practices is how they foster students’ abilities to creatively move between disciplines finding opportunities for cross-pollination of ideas between fields, at times in “indisciplined” ways that simultaneously require depth of knowledge in one field, while engaging other fields.[13] Transdisciplinary pedagogy is also linked to innovation as it has the potential to harness intuitive thinking skills—non-verbal, non-mathematical, non-logical tools often employed by creative individuals—into new ideas.[14,15] Innovation has the capacity to break through with old conventions and present new ways of knowing, experiencing, and engaging the world.

Architecture and urbanism—and by extension landscape architecture—have been identified as a fertile ground for transdisciplinary research as they operate both within the academic and non-academic, theory and practice, discipline and profession.[16] Likewise, design pedagogy has great potential to integrate transdisciplinary practices by working across fields, bridging expert and local knowledge, and by incorporating artistic practices and scientific research in design. However, while it could be argued that design pedagogy already supports both the emotive and bodily intelligence, with analytical intelligence –arguably through artistic explorations and incorporation of technological approaches—it may not fully explore the possibilities of promoting innovation by largely keeping these two approaches separate. It is not uncommon for artistic practice to occur during initial explorations to generate design concepts, while technology is often taught outside the design studio in seminar settings, as a fixed set of knowledge that is meant to be understood and implemented rather than challenged.

Step & Flash & Material Experiments

The following examples address pedagogical experiments by the author that explore ways in which landscape architecture education can provide opportunities for technological innovation through material experimentation. Two courses, taught at the University of Massachusetts, *Material Experiments in Landscape Architecture* and *Step and Flash: Creating a Piezoelectric Walkway*, will illustrate how transdisciplinary exploration and artistic inquiry led to technological innovations for prototypes involving energy exchanging smart materials. These explorations demonstrate how transdisciplinary pedagogy can foster increased opportunities for engagement with technology while simultaneously appealing to the senses and emotions.

Step & Flash: Making a Piezoelectric Lighted Walkway

Step & Flash was a one-credit course co-taught by landscape architecture and electrical and computer engineering faculty during the spring semester of 2017. The course, open to all students, sought to integrate art, design and engineering to explore novel applications of piezoelectric technology through interactive art installations. Piezoelectric technology is commonly used in energy harvesting by transforming vibration into electricity. The course explored the potential for piezoelectric technology to create an engaging art installation that harnessed biomechanical energy using footsteps to create light through an affordable and easy to build walkway for campus.

From its inception, the course adopted methodologies supportive of transdisciplinary practices to gain a new and expanded understanding of piezoelectric technology. In addition to being introduced to principles of electronics and conducting research in related technologies, students engaged on artistic exercises to explore conceptual and creative interpretations of piezoelectricity, and hands-on experiments which provided direct feedback and understanding to further understand the technology. These different ways of exploring allowed students to access their emotive, bodily, and analytical ways of understanding. The "multiple ways of knowing" provided a strong base by which to explore new uses and interpretations of piezoelectric technology, increasing creativity and flexibility in the development of prototypes.

After initial creative visioning exercises and a hands-on introduction to circuits, students tested the performance of a piezoelectric transducer to produce enough electricity to power an LED. This was achieved in two ways: by measuring the electrical output using a digital multimeter (DMM) while tapping the transducer, and by directly connecting an LED to the transducer. Students using the DMM realized that tapping alone would not provide the necessary power to light the LED unless the electric charge was stored and accumulated in a battery. Students who directly connected the piezo to an LED were more inclined to seek alternatives to tapping to make the LED light work. It was quickly established that by making the piezoelectric vibrate by rubbing it against a rough surface, it could light an LED—knowledge that would not have been realized if only the DMM had been used to measure the output.

Fig. 1. "Sandwich" prototype testing.

The discovery of light brought about by friction, led to the creation of early prototypes that looked at creating a tile in which piezoelectric transducers were placed inside a “sandwich” of wooden boards separated by springs, which when pressed could vibrate the transducer against the surface of screws or sand paper (Fig. 1). These early prototypes made apparent many of the challenges of this configuration: the piezo transducer could be easily damaged as its surface was eroded through friction, and the springs provided an unstable system. The investigation then took a turn away from springs and looked at three different alternatives by which to create vibration to cause the piezoelectric transducer to light LEDs.

Inspired by toy tops as a mechanism that could spin when pressed downward, two prototypes were created: one which modified a salad-spinner, and a custom-designed mechanical system which transformed vertical pressure into a spinning motion. The salad spinner was reconfigured to house fins that would rotate and make the piezoelectric transducer vibrate. The system was incased in a box and LEDs were installed on the surface: when the button of the salad spinner was pressed, the spinning action vibrated the piezo transducers, which in turn powered the LEDs. Although this prototype demonstrated the viability of the concept, it did not provide a promising configuration for a tile, as it could not support the weight of a person, was not accessible, and was too expensive. In a similar fashion, the custom designed mechanism for creating spinning motion from pressure, had many challenges. Designed by the most experienced design and electronics students, the system was almost exclusively made of custom 3D printed parts and focused mostly on the rotating mechanism rather than the whole system. Additional drawbacks included its complex, expensive, and time-consuming nature. Although a valuable development, it proved too complex to be completed or implemented to demonstrate its potential during the course of the class.

Fig. 2. Piezoelectric Strummer.

Alternatively, the third alternative, taken by the students with the least design experience led to the most effective prototype. This “low-tech” approach reconsidered the interaction of the human body with the piezoelectric transducer and realized that the pressure of walking may exceed the capacity of the transducer, causing the creation of complex systems to ameliorate the situation. As such, this approach explored creating vibration through a strumming motion with the hands. In this prototype piezoelectric transducers were inserted at the end of dowels, which were vibrated when strummed by hand. Using a simple wood frame and dowels, the *Piezoelectric Strummer* was developed to respond to human touch, effectively lighting up two LEDs per dowel (Fig. 2).

The transdisciplinary methodologies employed in the *Step & Flash* demonstrated the potential of this pedagogical approach in engaging design and non-design students in the pursuit of technological and design innovation. By setting up the project as an art installation, the project required consideration of aesthetics and human interaction from its inception—in contrast to technological developments which focus on efficiency. Through its “multiple ways of knowing” or “multiple ways of exploring,” the project demonstrated how a technological innovation may be achieved through direct experimentation and “low-tech” approaches that can find new uses or applications of the technology in relationship to human interaction and the body.

Material Experiments

Material Experiments in Landscape Architecture is an elective course in the landscape architecture department that also welcomes students from all majors. The course seeks to expand knowledge about innovative materials in landscape architecture through experiential learning opportunities that bridge knowledge between art, design, and science. As such, it employs transdisciplinary pedagogical methodologies by positioning students in a role of being “indisciplined”—by taking their experience in design (or science) and applying it to create a new innovative application that embodies both technological knowledge and consideration of human experience. The course encourages students to explore different ways of learning and engaging with the materials, from traditional research, through hands-on experimentation, and the final development of art installations or prototypes demonstrating potential new applications. Four major topics are explored: upcycling, smart materials, biomimicry and bio-design. Student work in the past has included new applications for mycelium-based forms such as floating planters, the use of bioluminescent bacteria to assess toxicity in water, the use of upcycled plastic bottles to create a temporary greenhouse, exploration of the capacitance of plants to produce sound when touched using electronics, and prototypes exploring the incorporation of smart materials.

Fig. 3. Orbs photoluminescent art installation.

A notable project involving smart materials was *Orbs* (Fig. 3), a temporary art installation that investigated the use of photoluminescent materials to create an interactive experience illuminating a garden on campus. The project explored the material qualities of photoluminescent pigments and transformed what can be interpreted as a challenge —the rapid decline in illumination after the materials are charged by sunlight or artificial light—to create an opportunity for interactivity. The project consisted of clear acrylic spheres coated with photoluminescent pigments which housed ultraviolet LEDs. The LEDs were programmed using a microcomputer chip and were activated by an infrared sensor which detected human presence. The acrylic photoluminescent spheres were then installed along an existing screen on a campus garden and were activated by people walking by. When activated, the LED’s charged the photoluminescent pigment creating flashes of intense aquamarine light which would slowly fade until activated again.

The project demonstrated how innovation can arise from understanding the limitations of materials, and from a quest to embrace the human experience through aesthetic exploration. By embracing the decay in illumination of the pigment, *Orbs* developed a new application with a built-in recharge system that allowed it to create a new choreography of light (ranging from the initial burst of light to a slow fade of illumination).

Through the use of motion sensors, the project increased the material's ability for interaction, play, and capacity for activating an outdoor space at night.

Although *Orbs* required electricity and did not exhibit energy harvesting potential, it presented a novel use of smart materials in ways that engage audiences and invite participation. From a functional perspective, the use of photoluminescent materials could contribute to reduction in the use of electricity for nighttime illumination, while contributing to minimizing light pollution. By creating an engaging environment, the project presented new ways in which these materials could constitute landscapes that have a poetic quality alongside with a technological function.

Discussion

The experience gained by teaching these two courses has led to the formulation of an initial set of guidelines to introduce transdisciplinarity as part of design education.

1. *Ask for the unprecedented:* challenge students to create original projects that simultaneously investigate the technical properties of a material or technology while evoking a significant aesthetic experience on the observer.
2. *Encourage disciplinary diversity*: when possible, co-teach with faculty in other fields or support teaching assistants from other departments to aid students in overcoming technological challenges. Foster a culture welcoming of non-design students in the course.
3. *Be "indisciplined"*: encourage multiple processes by which to gain knowledge, moving across fields, and considering contributions from outside academia.
4. *Simultaneously pursue the functional and the experiential*: by encouraging students to explore the technical and aesthetic qualities of a project, they are positioned to engage with multiple forms of exploration requiring the analytical, bodily, and intuitive thinking.
5. *Abandon representation:* creating original projects involving technological and experiential innovation can only happen when directly manipulating materials. This direct experimentation leads to rapid feedback and the possibility for haptic engagement, increasing possibilities for innovation.

Conclusions

This paper argues for the value of transdisciplinary practices as part of design pedagogy supportive of the development of landscapes for resilience and sustainability. By encompassing the rational and the emotional, transdisciplinary practices can support the continued quest for technical innovation while allowing for the richness of the human experience to inform the shaping of our environment. As such, these practices are positioned to be particularly relevant in expanding the reach of design practice as it relates to technological innovation and promoting the design of sustainable landscapes in ways that address both technical performance and engagement by the public. In this role, designers have unique opportunities for humanizing and making technology accessible.

In particular, the findings of these paper point to the potential for further exploration of the use of smart and energy-generating materials in landscape architecture and design curricula through transdisciplinary pedagogical practices. These materials are not only relevant for their ability to generate electricity or reduce its consumption, but also because of their intrinsic ability to react to environmental stimuli. As such, they provide a rich medium by which to provide students with "different ways of exploring" and "different ways of knowing" through scientific research, experimentation, hands-on exploration, and creative visioning.

In addressing challenges set forth by climate change, landscapes that can embody technological solutions become resilient, not only through their physical performance but through their ability to foster ongoing creativity and reflexivity in their users. Transdisciplinary practices in design education can foster the necessary skills and experience for future designers to become more active participants in creating innovative applications for technologies and materials in the landscape. These new practices and landscapes may contribute to the necessary cultural shifts required to address current and future environmental challenges.

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Testing is Teaching Too: Transitioning a Large-Lecture Course from Summative to Formative Exams

Robert Arens

Professor and Associate Department Head, California Polytechnic State University, San Luis Obispo

Brian Osborn

Assistant Professor, California Polytechnic State University, San Luis Obispo

Carmen Trudell

Associate Professor, California Polytechnic State University, San Luis Obispo

Abstract

For students and teachers alike exams can be a dreadful experience with both parties left questioning the value of the exercise. Large-lecture courses tend to employ an exam culture that is more focused on expedience than efficacy as the promise of efficient grading often triumphs over the desire to create meaningful learning experiences. Within the Architectural Technology Fundamentals courses at Cal Poly we have found that machine-readable tests, which use multiple-choice and true-false questions, tend to assess students' understanding of course topics at only the most basic level and are misaligned with our aspiration to foster students who can integrate and apply their knowledge of course topics to their own design work.

In response, we have transitioned away from a mode of summative assessment and toward exams that we consider to be formative teaching tools in themselves. These include vignette-based exams that ask students to apply course topics to architectural scenarios. This paper discusses our use of vignette exams in large-lecture format architectural technology courses and reflects on the advantages and challenges. These insights come from three forms of assessment. First, grading the exams allows for an analysis of student performance. Second, dialogue with students through direct conversation provides input into their personal experiences with the exams. Finally, anonymous surveys assess the effectiveness of exams in supporting student learning.

Our findings indicate that the vignette exams allow for a more revealing assessment of students' understanding of course topics. With machine-readable tests we could see when a student performed poorly in a topic area, however, the nature of their misunderstanding was not always apparent. In contrast, vignette exams reveal specifically where within each problem a student makes a mistake and therefore which aspect of the topic was misunderstood. Further, students report that they experience a holistic and integrated way of thinking through the vignette exams and that they "feel like architects" having completed the test. This sense of working on something meaningful positively impacts students' perception of the relevance of course material to their education and their future lives as professionals.

Keywords: Pedagogy, Exams, Architectural Technology, Large-lecture courses, Course design

The Shift from Summative to Formative

Especially in a large-lecture course, instructors can rely on a small number of exam scores to determine a student's grade in the class. A common exam scenario follows a pattern of students cramming the night before a test by frantically reading the course texts—often for the first time, reviewing lecture notes, and conversing with classmates. Instructors also cram to write machine-readable exam questions that can be efficiently graded. While this has become the normal *testing* ritual, there may not be much *learning* or *teaching* taking place. It became obvious to our teaching team that the way we talked about, wrote about, and administered exams was about generating students' scores for the course. We poured over the numeric data and made judgements about how well our students *understood* and *knew* the content based-on how accurately they would choose between a list of possible answers. Our efficient tests were designed to inspire studying and memorization, which can definitely promote learning, but we realized that we were not designing tests where *learning* was the primary focus. These tests were designed to record *recall*, but did little to further students' *thinking*.

The 1993 publication "Measuring What Counts: A Conceptual Guide for Mathematics Assessment"[1] (MSEB) outlined three principles for assessments. We have found these principles to be useful aspirational goals for own course assessments. The following paraphrase these goals while editing them to remove specific references to mathematics. *The Content Principle*: Assessment should reflect the content that is most important for students to learn. *The Learning Principle*: Assessment should enhance learning and support good instructional practice. *The Equity Principle*: Assessment should support every student's opportunity to learn important content.

It is especially important to note that there is no mention that assessment should be used to assign a grade or score to a student. The language in MSEB is formative in that the assessments are learning focused, rather than summative, in that they allow for a simple culmination of the course instruction.

In fall of 2016 we made a fundamental shift toward exams that are focused on learning. We shifted from machine-readable on-line exams with 50 to 90 questions to human-graded vignette-exams with 3 to 6 questions. Along with this came another change in the resources that we made available during the exam. The multiple-choice tests were administered in a closed-book scenario and required a student to have everything they would need to know accessible by memory. The vignette-exams are open-notes, open-internet, and open-book—encouraging students to know how to navigate the resources available to them (and to any practicing architect). The students now prepare for these tests by revisiting webpages, readings, and course notes. However they do not do this in order to memorize the content but, instead, to ensure that they can find what they might need during the test more quickly and then know how to apply it. The students do not need to know the answer to the fill-in-the-blank, but they do need to know how and where to source sound information to inform their answer. We believe this is a more equitable learning experience, as organization of resources versus memorization of information, is less targeted on a single and particular way of thinking. Students who may not be good at quickly memorizing and recalling are at a disadvantage by the multiple-choice assessment.

In order to have enough multiple-choice questions to fill the testing time, we'd generate a high number of questions that were very narrowly focused and specific. This was misaligned with our broader course goals of educating architects that are able to ask competent and confident questions about the technical aspects of design and practice, and helping students to develop values about the environmental and human impacts of development. The multiple-choice exams were misaligned with the learning principle, content principle, and the equity principle outlined by MSEB.

From School Work to An Architect's Work

L. Dee Fink is an educational scholar who has been an influential guide to how we are rethinking exams. Fink describes, "…significant learning is learning that makes a difference in how people live – and the kind of life they are capable of living. We want that which students learn to become part of how they think, what they can and want to do, what they believe is true about life, and what they value – and we want it to increase their capability for living live fully and meaningfully."[2] One of the challenges posed by Fink is to get students to think about their education in terms of their life, and not just as something they have to do while they are studying. We approached this by shifting the test away from an assessment that would be perceived as "school work" and moved toward an assessment that would be perceived as "an architect's work." We hoped that this would inspire students to see it as significant toward their chosen profession. We were quite confident our students only saw the multiple-choice as meaningful to their grade in the class, but not to their life. Anecdotally, when students turn in their vignette-exams, we've heard many of them say that "I feel like an architect" which is evidence that they are not in the "school work" mindset. The students perceive this assessment as authentic, and therefore valuable.

At the end of the first year with vignette-exams, we surveyed our class of 140 students about their experience. 110 students responded to the survey. When asked if they thought that the vignette-style exams were preparing them for their future profession (Figure 1), 58 responded either strongly agree or agree. While there is room for improvement here, this number does indicate that the majority of students see the activity of test taking as meaningful beyond the class.

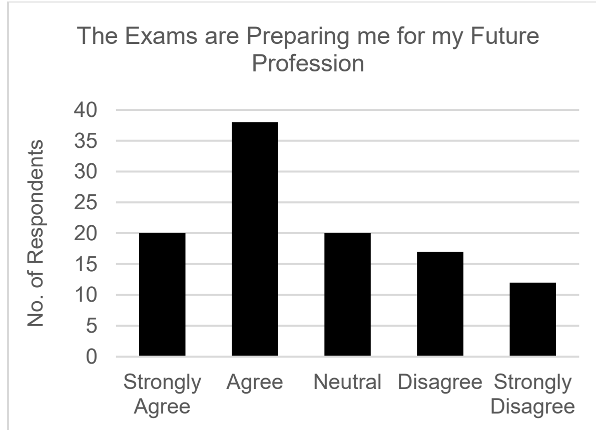


Fig. 1. Student responses to a year-end survey (June 2018) after the pilot year with vignette-exams. 58 of 110 respondents indicate a positive correlation with the exams and their profession after graduation.

Conversely, when asked if students thought that the vignette-exam tested memorization (Figure 2) only 24 students responded that they agree or strongly agree. Compare this to the results when students were asked if they felt challenged to think critically when taking the vignette-exam (Figure 3). 84 Students confirmed that they agree or strongly agree. These three questions taken together can lead to a conclusion that the students do perceive the exams as relevant to their future life beyond school, and also as an assessment that invites them to think critically about architectural issues.

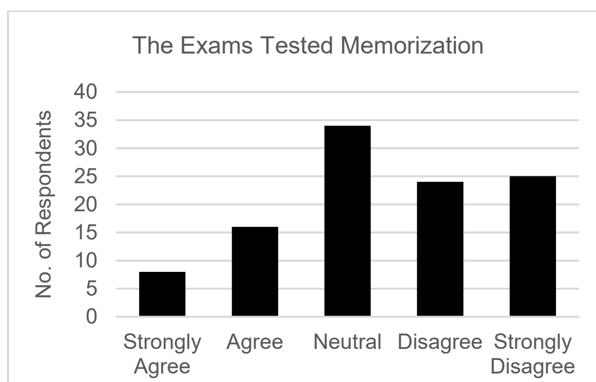


Fig. 2. 48 of 110 students responded that they do not believe the vignette-exams test memorization, compared to 24 students who agree or strongly agree that the exams do test memorization. (June 2018 survey)

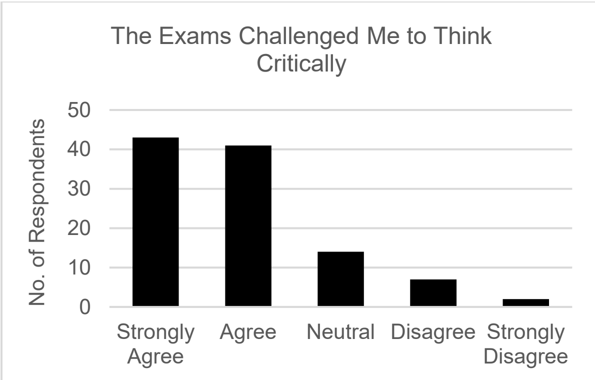


Fig. 3. 84 of 110 students responded that the vignette-exams challenged them to think critically. (June 2018 survey)

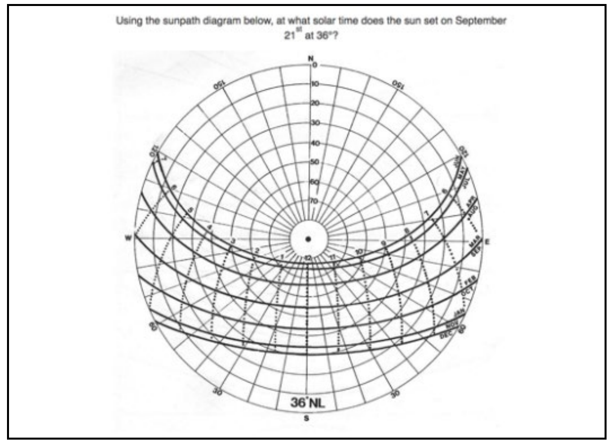


Fig. 4. A multiple-choice exam question assessing ability to read a polar sun path chart. 76% answered correctly (fa 2016).

From Finished to Feedback

We believe that exams are powerful educational tools and that, if done well, they can be "concrete illustrations of the important goals to which students and teachers can aspire."[3] We will use an example from our 2017-18 course to illustrate how the vignette-exams have increased the quality of communication from student to teacher, and in turn from teacher to student. One of the topics taught in the Architectural Technology Fundamentals class is solar geometry. This foundational knowledge is employed throughout the lessons on daylighting, passive solar heating, solar shading, building orientation and massing. In our class we rely most heavily on polar sun path charts (Figure 4), which is a graph of the sun's positions over a year by latitude drawn in plan (horizontal projection). Understanding how to read the sun path chart is a skill required to be successful in many subsequent topics in the courses.

When assessing students with a machine-readable exam we would present a polar sun path chart and ask students to read it. In general, students did quite well on these questions, whether given in multiple-choice or fill-in-the-blank format. For the example shown in Figure 4, 76% of students answered the question correctly. This result would lead the teaching team to believe that our teaching practices were highly effective.

When assessing the same course content with the vignette-exams (Fig. 5), students first read the sun path chart based on given criteria and then apply that reading to an architectural situation. In the midterm exam for the fall quarter of 2017, the architectural situation given to the students was to locate the best area of a site where a café with rooftop solar photovoltaics should be placed, and to also locate the best location for outdoor seating that would be shaded in the afternoon. To answer this question, students had to use the sun's location to determine shadow lengths and directions and then sketch these shadows on the provided site plan. Grading this question revealed to us that 1/3 of our students were reading the sun path chart incorrectly even though they could answer the first part of the question correctly. Through the three-part vignette question, we found that many students were drawing the shadows inverted from the direction they should have been drawn in. This mistake indicates that students were reversing the position of the sun in relation to the position of the site/body. Without the follow-up questions that required students to do something with the solar information, the instructors previously believed that there was widespread understanding of solar geometry in the class. The reality was that there was a very common misunderstanding that only came to light when students were asked to apply solar geometry to an architectural problem.

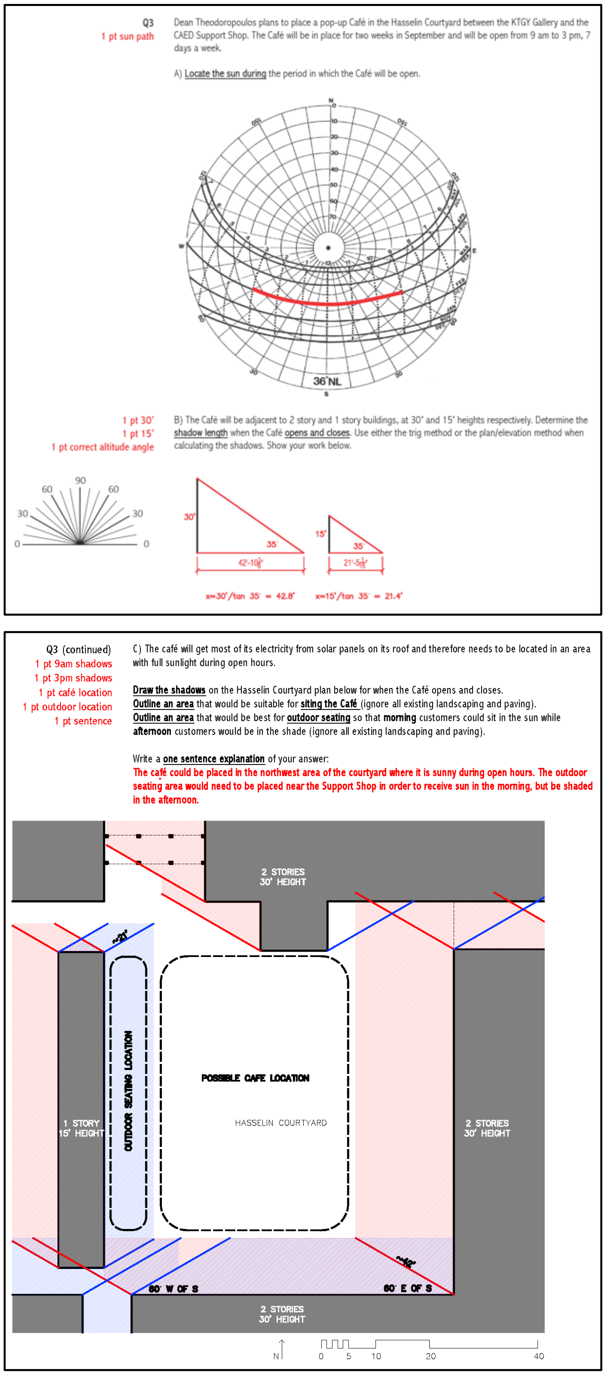


Fig. 5. A three-part vignette question where students first read the sun path chart, then determine the shadow lengths for given sun positions, then sketch these shadows on a site plan to determine the best location for a solar powered café on campus. (fall 2017)

Incidentally, other assignments (not exams) in the class also did not bring this issue to light. The third part of the three-part vignette question asked students to locate two outdoor programs on the site with particular time-based requirements for sun/shade. The question was written such that If students misunderstood the solar geometry they would provide a site design that does not meet the users sun/shade needs. While it may seem like a small misunderstanding initially, the result is an architectural proposal that does not meet the user's needs, which is a significant failure in our eyes. Because of this feedback, and more clear understanding of the student's specific understanding, we have adjusted our teaching practices around this topic. Making visible these learning issues is not just an Architectural Technology Fundamentals problem, but an Architecture problem. We see students making mistakes of a similar nature in their design studio work, and we assume this continues into their early career. Without an assessment tool that provides a concise and clear venue for each of the core learning goals and skills to be expressed, we were not able to fully learn about the quality of the teaching and the learning taking place in the class.

Examining the Exams

There have been many challenges involved in writing and grading vignette exams with many possible correct answers for large numbers of students, often with turn-around times of only a week.

Challenge 1: Generating Questions

After the vignette-exams are graded, our practice is to return exams to students, and provide a detailed rubric showing how to derive correct answers. We see this is an important step in learning-focused exams. Each term and year we then must write new questions to prevent simple copying from last year's rubric. At this point the team is committed to generating new questions, which entails creating CAD drafted base drawings and continually creating new scenarios. While it is time-consuming, we believe this work is worth the effort.

Challenge 2: Human-Read Exams

We work with a team of 4 instructional student assistants (ISAs) who grade exams based on faculty-generated rubrics. Each ISA grades one question for the entire cohort of students ensuring consistency of grading by question. ISAs spend between 8 and 12 hours each per exam, and it typically takes about 5 days to complete preliminary grading. The team of instructors then randomly checks exams, and if an evaluation issue presents, the instructor will look through all the exams and fix evaluation errors.

Prior to beginning the evaluation period, the ISAs and instructors will meet and look through a number of student exams while also dialing-in the grading rubric. We devise a method of assigning points to particular types of answers. We cannot anticipate the range of answers that will be provided, even when we think we have limited the conditions sufficiently. In some cases, answers are quite clever and clearly demonstrate understanding of the concepts. In other cases answers are bizarre and it is unclear if the student knows what they are doing.

A key to our grading approach is placing an emphasis on the process over the final answer. We allocate points for each step in the process, so that students who demonstrate the right methodology with minor errors are assessed accordingly. In some cases, such as in a question which asks for an answer to be sketched, a student will realize that they made a mistake in the drawing but they won't have time to re-do the work during the exam. We encourage students to explain themselves in the margin if needed. We do not deduct points from a student's score if they provide an explanation that clearly demonstrates understanding, even if there's inaccuracy in the sketch.

Once the exams are returned to the students, the educational experience continues. Because vignette-exams do not necessarily have a single *correct* answer, there is some room for *negotiation*. After the first vignette-exam, students who wanted to know why they were marked-down for their responses inundated our office hours. The discussion quickly degraded to one about scoring which was not the discussion we wanted to have about the course content or about how to learn. In order to reframe these discussions, we introduced an exam wrapper[4]. The exam wrapper is a handout that students completed prior to coming to office hours to discuss their exam. We would give modest credit for completing the wrapper to incentivize those students who didn't do well on the exam to meet with a professor. The exam wrapper asks students three types of questions: How did they prepare for the exam? What kinds of mistakes did they make on the exam? What would they do differently before/during the next exam?

The exam wrapper highlights study practices that are not shown to be effective, such as re-reading class notes, as well as study practices that are highly effective, such as working on sample problems with classmates. Students list the amount of time they spent doing each type of preparation, allowing us to talk about exam study habits rather than points. Another helpful aspect is that the exam wrapper asked students to explain the types of mistakes that were made. This has enabled us to better understand which parts of the exam were confusing to students and write clearer questions with better scaffolding.

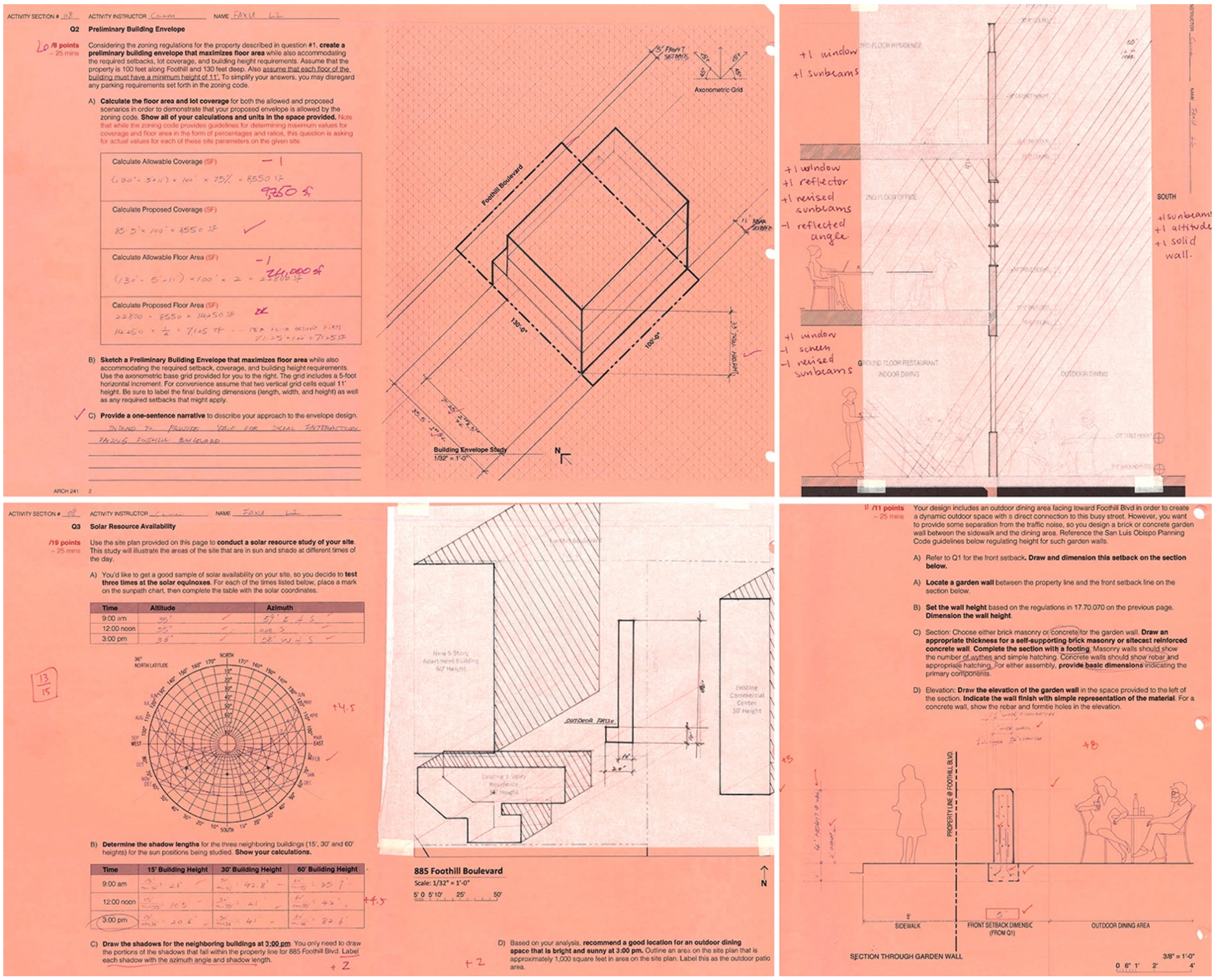


Fig. 6. A final exam where students work through the topics of materials, assemblies, environmental control systems, and site systems sequentially (fall 2018). Actual student answers and grader notes are shown.

Challenge 3: Integrated Topics

The Architectural Technology Fundamentals courses integrate the topics of materials, assemblies, environmental control systems, and site systems, which are taught by three instructors. The first challenge is to write exams that integrate these topics while also not overwhelming students. Our approach has been to write each exam as a single vignette where questions are answered sequentially (Figure 6). In Fall 2018, we provided an urban site in San Luis Obispo, California. Questions 1 and 2 asked students to look up the zoning code online and sketch a diagram of set-backs and lot coverage, then sketch a possible building massing for the given program (site systems). Question 3 analyzed solar geometry, sketched shadows for the adjacent structures, and determined the best location for an outdoor patio (site systems). In Question 4, students were given a skeleton of a wall section for one wall in their proposed building massing to sketch over in order to design three daylighting schemes (ECS). In Question 5 students chose masonry or concrete to design a code-compliant site wall, documenting their proposals with a section of the wall and its footings (materials & assemblies). In Question 6 students wrote a short essay explaining their material choice in terms of physical properties and human perceptual experience (materials & assemblies).

Fall quarter is the student's first term of Architectural Technology Fundamentals. Great care must be taken when crafting the exams to not overwhelm students, nor to write an exam where a misunderstanding early in the test leads to overall failure in following topics.

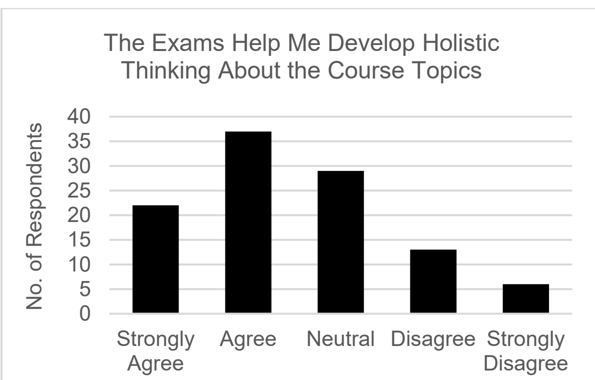


Fig. 7. 59 of 110 students responded positively (June 2018)

When asked to reflect on the vignette-exam and students holistic thinking about course topics, most students reported affirmatively (Figure 7). As vignette-exam designers, this process of writing exams that can successfully integrate the wide-ranging course topics into one coherent scenario, is an excellent litmus test. If the subjects do not work well in a scenario, then perhaps the course content proportions and sequence need to be reassessed.

Challenge 4: Time

The most consistent negative student feedback we receive is that there is insufficient time to complete the exams, and that this time pressure leads to stress and mistakes. We continue to explore solutions to this problem in several ways. We strive to remove repetitive tasks, such as calculating areas of numerous spaces, which are not necessary for assessing student ability. We have also added recommended lengths of time next to each question to help students better manage the 2 to 3 hours allocated to complete exams. Recently we experimented with a take-home final exam. Even with this format, students expressed concern that they spent too much time on it. Apparently when given multiple days to complete the problems, students spent that entire time. We did not see a drastic change in grades for the take-home exam, but we did hear that it was less intimidating and caused less anxiety

Conclusions

Course redesign is a constant for all educators, especially those teaching Architectural Technology who endeavor to present engaging and relevant content while sparking student interest in technical knowledge necessary for bringing their designs to life. Sometimes course redesign is centered on format or delivery methods. Often it is focused on the proportion, sequence, or nature of the content. Most of the time, however, assessment methods tend to remain constant: multiple-choice midterm and final exams.

As part of our course redesign efforts our teaching team questioned the benefits of conventional test-taking, both for students and instructors. Inspired by scholarship from teachers and experts in other disciplines, we considered ways that assessment could advance student learning while at the same time modelling methodologies used by architects and designers in daily practice. The vignette-exams we created emphasize lifelong learning over memorization (formative vs summative) by asking students to apply an analyze/research/apply methodology to problem solving, a strategy that will serve them well in the rest of their education and throughout their careers.

Feedback we've gained through direct contact with students and anonymous surveys has reinforced our initial assumptions. Figure 8 shows the results from two years of student surveys that indicate a clear majority of students find value in the four stages of the vignette-testing scenario: studying prior to the exam, problem solving during the exam, using rubrics to reflect on the exam, and discussing the exam with peers and instructors. Far from conclusive, this feedback is nevertheless encouraging enough to pursue further refinements and face the challenges outlined in the body above. Our refinements will be guided by further feedback (we're currently surveying upper level student perception of the learning methods discussed here and the impact on their work) and by further research into innovative and best practices in other disciplines.

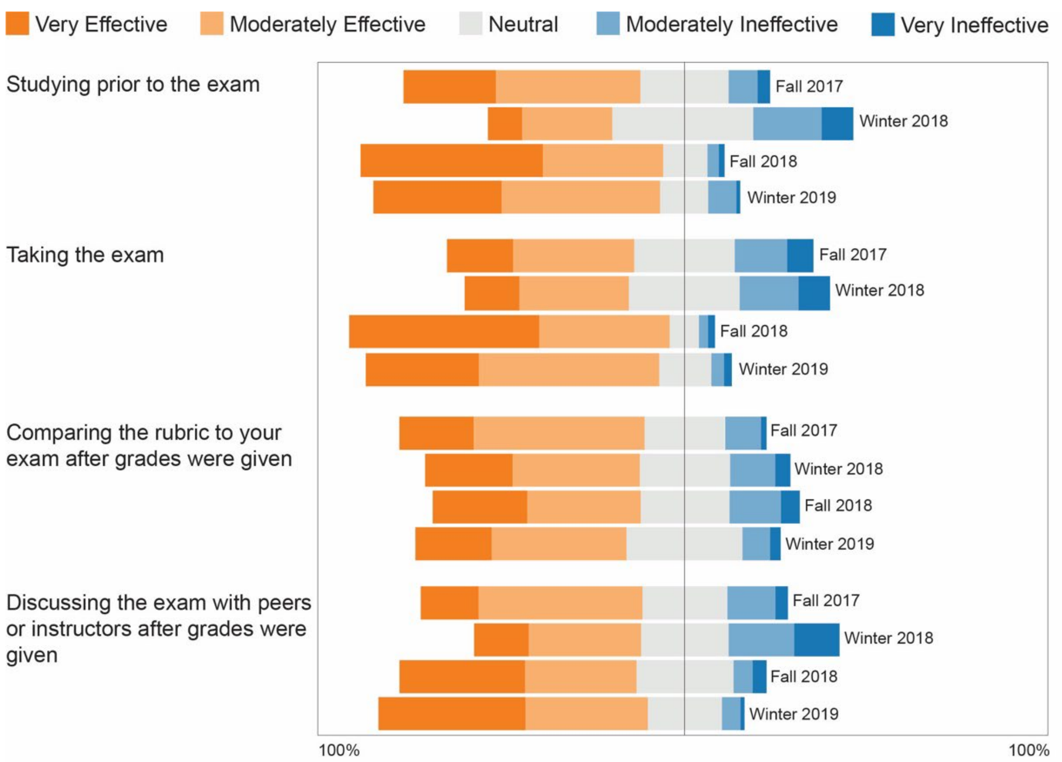


Fig. 8. Four quarters of student survey results showing that the majority of students find studying, taking, and reviewing the vignette-exams as effective in contributing to their learning. We also see improvement from the first year (fall 2017 and winter 2018) to the second year ((fall 2018 and winter 2019) indicating that our approach to exam writing is also improving.

References:

1 Mathematical Science Educational Board (MSEB) "Measuring What Counts: A Conceptual Guide for Mathematics Assessment" National Academy Press: Washington, DC. 1993

2 Fink, L. Dee. *Creating Significant Learning Experiences: An Integrated Approach to Designing College Courses*. Jossey-Bass Publishers: San Francisco, CA. 2013.

3 Fink. p 7

4 From Chapter 2, Make Exams Worth More Than the Grade, by Marsha C. Lovett in the book, *Using Reflection and Metacognition to Improve Student Learning*, edited by Matthew Kaplan, Naomi Silver, Danielle La Vaque-Manty, and Deborah Meizlish. Stylus Publishing, LLC: Sterling, VA. 2013

Exposed! The Impact of Structural Materiality on the Design of Architecture

Terri Meyer Boake BES BArch MArch LEED AP
University of Waterloo

Abstract

There is a formative connection between structural choice and architectural design. Where the term "low hanging fruit" has often been used with reference to critical first choices towards climate responsive sustainable design, a similar approach can be applied to design-thinking when it comes to structural choices. The consideration of the material nature of the primary structure at the conceptual stage of design can allow for improved focus during the design process. This is particularly critical when working with exposed structural systems as the materiality also directly impacts the aesthetics. Exposing a structure requires that the architect be significantly more technically knowledgeable in order to remain in control of the design outcomes.

This paper will elaborate an approach to instilling this type of design-thinking as it pertains to structural systems. It will look at the advantages of adopting a directed or limited structural palette in earlier design based exercises as a means of acquiring a higher level of expertise that can lead into more adeptness when dealing with the complexity associated with multiple materials. It will demonstrate that limitations can actually be liberating. Sample case studies will be used as a means to support and explore this pedagogical approach to design.

Keywords: Materials and Construction, Structures, Architecturally Exposed, Design Thinking, Pedagogy

Introduction

The last 300 years of evolution towards contemporary architectural design have demonstrated an undeniable link between the material choices we make when designing a building and its potential for excellence. There is a formative connection between structural choice and architectural design. Material understanding focusing on the ability to resist tensile and compressive forces is able to direct design choices and detailing. In departing from a technique-based historic dependency on stone, and the maximization of span through compression based domes and vaults, the technological inventions of steel, concrete and engineered timber systems have been able to realize a significantly new range of building forms and types via their relative abilities to resist tensile forces.

Where the term "low hanging fruit" has often been used with reference to critical first choices towards more passively directed sustainable design, a similar approach should be applied to design-thinking when it comes to structural choices. The consideration of the material nature of the primary structure at the conceptual stage of design can allow for improved focus during the design process and assist the decision making process. Limitations remove the "blank page" issue and can be seen to accelerate design explorations by restricting material choices. This is particularly critical when working with exposed structural systems as the materiality also directly impacts the aesthetics. Although this type of thinking initially emerged as Structural Rationalism during the 19th century, the present intentions are not necessarily as historically “formal” or classical in terms of suggesting strong impositions of symmetry in the setting out of the plan and section. The intention is simply to allow for a clearer understanding of the intrinsic relationship between materials, spanning systems, the sizes and types of spaces that they support and the resulting character of the architecture.

Learning to Expose Structure

In an age of design that is seeing unparalleled complexity, propelled by digital design tools as well as sustainable design, and that is attempting to do more with less materials, many structures are no longer able to be either simply designed or relegated to the structural consultant. Many graduating structural engineers are equally unprepared to design and detail complex structures, as such design exposure is not part of a typical civil engineering curriculum. This critical overlap of structural design thinking may be present in Architectural Engineering programs, but these programs are uncommon in many parts of the world.

Material choices can be less important when a structure is concealed as the detailing is not exposed and therefore not a part of the architectural aesthetic. The impact of material choices on design may not have been an issue in previous times when much of the structure was routinely concealed with interior and exterior finishes. However, exposing a structure requires that the architect be significantly more technically knowledgeable in order to remain in control of the design outcomes. This includes an appreciation of span limitations, fire protection requirements, fabrication methods, connection detailing and construction processes. Where is this sensibility learned? Likely not in a calculation based structures course. It is more likely acquired in a design project.

Studio projects are often program-based rather than material-based explorations. In an age of increasingly complex design, there has been a pedagogical tendency to avoid the constraints imposed by a highly formalist narrative and this seems to have largely precluded the specification of a directed structural palette within a design studio. Students are intentionally left free to explore form based on programmatic requirements. However, students often run into difficulties when attempting to apply structure (after the fact) to a project after working out spatial and volumetric relationships. This can compromise the plan, the structure and the design in a forced-fit scenario.

Fig 1: Ste. Genevieve Library, Paris (iron), TAMA Art Library, Tokyo (reinforced concrete); Scarborough Library, Toronto (timber). As can easily be seen by the above three images of libraries, materiality plays strongly into form, feeling and detailing in spite of programmatic similarities. A high level understanding of materiality was required of the architect. Photos by author.

Design studios are often sequenced from smaller buildings to larger ones as a means to increase a student’s ability to deal with increasing complexity. A similar approach can be applied to learning structural systems application and detailing. There are advantages to adopting a directed or limited structural palette in earlier design based exercises as a means of acquiring a higher level of expertise that can lead into more adeptness when dealing with the complexity associated with multiple materials.

Design Precedents

A dramatic change in architectural design, one that began to embrace structural materiality, began during the Industrial Revolution. The invention of cast iron, wrought iron, steel and reinforced concrete allowed for significant changes in structural capabilities that manifested in changes in design style. Although there were previously a multitude of "formal styles" that could be associated with western stone architecture (classical, humanist, mannerist, baroque, neo-, etcetera) the variation in appearance was largely associated with expression in the decorative stone elements and less so in the detailing of the structure itself. The exception to this would be the Gothic style as the pointed arch impacted the capabilities of span and led to the addition of structural buttressing which in turn allowed for increased levels of fenestration. That this expressed structural choice greatly impacted the architectural expression of the building would be the basis for the extrapolation into the current 21st century period that this thesis presents.

The majority of the architects whose skill in design continues to be celebrated and seen as exemplary can also be seen to have strong connections to material expression in their architecture. Structural Rationalist architects such as Henri Labrouste adopted cast iron through a curious exploration of the new material. At that time the ability of casting to incorporate a high level of decorative detail helped the public to accept the material as used by Labrouste in his two signature libraries, Bibliothèque St. Genevieve and Bibliothèque Nationale in Paris. The Italian Futurist Antonio Sant'Elia less than a hundred years later, declared a hard break with decoration and historic styles and proactively adopted modern construction materials as one of the means to achieve his design goals. These materials coincidentally did not lend themselves to decoration as part of the manufacture or construction process (in direct contrast with the decorative nature of historic cast iron). Each material would not support the other style due to their intrinsic characteristics and resulting aesthetic limitations.

"Calculations based on the resistance of materials, on the use of reinforced concrete and steel, exclude "architecture" in the classical and traditional sense. Modern constructional materials and scientific concepts are absolutely incompatible with the disciplines of historical styles, and are the principal cause of the grotesque appearance of "fashionable" buildings in which attempts are made to employ the lightness, the superb grace of the steel beam, the delicacy of reinforced concrete, in order to obtain the heavy curve of the arch and the bulkiness of marble…." Antonio Sant'Elia 1914

Le Corbusier in his 1931 book "Towards a New Architecture" reinforces the divorce between modernity and historical styles. His exploration of industrial architecture in North America supported his focus on new materials and associated forms. Although he did not explicitly reject structural steel, the majority of his projects employed reinforced concrete, a material that buoyed his design ideas and fascination with industrial reinforced concrete grain silos. His five points towards a new architecture became synonymous with many of his built concrete projects such as Villa Savoye and Unité d'Habitation. Even as his work extended into its Brutalist phase, reinforced concrete expressed structural systems are easily seen as being central to the manifestation of his ideas.

Mies van der Rohe's portfolio of work claimed structural steel at its center. Even as his practice migrated to North America where fire protection laws forced the concealment of his steel structures, the presence of the material was reflected in the added mullions on the Seagram Building and its many clones. Although Pier

Luigi Nervi's work included steel, it also tended towards a preference for reinforced concrete as it supported his fascination with cantilevered shapes and a complex but repetitive forming process. The ability of concrete to be formed aligned with the circular shapes of his stadia in Rome. Other modern architects also tended to focus their practice on a limited palette of structural materials. The simplicity of form worked well with the narrow range of material choices of the time alongside the limitations presented in structural design in the pre-computer era.

The High Tech Architecture of Foster, Rogers, Piano and Grimshaw introduced expressed structural steel, and with it a style whose member and connection design proactively acknowledged the force systems within. This type of architecture was slow to be adopted into what was to become mainstream architecturally exposed structural steel (AESS) as the majority of architects were incapable of conceiving of the structural design thinking required to be closely involved with this level of expression. Few engineers were also able to comprehend the intentions and possibilities of these systems. The nature of the education of both professions has still not approached a level to enable the widespread level of expertise required to confidently design and detail in architecturally exposed structural steel systems.

Global Influences

In the more global design environment of the 21st century, regional preferences or traditions that are based on the availability of materials and skilled labor will also have a great influence on structural material choices. Firms also tend to develop a focus as a function of developed expertise and success in detailing and construction. Indeed detailing and building science issues are far more challenging now than in the past as expectations of performance are much higher given the litigious nature of today. However global practices tend to explore a variety of structural materials as suits the needs and limitations of the local economies. Where inadequate local skilled labor is available, problems often ensue during fabrication and construction if materials are used that are beyond the skills of local labor forces.

Graduates must be prepared to work globally and gain experience prior to specialization. A limited palette limits opportunities. The same can be said of limiting complexity in structural design thinking. A mismatch between courses provided and design aspirations is simply not helpful and leads to insufficiency within the profession itself. It is therefore helpful in design education to ask students to fully explore and gain confidence in designing with a wider range of structural materials as it will better prepare them to adapt to requirements that fall outside of their local architectural context. Much like design professionals that become too comfortable in one material, students may not willingly take on learning to design with materials that may make a design project more demanding to detail unless such explorations are proactively supported by the supervising faculty.

Promoting Structural Design Thinking

The current state of architecture is dramatically different than it was during the past century. There is now an excessively high level of complexity that has been fueled by inventions in the areas of computing, manufacturing and materials. The simplicity presented by orthogonally based design that primarily used either steel or reinforced concrete systems is gone. Generally speaking, the nature of structural design education provided for future architects (and structural engineers) has not advanced significantly beyond what was provided during the Modern Movement. There is still a tendency towards thinking in terms of simple orthogonal systems applied to steel and reinforced concrete systems as these are easily designed, calculated and member sizes selected from prepared tables. These are often taught by structural engineers, often on an adjunct appointment, so contractually limited in their overall engagement.

It is likely neither feasible nor desired to provide architecture students with advanced structural design courses that are numerically based to address this gap. This was discussed in detail in a previous paper presented at ICSA 2013.[1] However there are ways to provide a higher level of understanding of more complex structural design issues if we incorporate project based experience. A focus on exposed structural systems, integrating the visual outcomes of the structural systems into the architectural aesthetics can provide the motivation needed to encourage students to undertake this added challenge in a design project. Repeated experience addressing detailing and member/system selection can buoy structural design thinking.

Design by Structural Type versus Program

It is also important to recognize that there is a disconnect between structural materiality and program and vice versa. As illustrated by the libraries in Figure 1, one does not necessarily infer a choice in the other. So where a design studio may base a project on a given program, as is traditionally the case, a wide range of structural materials may be suitable and not direct or inhibit the ultimate design outcomes. In the same vein, beginning a design project with a structural material does not inhibit the number of program choices and quality of the outcomes. Both present complexities in the discourse and teaching of the studio that can be beneficial. Structural design can be equally as valid a subject for exploration as program driven projects given that the structural design focused project will also have a program and demands for spatial arrangements. Designing from the perspective of structural choice is proposed to be considered as an additional lens for viewing design projects that can serve as a complementary approach to an evolution of design thinking that can include structural design thinking in a more developed and therefore, useful way.

Structural Material Selection

Given increasing pressure on teaching ratios in light of shrinking budgets, it can be problematic when students pursue a wide range of structural choices if expertise is not readily available to guide and correct. Where faculty may have been adequately prepared to advise on traditional orthogonal structural systems, many have themselves not kept up with the variety of more geometrically driven contemporary solutions. The pedagogy of this paper proposes using design projects that limit the structural materials, with a primary focus on one material, as a means to accelerate structural design thinking about that material. This also allows the faculty to expand their own understanding of new systems at a less frenetic pace. The design projects can be housed in a regular design studio or be a significant project for a course with a construction or structures focus. Again, exposed structures are preferred as they have the greatest visual impact on the design outcome.

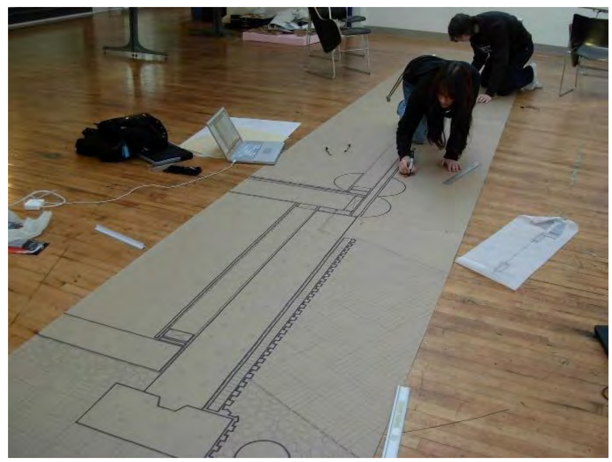
The design projects that I have thus far used to explore the validity of this approach have excluded reinforced concrete as a primary material. Reinforced concrete is permitted in an ancillary fashion for foundations and minor elements but is otherwise discouraged. The reason for this exclusion is derived from situational experience over time. Projects assigned to junior students have seen them tend to select reinforced concrete “by default” as it is perceived by them to match well the poché of their studio drawings and seems to them to require no thought as to detailing. While this may not actually be true, it seems to persist as an attitude that seems not to be discouraged in studios. That is, the studio is program and not material driven and so materiality is seldom discussed in great detail and cast in place concrete aligns well with simple modern forms and load bearing systems.

Reinforced concrete has also been excluded as a primary structural system in a comprehensive design studio for incoming masters students, the majority arriving from countries where most buildings are constructed out of reinforced concrete and so they already have this experience. Reinforced concrete does not provide them with a high level of structural learning again due to its monolithic nature and relative low level of required detailing for construction. Architects in practice are not involved in rebar placement, for instance, and much of contemporary reinforced concrete design tends to use less than challenging (or inspiring) structural typologies. The prevention of thermal bridging in cold climate buildings would be the detailed exception in this case.

Materials that are "framed" tend to provide the most benefit to structural learning. Steel and Timber systems would fall into this category. They are typically comprised of unique elements that include a choice of shape, that are assembled into larger units via connections. Most framed connections act as either hinge or pin connections and are considered determinate systems, so can even offer a link to parallel structures courses. Connections become the focus of much of the design problem as they need to transfer forces, answer to load path issues and influence constructability and ultimately, cost. Connections also feature heavily in design expression.

Design Projects Driven by Structural Materials

The first project sits as a terminal project for the first building construction course in the undergraduate pre professional degree (typically 18 year old students coming directly from high school). It is done in groups of four students and the requirement is to design a small getaway cabin out of wood frame. Although the structure in this case is not exposed, the students are required to construct a structural axonometric of the framing (thereby featuring its exposure in a way) as well as a full scale, 1:1 wall section that is drawn without cuts. The structural axonometric of a wood framed building is challenging to draw but is capable of helping students to understand the 3 dimensionality of a structural system and begins to address constructability and construction sequencing. The full scale wall section makes them aware of the scale of building materials without the expense and trouble associated with managing a design/build type project at this early stage. It also forces them to confront detailing for the first time in a manner that requires a lot of thought. It is easier to fudge details at a smaller scale and remain unaware of the relationship between materials. The attitude that I attempt to have them understand when they are making these drawings is that they are not actually creating a "drawing" but rather, a building. The type and nature of this challenge works well as an introduction to structural design thinking.



Fi. 2. First year undergraduate students drawing a full scale wall section of a small wood framed building.

The final term project for the second course in building construction is based upon a competition that is sponsored by the Canadian Institute of Steel Construction. As with most material sponsored competitions, it is expected that the material become a central focus of the design. The sponsor is looking for high quality innovative solutions. The subjects have always been very open, mostly using a single word to define the scope – cantilever, tension, bridge, span, recycle, surfaces, tower. This has been immensely helpful in permitting students to experiment with the form and forces in the structures as the program is "light". The project is shared by the digital design course which has the added benefit of pushing their designs even further in terms of representation skills gained. That the project is housed in a course whose focus is construction both makes the material focus allowed but also presents a conflict as this is a summative project and as such should test on a wider range of expertise. In this case I am also teaching a parallel course in environmental building design where the "rest of the materials and details" can be evaluated, establishing the pair of projects as a balanced evaluation of learning.

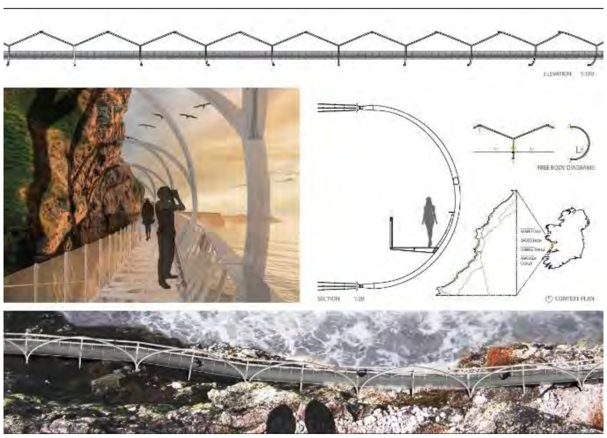


Fig. 3. The CISC Competition has been employed for over 12 years as an effective project to learn about materiality and detailing.[3]

Competitions that focus on materials can provide additional learning opportunities outside of required courses. An elective course focuses on architecturally exposed structural steel design includes a series of very detailed lectures on design and detailing that look at design impact and not calculations.[2] This course uses the CISC competition as well as the annual ACSA/AISC steel design competition. The latter is typically more program focused, so the students first complete the CISC Competition to gain proficiency in thinking about AESS details and then follow with the more program centered competition as the general difficulty level is greater. Competitions in general are a great way to add design motivation to a construction or structures focused project, taking the resulting submissions well above what might normally be expected from a purely graded element in a structures course.

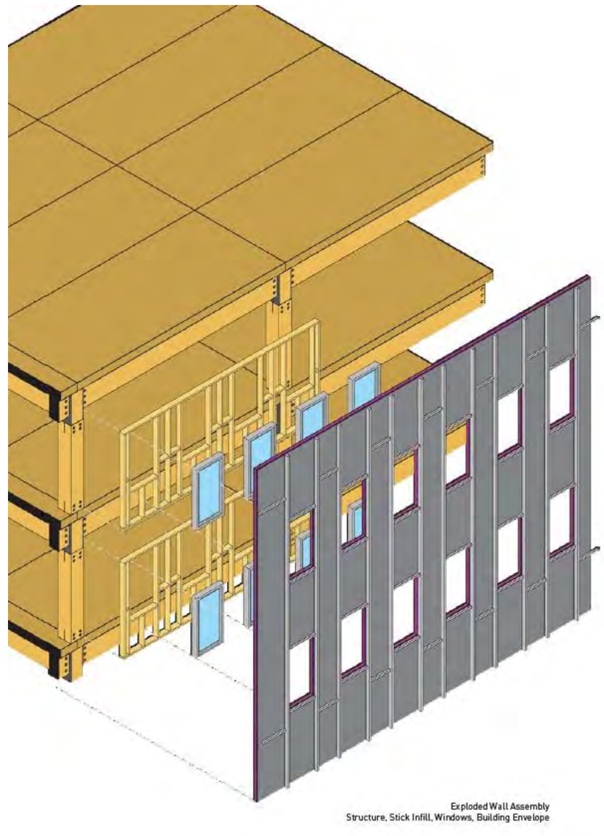


Fig 4. Project drawing of the wall and structural system from a Masters project looking at the application of CLT and glulam systems.

The Comprehensive Studio that is taken by predominantly foreign students entering our Master of Architecture Professional degree has recently mandated wood construction as the required structural system. Given the scale of the building program given, this means using glulam, larger engineered wood and cross laminated timber systems. Heavy wood systems have recently been approved for use in larger buildings in an exposed fashion provided that proper sizing and fire protection are provided. So again the potential for exposure of the wood systems add interest to the ultimate design and aesthetics of the project. Initially the move was simply to exclude reinforced concrete, as previously mentioned, but there seemed to be continued interest by the students in learning how to design and detail wood systems as they understand it to be essential to eventually gain employment in Canada. This allowed the supporting lectures to focus on providing more detailed information and feedback, and also review sessions could have feedback on this system in common so be more valuable to their learning experience.

Due to accreditation requirements, this studio has the mandate to be technically driven as well as look at program, environmental systems, envelope detailing and sustainable design. There is a parallel Technical Report course and graded element with additional submission requirements, most of which are expected to be presented during the final reviews. Of note is an axonometric drawing of the entire structural system. As with the wood frame axonometric given in first year, this is an excellent way to get students to visualize their structural systems in 3D and begin to understand the process of construction as well as stability and connection issues. There are significant elements that look in detail at the construction and detailing of the building envelope. Additionally climatic differences pose envelope detailing challenges as ours is cold, winter driven climate. There is an additional parallel required course in Advanced Envelope Design that reinforces the importance of detailing and provides a suite of detailed lectures to assist with this subject matter. Although our own undergraduate students also take a Comprehensive Design term, it is run in a more open fashion as far as materials and detailing is concerned. They have had numerous previous courses and cooperative education experiences with which to prepare for the detailing demands of this term. The Masters studio for our external students needs to take a somewhat "catch up" approach to level up some of their technical skills as pertains to cold climate and Canadian design standards and expectations.

Fig 5. An interior rendering of the Masters level project showing a high level of engagement with the materiality of the glulam and CLT system and the impact of its materiality on the aesthetics of the space.

Conclusion

Design exploration is not a studio exclusive project type. This paper asserts that students can benefit in terms of structural learning by also incorporating project based work that requires a focus on a limited palette of structural materials. This is seen to be able to allow for a focused experience that can result in a much deeper understanding and appreciation of the relationship between the relative capabilities of structural materials and the architecture that they support. This type of design thinking supports a comprehensive learning experience.

Notes:

1 Boake, Terri. The Dynamic Phraseology of Structures: Enabling the Design of Complex Systems. ICSA Conference Proceedings, 2013.

2 Website and course information for Arch 570: Architectural Steel Design. http://www.tboake.com/AESS_winter2018.html

3 Canadian Institute of Steel Construction Student Design Competition. https://www.cisc-icca.ca/architecture-student-design-competition/

Classroom as Laboratory: Engaging Architecture Students in Hands-on Building Science Research

Gabrielle Brainard
Pratt Institute

Cristobal Correa
Pratt Institute

Abstract

Knowledge of building science – how buildings perform with respect to energy efficiency, durability, comfort, and health – is a key aspect of sustainable architectural design. Although most building science courses are taught in a traditional lecture format, experiential teaching methods have the potential to improve student engagement and comprehension of technical subject matter.

This paper describes a case study of experiential learning in building science education. In Spring, 2018, we conducted a thermal comfort study as part of an integrated design studio at Pratt Institute in Brooklyn, NY. We measured temperature and relative humidity in the studio space and asked students about their thermal comfort via daily point-in-time surveys.

We analyzed the sensor results using the PMV model, finding that the majority of the studio (87% of sensor locations) was within the comfort zone (PMV between -0.5 and +0.5) during the study period. Students' average reported thermal sensation over the same period (AMV, or actual mean vote) was -0.46, a result that suggested cold discomfort. The discrepancy between PMV and AMV suggests that factors not measured in this study – such as mean radiant temperature or air speed – may have negatively impacted students' comfort.

This case study suggests the potential for integrating hands-on building science investigations into technical architecture courses. Areas for improvement include tighter integration of these investigations into individual courses and the broader architecture curriculum to achieve the greatest impact on student engagement and learning

Keywords: Pedagogy, Experiential Learning, Building Performance, Thermal Comfort

Introduction

Knowledge of building science – how buildings perform with respect to energy efficiency, durability, comfort, and health – is a key aspect of sustainable architectural design. However, methods of teaching building science, which are primarily lecture-based, can fail to engage architecture students who are accustomed to the project-based pedagogy of the design studio.

This paper describes a case study of a hands-on, experiential approach to teaching building science that involves students in field studies of existing buildings. This approach invites students to discover links between design, performance, and occupant satisfaction through their own observations. In Spring, 2018, we conducted a thermal comfort study as part of an integrated design studio in the Master of Architecture program at Pratt

Institute in Brooklyn, NY. We installed a sensor network in the studio space and monitored temperature and relative humidity during the month of April. At the same time, we asked students about their perceptions of thermal comfort via daily point-in-time surveys. We analyzed the data to determine where and when the studio was comfortable, and whether students' perception of comfort matched the predictions of industry-standard comfort models. At the conclusion of the semester, we presented our results to the students so they could understand the connection between their experience as occupants and the architectural design of the space.

Our experience with this study suggests the potential for integrating hands-on building science investigations into the architecture curriculum as a way to boost student engagement and comprehension of this critical subject matter

Pedagogic Context

Experiential Learning and Building Science Education

Learning by doing – also known as experiential or haptic learning – refers to learning via physical engagement with the environment. While traditional teaching relies on aural and visual methods, research suggests that much of what we know about the world is learned through touch.[1] Haptic learning has a long history in architectural design education, where physical models are used to test and represent the physical configuration of buildings.

Building technology educators have demonstrated the potential of haptic methods in technical architectural courses, in addition to the design studio. Student feedback suggests that haptic techniques – such as analytical models or design-build projects – reinforce content from lectures and increase student engagement with technical subject matter. Students reported that hands-on lab work "made a real connection between what was taught in the lecture and the problem set" and what architects need to know in practice.[2]

Despite these benefits, most building technology courses are taught in a traditional lecture format. A 2017 survey of building technology educators found that 86% of respondents used lectures as the primary delivery method for building technology course content; fewer than 50% used hands-on methods like workshops, field trips, or design-build projects. Furthermore, 87% of educators reported that technology classes were taught as stand-alone subject matter, with fewer than 50% reporting that technology courses were integrated with each other or with design studios.[3]

Hands-on teaching methods are more likely to be found in building technology courses that address structures and construction systems – subjects that have a tangible physical presence. Common modes of inquiry include large-scale physical models, full-scale prototypes, and even complete, functioning buildings.[4] These methods aim to help students understand materials, construction systems, and assembly sequences through the physical act of building.

Less common are examples of hands-on methods in building science courses, which focus on the less tangible phenomena of building performance. A notable exception is the Vital Signs Curriculum Materials project, which began at the University of California, Berkeley in 1992 and ran until the mid-2000s.[5] This project engaged students in field studies of existing buildings. Students measured building performance ("vital signs") in areas related to building physics, energy use, and occupant health and well-being, and produced written reports ("case studies") of their observations and analysis. The project included curriculum guides, monitoring protocols, peer-to-peer training workshops, and an equipment loan program, enabling faculty to replicate the investigations at other institutions.[6]

As the founders of Vital Signs wrote, the “key to the learning process” in an investigation was “the direct experience with existing buildings, asking questions, testing hypotheses, and ultimately finding answers that [would lead] students to greater awareness and comprehension” about the impact of their design decisions for the environment and building occupants.[7]

Sensing and monitoring equipment has evolved greatly since the conclusion of the Vital Signs project. Inexpensive, off-the-shelf wireless sensor networks can log data and upload it to the cloud, where it can be viewed from anywhere, or downloaded for further analysis and visualization. The availability of large amounts of data about the built environment is reshaping the architecture profession. Data literacy – the ability to understand and communicate information with data – is becoming a core competency for architects.[8] In this context, it is an opportune time to revisit curriculum models like Vital Signs, and apply their pedagogical goals to a changing technological and professional landscape.

Building Technology Education at Pratt

Pratt’s 3-year accredited Master of Architecture program includes a 4-semester core sequence of building technology courses in the first and second year. In the first year, students take two semesters of structures, followed two building science lecture courses in the first semester of the second year (Materials and Assemblies and Environmental Control Systems [ECS]). Core building science content is delivered in ECS, which covers the fundamentals of environmental design (climate, daylighting, thermal comfort) and building systems design. Topics such as heating, cooling, lighting, and electrical service are introduced in the context of the 3rd semester design studio project, and the ECS final project is a simplified study of these systems applied to students’ third semester studio project.

In the fourth semester, content from the design and building technology courses is synthesized in an integrated studio project, comprised of two studio courses taken simultaneously: the capstone design studio (CAP), and the capstone technical studio, Integrated Building Systems (IBS). Students work in teams on a medium-sized institutional project, which they develop with input from design faculty and a team of technical instructors who are practicing structural engineers, mechanical engineers, and facade specialists. In 2016, the CAP/IBS curriculum was cited by the NAAB accreditation committee as an exemplary model of integrated design and technical education.[9]

The thermal comfort study described in this paper was conducted by IBS studio faculty in the context of this capstone technical studio. The classroom monitoring and thermal comfort surveys happened in parallel to the studio activities. Although independent of the class content, these activities reinforced concepts introduced in the ECS lecture course, and influenced discussions with the IBS technical instructors about environmental design and control systems for the CAP/IBS studio projects.

Methods

Building Context

Our investigation took place in an architecture studio on the top floor of Higgins Hall, an uninsulated mass masonry building built in 1868 on Pratt’s campus in Brooklyn, NY. The 4,000 sf space had exposures on the north, east, and south, with six operable double-hung, single-pane wood windows on the north and south walls, and two windows on the east wall (Figure 1). The room was cooled by two ceiling-mounted fan coil units, each with its own thermostat. Heating was provided by a

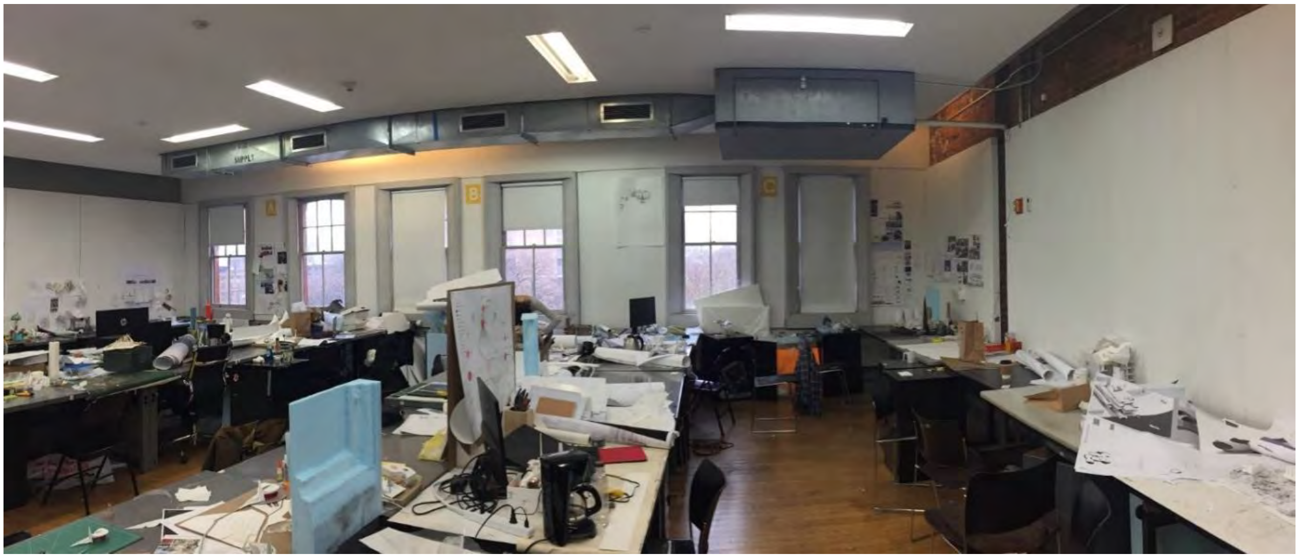


Figure 1 Interior of studio space

perimeter hydronic fin-tube radiator installed at the base of the three exterior walls. Heating and cooling were controlled by the campus BMS system, with a cooling setpoint of 74°F for occupied hours between 7:00 am and 10:00 pm, Monday through Sunday.

Occupants

The studio was occupied by 59 architecture graduate students. Students were between 20 and 30 years old; 46% were female and 54% were male. The students had unlimited 24-hour access to the studio space. Student desks were arranged in an open office layout. Each student had their own desk, where they did the majority of their work during the semester.

Sensor Hardware and Software

The study period ran from April 7 to May 7, 2018. During that time, a roof-mounted weather station recorded data about outdoor conditions every 5 minutes. The weather station (WS-1400 Observer manufactured by Ambient Weather) measured environmental conditions including temperature, relative humidity, wind speed, wind direction, precipitation, and solar radiation.

Inside, a network of 52 temperature sensors and 2 relative humidity sensors measured and recorded indoor conditions every 5 minutes. The sensor network was a beta version of the Pointelist wireless sensor network developed by KT Innovations, an affiliate of the Philadelphia-based architecture firm Kieran Timberlake.[10] Sensors were arranged on a 6 ft x 15 ft grid, with each student workstation about 3 feet away from the closest sensor (Figure 2). Sensors were installed 43 inches[11] above the floor and shielded from direct light exposure with protective plastic tubing. Sensor locations were adjusted to avoid proximity to desktop items that could influence temperature readings, such as computer monitors, 3D printers, and electric kettles. Our study did not measure other environmental factors affecting thermal comfort, such as mean radiant temperature and indoor air speed.[12]

Thermal Comfort Surveys

During the study period, students received a daily thermal comfort survey via email. The survey software was a beta version of the Roast survey application, also developed by KT Innovations.[13] The survey was sent at 9:00 am and 9:00 pm. Students could answer once every 12 hours,

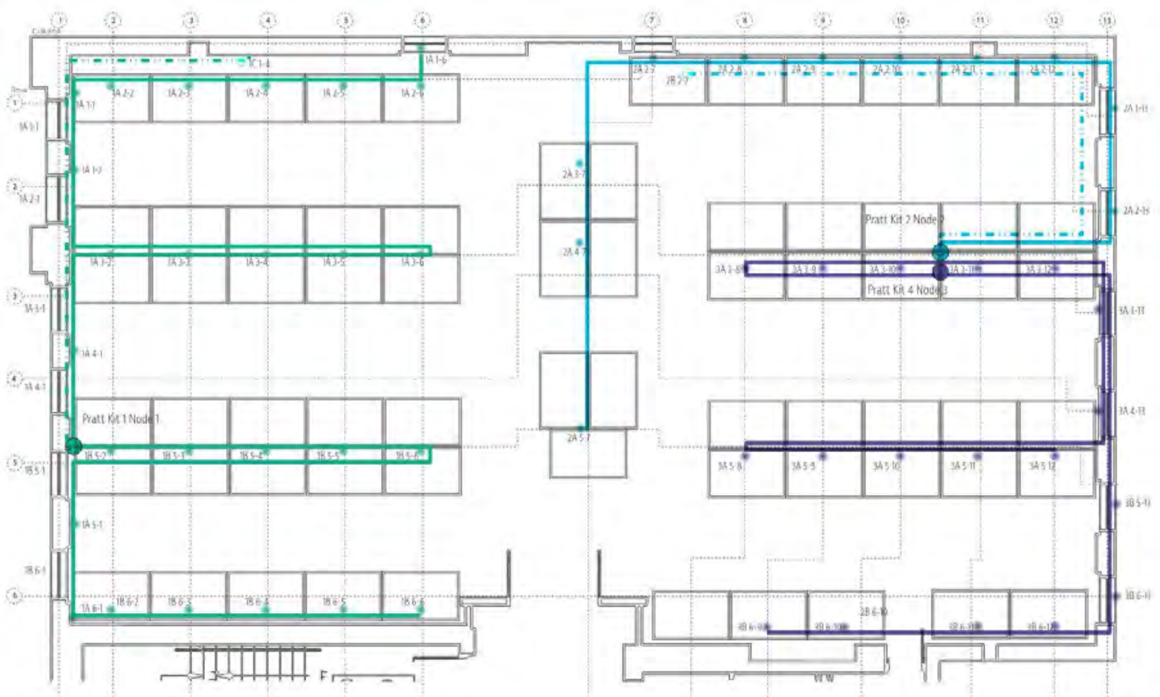


Figure 2 Sensor layout

and their responses were timestamped. The survey asked students to specify their location in the room, clothing, and activity level, and to describe their perceptions of thermal comfort, humidity, air speed, and productivity at that point in time. Responses were quantified on a 7-point scale from -3 to +3, with 0 being the neutral sensation. Descriptions of clothing insulation and activity level were converted to clo and met values using tables from established thermal comfort standards.[14] To incentivize students to participate in the survey, we offered gift cards to the three students with the highest response rate at the conclusion of the study. We conducted follow-up interviews with seven students who were frequent survey participants to better understand the factors affecting their comfort in the studio.

Results

Over the course of one month, we generated approximately 37,000 hourly sensor measurements and 359 survey responses. The dense sensor grid enabled us to characterize thermal comfort in the studio with a high degree of spatial resolution. The dense grid also enabled us to match survey responses with simultaneous sensor measurements to compare students' perceived thermal comfort with comfort predictions (PMV model) for the same conditions.

Indoor and Outdoor Environmental Conditions

Outdoor temperatures during the study period ranged from 32°F to 91°F, with an average of 54°F. Diurnal outdoor temperature swings ranged from 9°F to 16°F per day. Outdoor relative humidity averaged 56%, and dewpoint averaged 37°F. Indoor temperatures were relatively steady during the same period, ranging from 69°F to 81°F with an average of 75°F. Diurnal indoor temperature swings ranged from 1°F to 8°F per day. Indoor relative humidity ranged from 14% to 61% with an average of 32% (Figure 3).

Plotting average temperatures from each sensor on their location in the studio revealed local thermal anomalies, particularly at the perimeter of the room. Cold

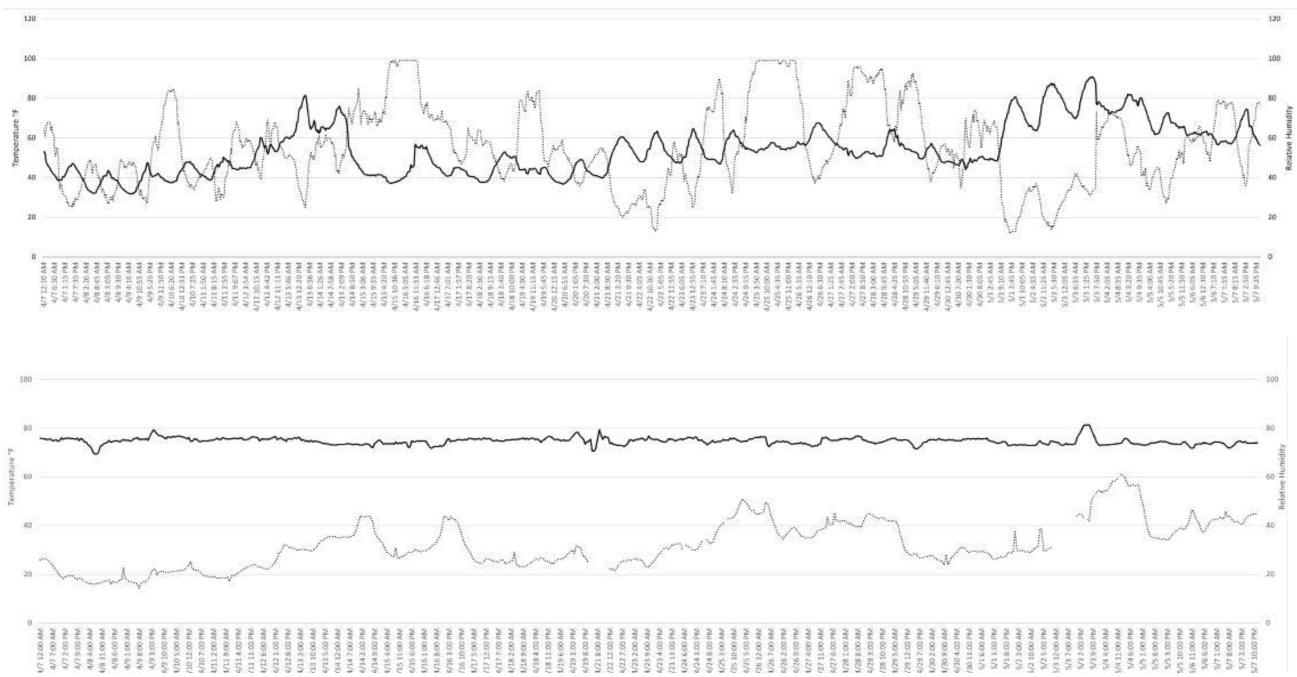


Figure 3 Outdoor (above) and indoor (below) temperature (black line) and relative humidity (gray line)

microclimates may have been caused by air infiltration from drafty windows or low surface temperatures at windows and exterior walls. Warm microclimates were likely caused by heat from the perimeter radiator. Hotspots may have been exacerbated by the furniture layout. Cold microclimates in the middle of the room were located under registers for the HVAC system (Figure 4).

Predicted Thermal Comfort

Predicted Mean Vote (PMV) is a widely used thermal comfort metric for mechanically conditioned spaces.[15] The PMV equation takes into account six factors: two personal factors (clothing and activity level) and four environmental factors (air temperature, mean radiant temperature [MRT], air speed, and relative humidity).[16] To characterize thermal comfort in the studio, we calculated PMV for each measured combination of temperature and relative humidity. We used standard clothing and activity levels for office environments, and assumed negligible effects from radiant temperatures and air speed.[17]

PMV is expressed on a 7-point scale ranging from -3 (cold discomfort) to +3 (warm discomfort). PMV values of -0.5 to +0.5 define the comfort zone, with a PMV of 0 representing a neutral thermal sensation (optimum comfort). Average PMV values for each sensor indicate that that majority of locations (45 of 52 sensors, or 87%) were within the comfort zone (-0.5 < PMV < 0.5) during the study period. Seven sensors (13%) had an average PMV greater than 0.5; all were located at the perimeter of the room (Figure 5).

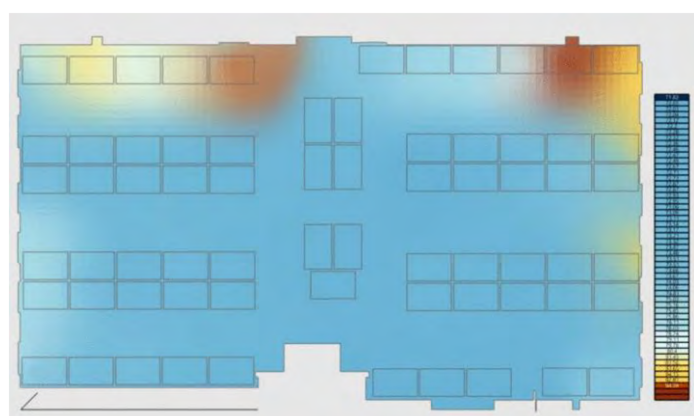


Figure 4 Thermal microclimates (May 1st, 2018 12:00 am)

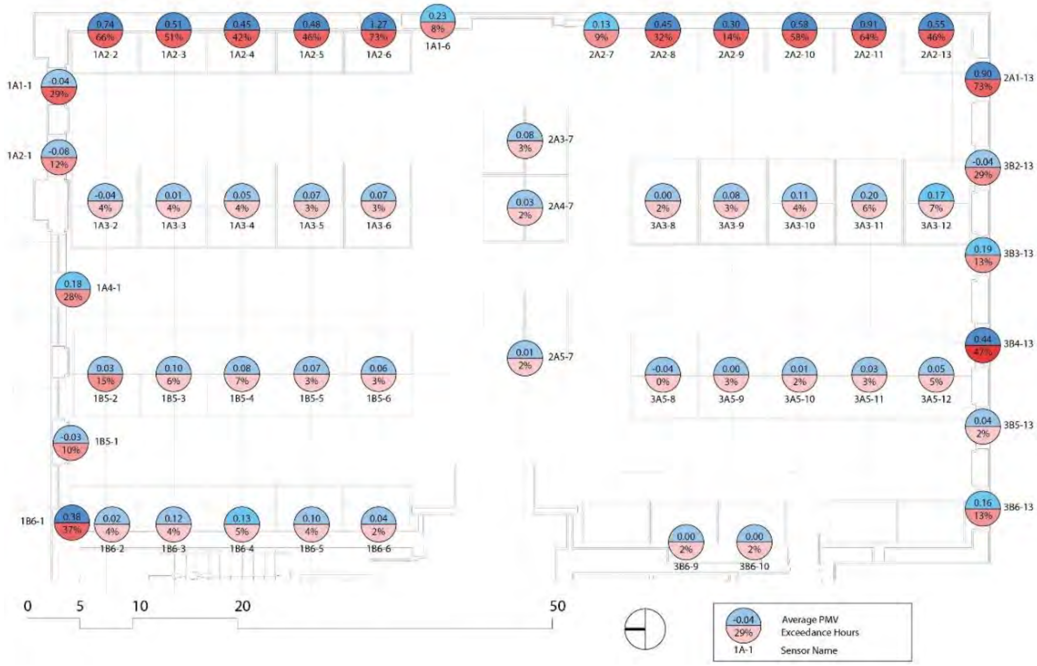


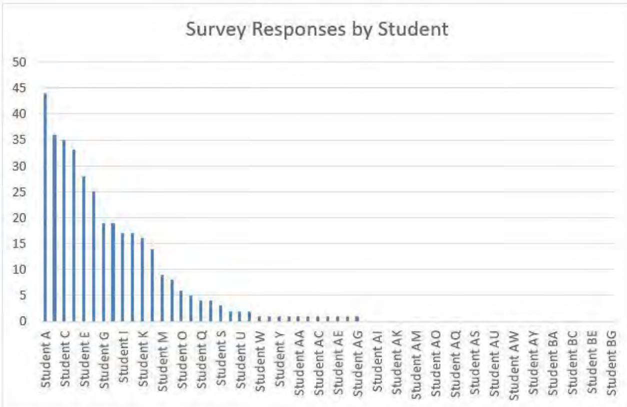
Figure 5 Average PMV and Exceedance Hours for each sensor

Thermal discomfort can also be expressed as exceedance hours: the number of hours in a given time period in which conditions are outside the comfort zone. While ASHRAE-55 does not prescribe minimum standards for exceedance hours, we observed that 33 sensors (63%) had exceedance hours of less than 10% over the study period. The remaining sensors had exceedance hours of 10% or greater, with a maximum of 73%. Sensors with high percentages of exceedance hours were located at room perimeter (Figure 5).

Survey Analysis

We sent 3540 surveys over the study period and received 359 survey responses, a response rate of 10%. Of the 59 students in the class, 33 students (56%) responded to the survey at least once. Of these, 11 students (33%) responded only once, and 12 students (36%) responded 10 or more times. ASHRAE-55 does not prescribe a statistically significant response rate for point-in-time surveys.[18] However, a majority of students (37 students, or 63%) did not answer the survey at all, or answered only once, raising the possibility that the survey results may not be representative of the overall student group. Survey responses averaged 15 per day. Most surveys were answered between 8am and 5pm, with the majority (92 surveys, or 26%) answered at 1 pm, just prior to the start of the 2 pm studio (Figure 6).

The average clothing insulation (clo) value over the study period was 0.87 (median: 0.73); this reflects clothing insulation between summer (0.5) and winter (1.0) levels, as would be expected for the month of April. The average activity level over the study period was 1.11 met (median: 1.0), which reflects typical office activities like reading (1.0) and typing (1.1). The average thermal sensation over the study period was -0.46 (median: 0), which suggests that, while many of the students were comfortable, some were uncomfortably cold (Figure 7). Average perceptions of humidity (-0.25, median: 0) and air movement (0.19, median: 0) were more neutral across the student population.



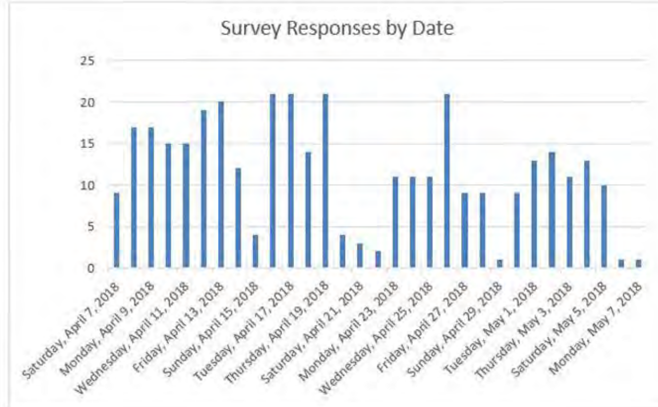


Figure 6 Survey responses by student and date

Actual vs Predicted Thermal Comfort

PMV was calculated for each survey response using the students' reported clo and met values and simultaneous temperature and relative humidity measurements from the closest sensor.[19] Average PMV for all survey responses was -0.01 (median: -0.14), suggesting that students' perceived comfort should have been neutral for the given conditions. However, the average reported thermal sensation value (actual mean vote, or AMV) was -0.46, suggesting that, on average, students were experiencing cold discomfort when PMV predicted a neutral sensation (average [PMV – AMV]: 0.44; median: 0.26).

While we may conclude from these results that PMV is over-predicting thermal comfort conditions for the studio, many studies have validated the PMV model in air-conditioned buildings.[20] The discrepancy between AMV and PMV may be related to factors that were not measured in this study. Follow-up interviews with students cited proximity to cold, drafty windows or blowing air from the HVAC units as sources of cold discomfort, particularly at night. Further study is needed to quantify these effects.

Discussion

This study suggests both the potential for integrating hands-on building science investigations into the technical architecture curriculum, and areas for improvement. Student participation in the thermal comfort survey was low. Aside from several dedicated participants, the majority of students (63%) answered the survey once, or not at all. This was likely due to a lack of effective integration of the study with the technical studio coursework. Making the survey part of a graded assignment would have increased student participation, and, by extension, student engagement with the study content. Another missed opportunity for engagement was involving students directly in analyzing the study data. For example, students could have plotted their own survey responses on the psychrometric chart, comparing its predictions to their own experience of thermal comfort.

The next phase of our work will focus on opportunities for curricular integration via the creation of a Pratt Building Science Lab. The lab will serve as a central repository of monitoring equipment for the Pratt community, and as a framework for developing hands-on STEM exercises with educators from several Institute departments and schools (including Graduate and Undergraduate Architecture, Interior Design, and Mathematics and Science).

While we see great potential for this collaboration, we recognize the challenges in developing innovative building science curriculum in architecture schools. Existing building science courses are often overloaded

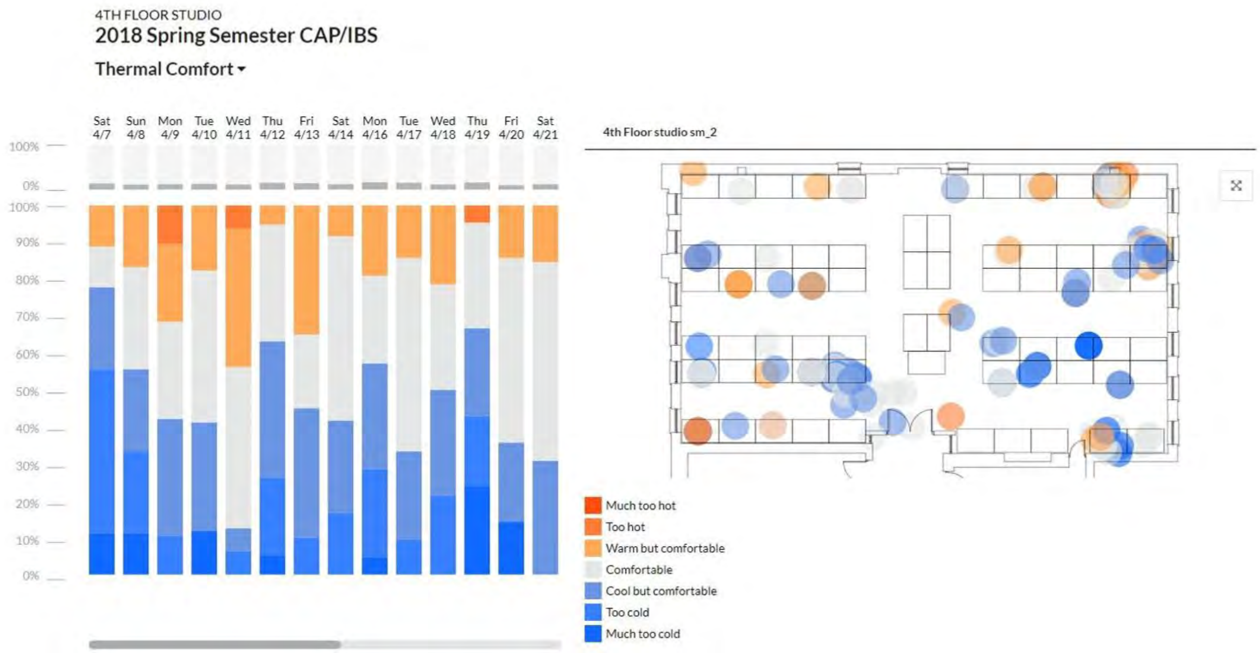


Figure 7 Survey results for thermal sensation

with NAAB criteria, and instructors may be reluctant to rewrite coursebooks. Administrators may be unable to allocate funds to purchase monitoring equipment. Finally, there may be cultural or institutional barriers to foregrounding technical education in design-focused professional degree programs. It is important to build support for curricular innovation among design faculty and administrators, who may feel that more demanding technical courses divert students' energy from the design studio

Conclusion

Although architectural education prioritizes hands-on, project-based exploration in the design studio, many technical courses employ a traditional lecture-based approach. This case study suggests the potential to integrate research-based inquiry into the technical architecture curriculum. As participants in the thermal comfort study, students were asked to make connections between the content of their building science courses and their own subjective experience of comfort – potentially deepening their understanding of and engagement with the technical subject matter.

Our study suggests that such investigations must be thoughtfully integrated into the broader architecture curriculum to achieve positive effects on student engagement and learning. This integration can happen at multiple scales and intensities – from a single lab assignment to dedicated seminars or advanced studios. Beyond any one course, implementation of innovative approaches to teaching building science requires both the initiative of building science educators and broad support from other faculty and administrators to achieve the desired impact.

Acknowledgements

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12 Air temperature was assumed to be equal to operative temperature (ta = to). Indoor air movement was assumed to conform to still air conditions (0.2 m/s or 40 fpm). ASHRAE (2013), Appendix K, Section K3.2.2.a.

13 “Roast,” http://www.roastsurvey.com (accessed April 21, 2019).

14 Clo and met values were extrapolated from ASHRAE-55 and ISO 9920. ASHRAE (2013) and ISO. ISO 9920:2007 Ergonomics of the thermal environment. International Standards Organization: 2007.

15 The predicted mean vote (PMV) equation, proposed by P.O. Fanger in 1970, is broadly used to predict indoor thermal comfort and is included in many comfort standards. ASHRAE (2013), Appendix C.

16 We calculated PMV using code adapted from the CBE Thermal Comfort Tool. Hoyt, Tyler, Schiavon, Stefano, Piccioli, Alberto, Cheung, Toby, Moon, Dustin, and Steinfeld, Kyle. “CBE Thermal Comfort Tool.” Center for the Built Environment, University of California Berkeley, 2017. http://comfort.cbe.berkeley.edu/ (accessed April 21, 2019).

17 We used the following assumptions for PMV calculations: air temperature = operative temperature, clo = 1.0, met = 1.1, air speed = 0.1 m/s.

18 For long-term surveys of more than 45 occupants, ASHRAE-55 requires that the response rate exceed 35%. ASHRAE (2013), Section 7.3.1.

19 The effects of radiant temperatures and airspeed were assumed to be negligible.

20 There is some evidence that PMV under-predicts thermal comfort. Beizaee, Arash and Firth, Steven K. "A Comparison of Calculated and Subjective Thermal Comfort Sensation in Home and Office Environment." People and Buildings Conference Proceedings. London: NCEUB, September 23, 2011.

Lines of Action: Investigating How Behaviors of Structural Systems Can Be an Informing Agent for Architectural Design

Sean Burns
Ball State University

Introduction

Students of architecture are required to take a series of courses that present concepts of statics, structural principles, and system analysis as part of an accredited curriculum. As the students participate within these courses, they often unfairly assume that the lessons taught of structures are peripheral or reactive to architectural design. This paper challenges this perception by introducing a pedagogical approach focused on investigating and embracing the performance of structural assemblies as an inspiration for architectural design within these supporting structures courses. A series of exercises that required students to design and fabricate physical models to be tested under various performance criteria challenged the students to consider ways in which structural behaviors and architectural design might inform one another. Along each of the phases for these projects, students were asked to consider the mode and method of failures as well as how the actions of constituent parts systematically contributed to the performance of its composite assembly.

Concerning Architectural Form and Structure

In many instances, students of an architectural curriculum formulate opinions of architectural form as enveloping shape generating procedures limited to the three-dimensional massing of an architectural act. Similarly, structural considerations are frequently perceived by students as consequential of form making processes and devalued within the creative design process. Often, these assumptions result in students over-emphasizing the appearance of an architectural act, as opposed to how it performs, offers spatial organization, and engages the site and its users.

In his book, D'Arcy Wentworth Thompson describes nature's form generation processes: "In short, the form of an object is a diagram of forces that are acting or have acted upon it."[1] Peter Pearce and Susan Pearce expand upon Thompson's writings as they argue for designers to consider the capacities of a body's structural disposition to respond to all influential intrinsic and extrinsic forces as governing principles towards the manifestation of form. "To minimize the arbitrariness of form in the built environment is to maximize its performance…One of the limitations of a visual effects approach to form is that it encourages a direction that is not particularly sensitive to performance-orientated solutions."[2]

Alexander Zannos offers the argument that form and structure should not be viewed as interchangeable terms, yet both are integral to the design process: "The term *form* is more suitable when applied to an entity taken as a whole, to the end product of the creative process, whereas the term *structure* should be used when the whole is to be analyzed by its components."[3] Zannos' definitions acknowledge that structural considerations and form generating procedures should not be seen as disassociated terms within the creative design process or when analyzing how an architectural act was created. By embracing these lessons, students can learn a great deal about how architecture and structure can inform one another by focusing on how the constituent elements within a composite entity speak to one another through performance-based design objectives throughout the design process.

Lessons though the Evidence of Performance Failure

Structural analysis and strength testing methods are honest and objective for how they reveal evidence pertaining to the behaviors of a system and properties of materials. Often these lessons are best delivered through discovering failures and vulnerabilities. In the case of studying structures, testing for failure is something that should be valued as it not only confirms or refutes whether initial assumptions are true, but also hints to address the questions: *why* or *why not*.

Engineer, inventor, and mathematician Robert Le Ricolais placed value on discovering how things performed with an investigative mindset as he states, “To discover the nature of things, the secret is to be curious."[4] Throughout his work, Le Ricolais was skeptical that initial assumptions and findings may be misleading as he gave preference to the use of physical models within his testing of concepts, asserting that we need to experience a physical “contact with things” to provide knowledge with truth and evidence. In interviews with graduate students at the University of Pennsylvania Le Ricolais commented, “Things themselves are lying and so are their images – therefore, experimental evidence is of critical importance in order to evolve beyond the arbitrariness.”[5] Further, Le Ricolais believed that the strength of the physical model within a project was as a “hierogram,” which he deemed as an abstracted model of a conceptual intention that acknowledged properties of materials, rather than as the literal representational “apparatus” device.[6]

In architectural school, students primarily are asked to complete a project or assignment and receive feedback as part of the final submission. The assumption is that the students will learn from the reviewers’ comments and integrate or expand upon this feedback in subsequent assignments. The projects described within this paper celebrate the intersection of structural behaviors and architectural form generation, while challenging the aforementioned model of teaching and learning by placing value on failure as an integral step required to complete each project. In this way, curiosity is promoted as the students are given opportunities to test the limits of their projects and discover strategies to recalibrate their design maneuvers.

Project 1a: Hollow Column/Stick Tower

Design and Fabrication Phases

As part of the introductory structures and statics course, the first physical project that was presented provided an opportunity for the students to build upon their understanding of the structural principles that were concurrently being taught in class. The project was dually titled “Hollow Column/Stick Tower” to urge students to consider the project at a variety of scales, instead of assuming their designs of a structural system were representative of a singular architectural typology. Presenting the project in this way encouraged the students to concentrate on the performance of their designs of a structural assembly, as opposed to potentially inheriting associations for form generation and organizational strategies based on preconceived notions of architecture and structure. Delivered over a series of sequential phases, the project was intended for students to predict, test, acknowledge, and reconsider how loads are transferred between constituent members of an organized system and determine whether these forces, deduced graphically as linear vectors, acted in compression or tension within their assembly designs.

Working in teams of three, the students were asked to design and fabricate a thirty-inch tall vertical structure, using repetitive or modified pattern formation strategies, to successfully support an externally applied gravitational load of seven pounds. Material restrictions were limited to only 1/8” diameter dowel rods, glue, and quilting thread. Further, all dowels were specified to be circular in cross section, requiring the students to give thoughtful consideration for how adjoining members might be detailed with the thread and/or glue as either rigid or soft joints to optimally transfer the forces in tension or compression among the members of the design. In this way, the thread assumed an expanded role beyond a diagonal tensile chord in many of the designs as several student teams opted to lash the dowel connections to increase the structural integrity and capacity of the system at these junctures.

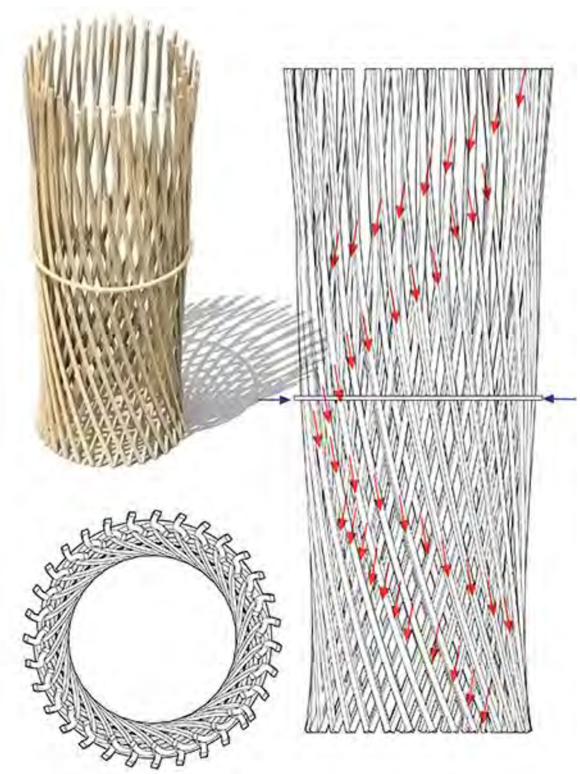


Fig. 1. One of student team’s initial options for consideration indicating ability of structural assembly to flex upon its acceptance of applied load. Student work by Eric Peters, Caitlin Liskey, and Andrea Wesson.

Each student team was tasked with developing an authentic assessment criteria for the design of the structural assembly, beyond its ability to meet the established structural performance requirement, to assist them in their design decisions throughout this preliminary phase. Student responses included emphasis on weight-to-load capacity efficiency, asymmetrical organization of patterns, capability of the structure to accept eccentric loading, and the ability of the structure to absorb the applied load and reactively respond by changing its original configuration. Prior to fabricating a model for testing, each of the student teams presented three diverse design options for review and consideration that included predictions for how the externally applied gravitational load would be transferred as compression or tension forces through the structural assembly’s members and joints [fig 1]. As many students struggled designating the correct path of travel for the forces within their structural assembly, this process provided an opportunity for the teams to present and discuss their initial assumptions and reflect on strategies to best meet the structural performance and assessment criteria requirements prior to committing to a final solution.

Each team then revised their design, or developed a hybrid option, and constructed their final “Hollow Column/Stick Tower” with a high level of craftsmanship and precision. The resulting assemblies exhibited a variety of thoughtful strategies for how the load would transfer as vector forces among and throughout the assemblies. The student team of Lauren Afendis, Conner Million, and Jake White developed and fabricated a design that utilized a five-inch tall tripartite modular unit. The module was stacked upon other replicated units to create six horizontal tiers, each rotated 10-degrees clockwise in the x-y axis from the contiguous module below. While this addressed their team’s assessment criteria of using a single modular unit in an altered configuration, it did result in interrupting the continuity of the lines of action at each tier. Thus, the overall configuration of their design suggested a prolonged path of travel for the load through the assembly and to the ground. Further, the team discovered that the connection points along the horizontal bands at the extremities of the stacked modules became critical junctures that required additional lashings, beyond what was initially anticipated, to provide the necessary structural integrity for the composite assembly and ensure the structure's ability to withstand the applied force. Alternatively, the benefit of their design approach was that the team utilized shorter lengths of dowels to prevent buckling failure as the load was successfully absorbed by the tiers, in sequential manner, and then transferred to each successive lower tier along the horizontal banding of each module [fig 2].

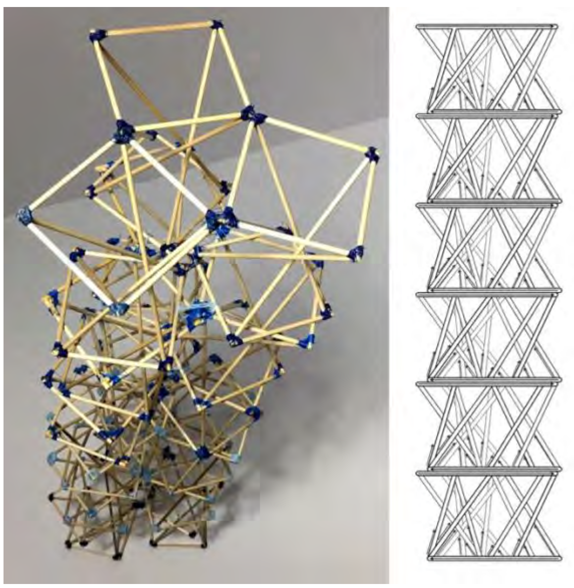


Fig. 2. "Hollow Column/Stick Tower" final design by students Lauren Afendis, Conner Million, and Jake White using a stacked, modular strategy to accept and transfer the anticipated load.

Testing towards Failure

Prior to testing, each of the team's physical models were weighed to compare the efficiency of the use of materials for the project among the class, in the event that this was a factor in the team's assessment criteria. Students were also asked to predict the point of greatest concern for ultimate failure and inscribe this point on their diagrammatic drawings for their design. It should be noted, that all of the team projects successfully met the minimum loading criteria for this initial charge without incurring any noteworthy damage.

The testing phase of the project was then continued to allow the students an opportunity to physically test their structural assemblies to a state of structural casualty and reveal the prominent points of failure within their designs. Each of the projects were placed beneath a Kuka robotic arm, which applied an incremental compressive force to the respective structures. The goal of this process was to damage the structural body, but not induce catastrophic failure, for each of the student team's structural assembly.

Project 1b: Prosthesis Design

Upon competition of the critical compressive testing exercise, the teams were then each given the opportunity to accept the edifice in its newly-established damaged condition and design a prosthesis that would allow their structural assembly to again be capable of supporting an externally applied gravitational force of seven pounds. The prosthesis was to be envisioned as a secondary device to be grafted to the impaired structure and constructed of dissimilar materials from the original "Hollow Column/Stick Tower." The task of this exercise was not to repair the original structural assembly to its previous condition. Instead, the students were asked to physically examine the current vulnerabilities and failures of the injured assembly in its new configuration and upon their analysis, create a device that acknowledged and responded to these deficiencies to extend the life of the original assembly as a structural element.

The critical loading applied to the "Hollow Column/Stick Tower" by the student team of Antonio Medina, Brooke Salyer, and Roberto Fayad inflicted buckling and shear damage to their structure. This resulted in their structural framework being severed along all dowel members near the midpoint of the entire assembly, thus causing their physical model to fold over into two parts. The thread that was originally used to transfer tension between the joints of the assembly remained connected to each broken side of the project and therefore, acted to hinge the two pieces

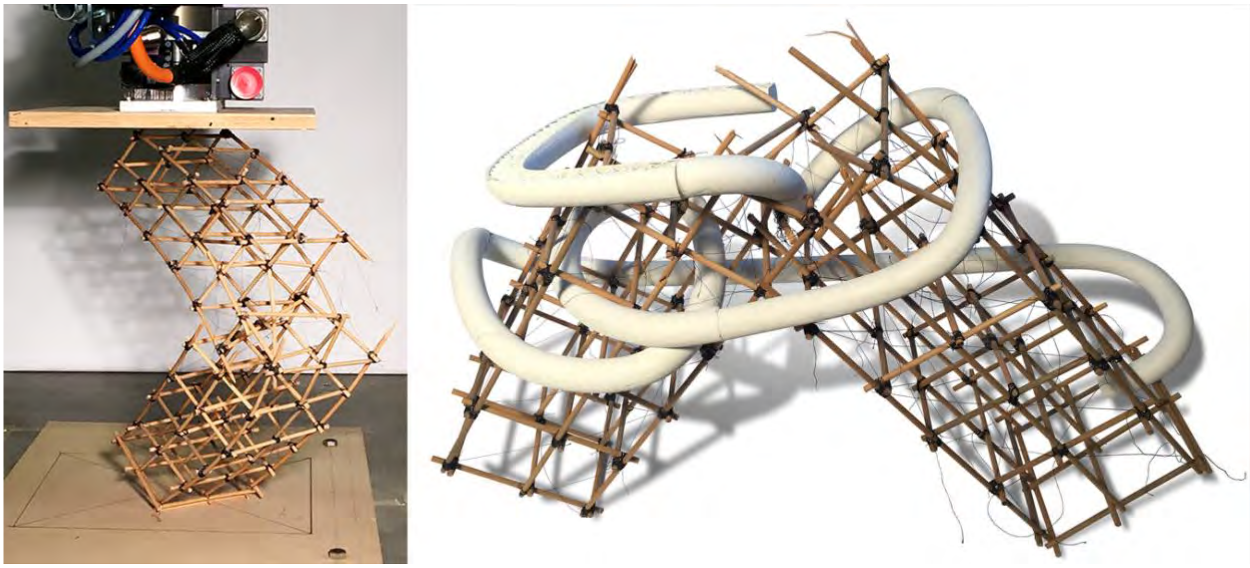


Fig. 3. Critical testing and prosthesis design and fabrication by students Antonio Medina, Brooke Salyer, and Roberto Fayad.

together. The project team evaluated their injured model and identified the greatest limitation, in its current state, was its tendency to spread apart at the base when a force was applied to the top of the broken structure. To address this concern, the team built a digital model of their project's new configuration to assist their design for a prosthesis device. Fabricated and assembled in sections using 3d printing technology, the prosthesis intertwined through the broken pieces to create rigid bracing through the composition as a means to oppose the lateral movement within the framework and ultimately allow the structure to accept the gravitational load successfully [fig 3].

Project 2: Equilibrium Scenarios Among Two Entities

The second project was presented as a collection of three separate studies, or scenarios, that targeted students working in teams of three to explore concepts of equilibrium, including mass and weight distribution, overturning moment, and the discovery of the neutral axes among disparate entities. At the outset of each scenario, the student teams were tasked with fabricating an unstable body, incapable of standing on its own accord, with stipulated rules provided to generate its formal language and configuration. As a response to the created unbalanced conditions of their physical model, each team was then asked to design and fabricate a secondary support system that was independent of their original assembly, using specified guidelines and constraints to bring the original object into balance. The two entities working in harmony to achieve balance was to be realized in a different manner for each scenario. Teams were required to consider strategies for how the secondary system might engage the unstable body and how the forces were transferred within the unification of each assembly to achieve a state of equilibrium among their comprehensive designs. All student teams presented their strategies and discoveries, specifically related to their successes and failures to meet the project's objectives, graphically and orally at intervals within each scenario of the project.

Balance Amongst

Student teams began the first equilibrium scenario by constructing the unstable body as an aggregation of thirty 2” x 2” x 2” modular cubes, adhered together along the parallel faces of the units. The configuration of these units was directed to be asymmetric along the x-y-z axes and only three cubes were permitted to be in contact with the ground base plane, thus forming an equilateral tringle in plan view. As the assembly ascended, it was permitted to travel in multiple directions and pass beyond the confines of the implied triangle, although the entire assembly of units was to be arranged in a manner that it would overturn when at rest.

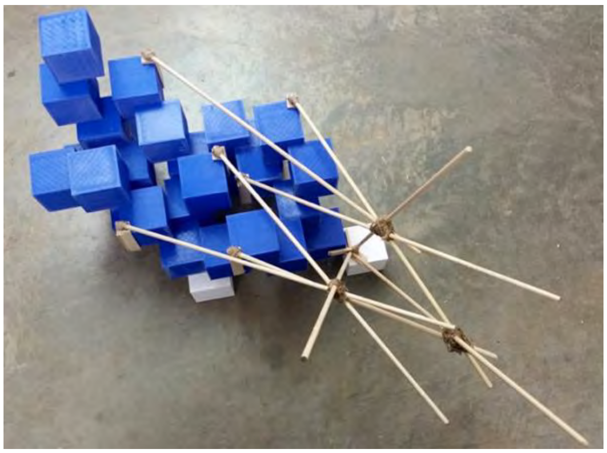


Fig. 4. "Balance Amongst" final solution by students Nick Conner, Eve Miller, and Hoff Campbell.

Upon presenting the leaning tendencies of their base models based on weight distribution, each team then strategized to design and fabricate a second system, using wood, glue, and thread, to offer support and counter the overturning moment of the modular assembly. Directions were given to the teams for this scenario that the secondary support system was not permitted to touch the ground plane or anywhere beneath the top surface of any of the three base cubes, although it was allowed to engage the cube assembly at multiple points. Further, the system was not permitted to be glued to the cubes and instead, was to be designed as a removable device to demonstrate that the modular unit model was unstable without the inclusion of the support system.

Students Nick Conner, Eve Miller, and Hoff Campbell utilized a tectonic frame that secured itself to their modular model at seven points before protruding from the unstable body in the inverse direction to counter the weight distribution of the original assembly. After several trials, the team discovered that binding the tectonic system together as a network offered the ability of the secondary structure to act as a system to best counter the overturning moment of the unstable body [fig. 4].

Balance Against

To create the form of the unstable base model for the second scenario, "Balance Against," the student teams were asked to translate their cube model from the previous submission as a homogenous form. The surface envelope of the homogenous form was to encapsulate the preceding modular unit assembly with a flowing path. The contoured boundary conditions of the form were to be smooth contours and were prohibited from exhibiting any sharp angles or creases. To achieve this, the teams worked in drawing format to initially define the boundary of the sinuous form and then cut sections in several axes to aid in fabricating the model [fig. 5].

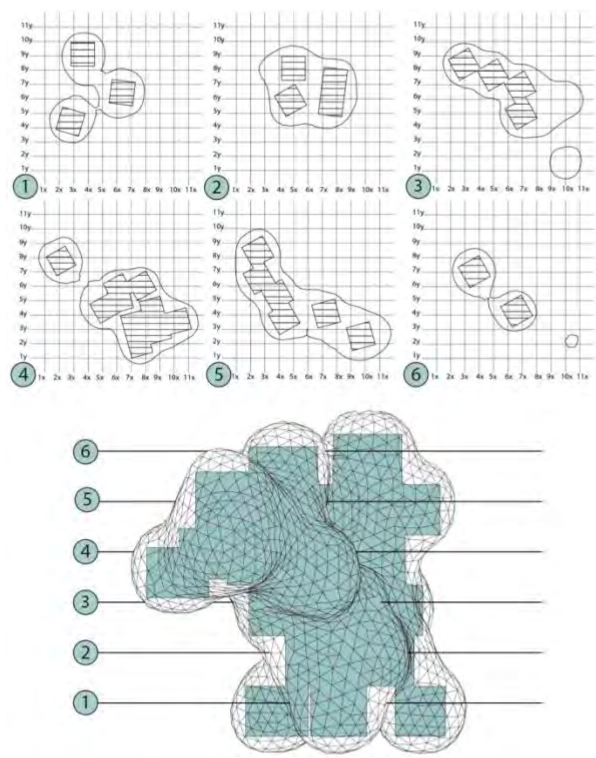


Fig. 5. "Balance Against" unstable body form generation study by students Sarah Fuller, Taylor Matthewson, and Simon Platt.

The secondary support system for this scenario utilized the same material guidelines of wood, glue, and thread from the "Balance Amongst" stage, yet the behavior and communicative constraints of the secondary system were amended for this scenario. Here, the support system was permitted to touch the ground plane at only one location within the implied equilateral triangle of its base condition to offer support to the unstable body. Students were also required to contact the homogenous form at multiple points, including one point along the apex of the base model, so not to create a wedge support for the unstable body. Further, the secondary system was not permitted to be adhered to the unbalanced homogenous form. To address these requirements, emphasis was therefore placed on the design of strategic connections for how the support system might successfully cling, grip, and or engage the smooth geometry of the base form and establish equilibrium among the interaction of both entities.

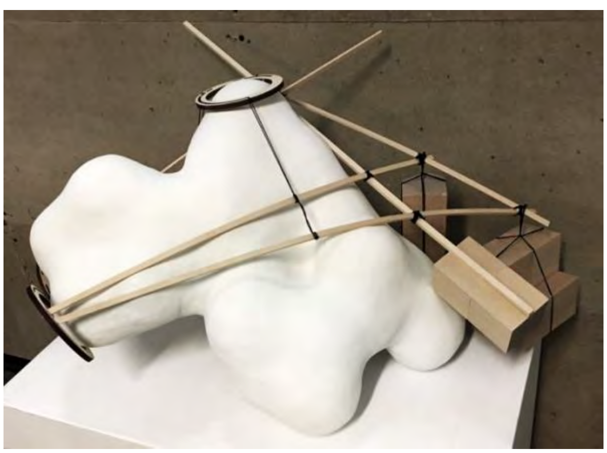


Fig. 6. "Balance Against" final solution by students Gage Workman, Gahyun Kim, and Jenny Cook.

To address the challenges of this scenario, the student team of Gage Workman, Gahyun Kim, and Jenny Cook began their design of the support system by first acknowledging the peak contours of their homogenous form to develop a series of standardized rings that would enable their counter-balanced system to successfully clutch the form through frictional resistance. Upon establishing these points of engagement, the team designed a network of linear elements that utilized the flowing surfaces of the homogenous body to influence the directional path and provide support for their network of linear elements. This network of wood and thread culminated in a calibrated counter-weight assembly, comprised of wooden blocks, that were tied to the system along the opposing axis of the unstable body's primary mass [fig 6].

Balance Within

The final scenario, entitled "Balance Within," required the student teams to translate their unstable body into a structural framework using strategies of triangulation, by means of rigid or tensile diagonal bracing members and designed connections constructed of wooden dowels and thread, to reinterpret the peaks and valleys of their homogenous form as a structural framework. Upon recreating their unbalanced body as a self-supporting structural system, the teams were requested to locate the centroid of their frame that would result in the edifice achieving a balanced state. After discovering the neutral axes within their design, the students were given the charge of applying a counterweight, in grams, to an internal area within their design of the unstable body to bring the composition into equilibrium and thus, stand on its own accord. This stage of the project distinguished itself from the previous scenarios in that it did not ask the students to develop a secondary support system to bring the unstable body into equilibrium. Instead, the students were required to compensate for the instability of their frame by locating the neutral axes, applying the counterweight, and compensating for any variations within their design by increasing the frequency of internal triangulation members at specific areas to calibrate their overall assembly.

After recreating the homogenous form from their previous exercise, the student team of Michaela Chrisman, Kristine Punzalan, and Michael Fleck applied a counterweight of 250g within their structural assembly near its presumed neutral axes, initially resulting in an over-compensation of weight distribution among the total assembly. As such, the team utilized dowel rods as internal members to redistribute the weight among their model and incorporated thread as diagonal tension members to disperse the load to the unbalanced portion of their physical assembly and ultimately, achieve the goal of this scenario [fig 7].

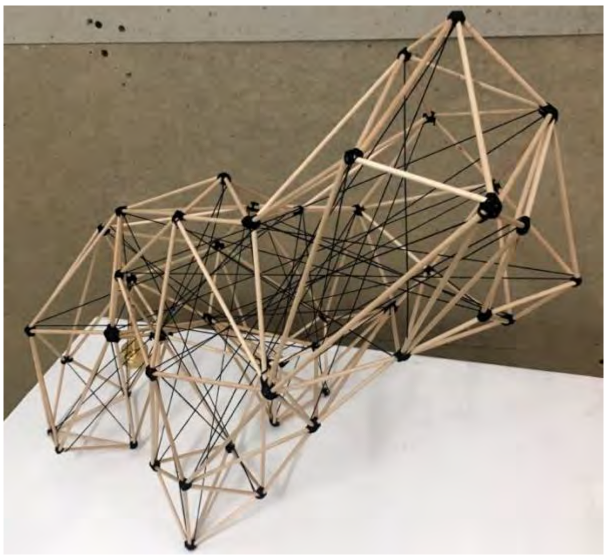


Fig. 7. "Balance Within" final solution by students Michaela Chrisman, Kristine Punzalan, and Michael Fleck.

Conclusions and Findings

These hands-on learning exercises provided the students an avenue to innovate, test, and reconsider their predictions for how systems behave and respond to applied external parameters. It is the author's observation, that by embracing failure as an integral part of the iterative design phase, students were discouraged from baseless form-finding exercises. Instead, the projects placed emphasis on the performance of dissimilar material systems in hopes of inviting students to integrate these lessons within their architectural studio projects. In future versions of the projects, students will be initially tasked with integrating case studies to better facilitate a design process that focuses on the interactions of forces and behavior of materials.

As commented by student Michaela Chrisman, who completed the series of balance projects: "All three phases of the project involved discovering how the systems worked together by first understanding how they failed. Each phase involved a process of trial-and-error testing to achieve a common goal, yet each exercise helped to inform the subsequent phase because of the knowledge that I gained throughout the process. The trials of the structures balance projects showed me how to use creative design strategies when thinking about fabricating new structural connections and how they work within a system."[7]

Notes:

1 D'Arcy Wentworth Thompson, *On Growth and Form*. (Cambridge: Cambridge University press, 1961), 11.

2 Peter Pearce and Susan Pearce, *Experiments in Form, A Foundational Course in Three-Dimensional Design.* (New York: Van Nostrand Reinhold Company, 1980), vii-viii.

3 Alexander Zannos, *Form and Structure in Architecture: The Role of Statical Function.* (New York: Van Nostrand Reinhold Company, 1986), 9-10.

4 Emma Nsugbe and Chris Williams, "Robert Le Ricolais — Visions and Paradox: AA Exhibition Gallery 11 January – 5 February 1999." in *AA Files*, no. 39 (1999), 55-60.

5 James Bryan, "Robert Le Ricolais: Things Themselves are Lying, and so are Their Images," in *Structures Implicit and Explicit,* ed. by James Bryan and Rolf Sauer. (Philadelphia: Falcon Press: Graduate School of Fine Arts, University of Pennsylvania, 1973), 197–199.

6 Maria Vrontissi, "The Physical Model in the Structural Studies of Robert Le Ricolais: Apparatus or Hierogram," in *Structures and Architecture: Beyond their Limits*, ed. by Paulo J. S. Cruz. (London: CRC Press, 2016), 1321

7 Michaela Chrisman, e-mail to author. January 10, 2019.

A Student-Centered Active Learning Approach to Teaching Structures in a Bachelor of Architecture Program

Marjorie Callahan, Shideh Shadravan, Yetunde Obasade, Elizabeth Hasenfratz

University of Oklahoma

Abstract

Nearly all programs of architecture focus on structures as independent coursework, rather than on integrating pedagogy (i.e. how to teach structures in studio). To fill this gap, an innovative freshman workshop was developed in this study with a student-centered active learning approach to teach structures. In the present study, this approach combines three types of active learning activities: think-pair-build; in-class, all comrades' shared discussions and review; and articulated student development reflections. The primary vehicle used for discovery is the Workshop Method. By focusing primarily on student's own creative genre (small group designs), the class responds to what is brought into the one period focus. Workshops are devoted to critiquing work, to generating new work through guided exercises and assignments, and to incorporating a combination of both approaches for instilling intellectual habits. This approach implemented and assessed in three workshops in a freshman studio (three semesters) at the Division of Architecture, University of Oklahoma by architectural and structural faculty and their graduate assistants.

The results show that this method was a fairly successful structures introduction into architectural form, not previously considered. Specifically, in pre-structure workshop survey, student observations on structural components not reflected. Later, in post-structure workshop surveys, much is retained from structural information from the two workshops. Then, by faculty observation, in final end-of-the-year studio reviews, studio projects demonstrated structure patterns in comparison to previous years' form-only outcomes. It is assumed that the structural activities in studio provided the students with added reinforcement in understanding how structural components work in design. From this first trial run, results prove integrating workshops and active-student learning techniques early influence students' knowledge and understanding of structures. Further research currently conducted to follow these freshmen students through their second-year matriculation in the program. The study will examine if these same architecture students: (1) retain and use structures in their designs long before they actually take traditional structure curriculum coursework in their third year; and (2), if structural components appear in their work. This study implies that the most effective method for students to learn how to develop an integral structural process in their work (pattern and strategy) is learning by doing in freshman studio.

Introduction

The importance of foundational structural knowledge for architecture students is manifested in the following three aspects. First, the earmark of their profession, to secure health, safety (structural integrity) and welfare in their professional projects. Second, the nature of the construction industry at large today, to design and build complex building projects with the skill to contribute collaboratively (to discuss options with consulting engineers). Third, in architectural curriculums, to have structural skills may be among the highly important skills for passing the Architectural Licensing Exam in the United States. An untapped resource in the architectural design process as a major creative venue is architectural structural awareness. Authors believe this is a problem.

In conducting research on first and second year students, early introduction of structures did not hinder design creativity, but it instead made their designs more practical and realistic. In juxtaposition, previously, structural education obtained from advanced, not early, undergraduate technical silo coursework. In fact, the current emphasis on these courses is to teach students to calculate loads and member sizes, rather than how to design systems into their processes and form. This implies structural knowledge is a specialty, not integral to the architectural mindset.

Clearly, the most innovative and inspired works of architecture are the ones with a creative structure that informs the project, and well. For example the famous architects like Frank Lloyd Wright, Frank Gehry, Louis I. Kahn, Renzo Piano, Rem Koolhaas, and Santiago Calatrava have designed buildings and bridges with advanced structural systems. These architects have highly developed their advanced understanding of technology, structure, and materials in their magnificent designs. Here are some of the superior buildings designed by the famous architects; Falling Water, U.S. (1939) designed by Frank Lloyd Wright, Resaurante Los Manantilaes, Xochimilco, Mexico (1957) designed by Felix Candela, Lyon-Saint Exupéry Airport Railway Station, Saugnieu France (1994) designed by Santiago Calatrava, and Auditorium Parco della Musica, Italy (2002) designed by Renzo Piano.

According to Salvadori (1986), architects and engineers must collaborate in design. Therefore, they need to have a common vocabulary to be able to work together successfully. The architect must have knowledge in structural analysis and design influenced by the engineer (Lonnman 2000). Certainly, structural knowledge is fundamental to the design process and architectural expression (Wetzel 2012). This fundamental must be developed from school when architect students begin learning about design and structure. Nearly, structures is taught as an independent course, rather than integrating pedagogy. One of the reasons behind this might be that architecture students must have structural skills to be able to pass the Architectural Licensing Exam in the United States. Therefore, the focuses in structural courses are to learn how to calculate loads and design elements with different materials, rather than how to design systems into their processes and form. Consequently, this method creates a gap between studio and structure course.

It has been a big challenge for many instructors to consider the importance of visualization to teach structures. Therefore, instructors investigated innovative teaching methods such as using physical models, digital model, and finite elements of structures. For example, Black and Duff (1994) used advanced structural engineering software, finite elements, to teach structures to architecture students. Students used the computer software to analyze small and large buildings and compare those with their hand calculations. Vassigh (1994 and 2005) developed a new program to teach structure to architecture students. The program was digital models to show the load-collection mechanism and load distribution path through the structural systems. This program animated the load path in the entire structure to help students visualize the behavior of structural system.

Lonnman (2000) used three types of structural models to help architecture students visualize structural behavior of structures' design. A three-dimensional diagram was also used to study the geometry, scale, and load path of structural system. Unay and Ozmen (2006) believed that it is the responsibility of the practicing architects to integrate the structural system to architectural design. Therefore, they had their students work with the help of real-life, structure instructors, and computer to create structural models in their design studio. Unay and Ozmen (2006) note that many architects in the industry assume structures to be a technical component that must be left to engineers alone. In an effort to counter this type of thinking and to better reinforce structures among architecture students; the primary method used for discovery is the Workshop Method. For the test group of first year students, we it was decided to conduct a fall, and spring, introductory presentation series of structural elements and components. According to Wetzel (2012):" integrating structures and design helps students to develop their design studio with an understanding of materials and structural systems." Therefore, Wetzel introduced dynamic modeling techniques and large-scale installations to help students visualize structures and integrate structural systems in their design studio. Fami, Aziz and Ahmend (2012) conclude that, "In order to achieve such collaboration goal, the visual approach in teaching is the appropriate method for architectural students."

This study implies that learning by doing is the most effective method for students to learn to develop an integral structural process in their work (pattern and strategy). For the purpose of this study, three types of learning activities were combined: think-pair-build; in-class, all comrades' shared discussions and review; and articulated student development reflections.

In an effort to better reinforce structures among architecture students, we researched and assessed different types of methods to teach structures. With the advisement of other professors, and multiple discussions relating civil engineering coursework to architectural, a blended method of teaching structures was employed. Therefore, two workshops format were developed in a freshman studio (two semesters) at the Division of Architecture, University of Oklahoma by architectural and structural faculty and their graduate assistant. The objective was to review work, to generating new work through guided exercises and assignments, and to incorporating a combination of both approaches for instilling intellectual habits.

Both presentations workshops were to be preceded by a survey that asked basic structural questions. The goal was to test how well the students thought of structural elements before and after being introduced to the material. Following each presentation, an exercise that was intended to help the students conceptualize structural components was conducted and a similar survey was given to the students again to see if their level of understating structures changed.

Workshop 1: 2017 Fall Semester Trial I Overview

For the fall semester, first a pre-survey was given to the students to fill out individually. The survey included basic questions about structural elements and structural system. The pre-survey included four structural questions, two multiple choices and two short answer. Figures 1 and 2 show two of the survey questions for this workshop. The rest of the questions have been followed after Figures 1 and 2. After the pre-survey, the structural professor provided an introductory presentation series in a PowerPoint format. The presentation consisted of a brief introduction to structural elements and components, structural system, materials, type of loads focusing on gravity load, description of a floor plan for the surveys, and introduction for the exercise. Then, the exercise the students participated in was the egg drop test.

Each student was put in a group of four to five and given supplies to construct a small structure that was intended to protect a raw egg. The finished design was to be dropped from a fixed height of approximately 10 feet. The group's designs were left completely up to their creative imagination. Each group had many different structural variations within their designs. During the actual egg drop, students were able to visualize just how a design can impact the strength and safety of a structure. At the end, after testing, the same survey given to the students to gather data and then compare the responses before and after.

In comparing the surveys, students demonstrated a higher selection of metal materials chosen after the presentation and the egg drop exercise. It appears that students associated metal with being a stronger material for column and beam construction. Many of the students had a gist of metal equating to strength, however, they could not quite distinguish that iron and aluminum are not materials that should be used in beam and column construction.

Votes for marble as an acceptable structural material dropped from survey one to survey two. Students seemed to understand that marble is not a structurally sound material capable of column and beam construction; however, it appears they still chose marble due to the association with its historical aesthetic use, rather than structural use.

In the short answer post survey question, students showed some understanding of how a structure should perform. Many of the student's answers contained a short analysis of how the structural components keep the building standing during impact and/ or load increase. Students also realized that structures that seem to be designed well did not perform the best, structurally. Students also identified that structures using heavier material were not always the better designs. Lastly, they observed that lighter material was favorable for optimization and was more efficient.

Many students were intrigued by how structures are inspired by nature and natural elements. The questions for surveys and analysis presented in following section.

Fall Pre- and Post- Survey Results and Analysis

Question 1: Which building type out of the four listed- have you noticed the design of the structural system?

For Figure 1, Question 1; the answers varied with selections of what structural system has been most noticeable to the students. The parking garage structural system maintained the highest selections throughout survey 1 and 2.

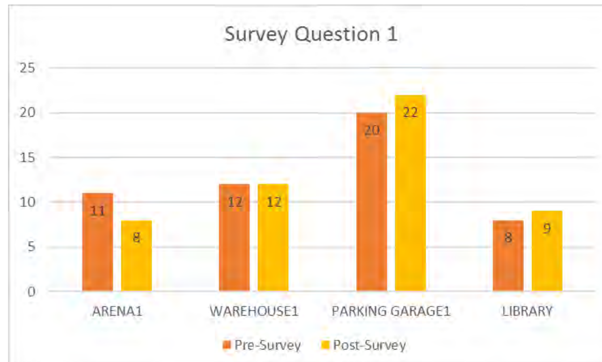


Figure 1: Students' answers to question one pre-survey and post-survey.

Question 2: What are acceptable materials to use for column and beam construction?

From Figure 2, Question 2- In comparing the surveys student exhibited answers having a higher selection of metal materials after the presentation and the egg drop exercise. First year students also appear to associate all metal with strength and favorable column and beam construction. Lastly, students cannot distinguish that iron and aluminum have a lower psi and are not materials that should be considered in beam and column construction.

Votes for marble as an acceptable structural material dropped from survey one to survey two. Students seemed to understand that marble is not a structurally sound material capable of column and beam construction; however, it appears they still chose marble due to the association with its historical aesthetic use, rather than structural use.

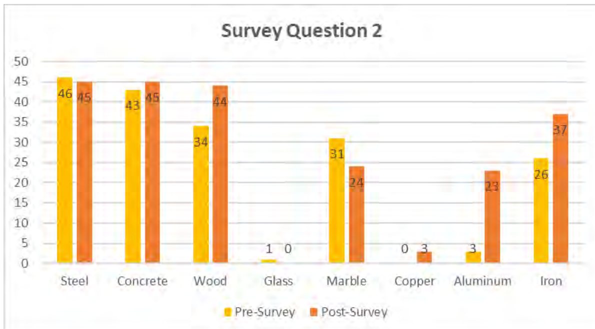


Figure 2: Students' answers to question two pre-survey and post-survey.

Question 3-Pre-Survey:

Tell us, from your experience, of a building/ bridge/ built environment project that caught you by surprise and you deemed it aesthetically beautiful. Do you recall if the structural system mattered in its inspiration? Why or why not?

A majority of students answered question 3 with descriptions of structures they have noticed prior to the presentation. Responses include awareness of height, comparison to nature and aesthetic beauty.

Question 3-Post Survey:

Tell us what you observed from your recent experience creating/ making a structures project in class. What fundamentals of structural design caught your attention and may influence your future designs?

Question 3 of the second survey resulted in higher structural responses. Students found structures interesting. Answers included awareness of column support, tension support, absorbing impact, and durability.

Question 4: On the next page is a familiar floor plan to your work this semester. Revisit this floor plan, however, this time with the structural system in mind. Thoughtfully, please mark where you believe:

a. Structural vertical supports (columns) are

b. Layout how you imagine the horizontal structural system (beams) run to hold up the roof membrane

Answers differ greatly within the student responses for column and beam placement in both the pre and post presentation surveys.

From the observations from the fall semester presentation, exercise, and surveys; in the short answer post survey questions, students showed some understanding of how a structure should perform. Many of the student's answers contained a short analysis of how the structural components keep the building standing during impact and/ or load increase. Students also realized that structures that seem to be designed well did not perform the best, structurally. Students also identified that structures using heavier material were not always the better designs. Lastly, they observed that lighter material was favorable for optimization and was more efficient.

This was concluded as a fairly successful workshop with structures introduction. Students gained new knowledge and some form of understanding structures with this first trial. This was apparent, as some of these observations were not reflected in their pre-structure presentation survey. It was clearly noticeable that many students were intrigued by how structures are inspired by nature and natural elements. Overall, some of the changes were not expected, this introductory lecture was effective, being such a short period of time that the material was introduced. Given that students maintained information after one class session and exercise, it can be deemed that earlier introduction of structural material is useful in student learning.

Workshop 2: 2018 Spring Semester Trial II

Following the research conducted in the fall semester on 45 first year students, a second round of structural systems was introduced in spring semester. The second round of implementation consisted of the same material introduced in the fall semester. This information was presented in PowerPoint format, and it included deeper descriptions of horizontal and lateral loads, material types and design examples in comparison to the fall presentation. This prior information was added as a refresher and as additional reinforcement. The newer information that was introduced consisted of lateral resisting load structural system; shear wall introduction, bracing types and delved deeper into the role of load bearing systems.

Structural Exercise Procedure

At the last part of the presentation, students were shown a 15-minute slide show to which they later utilized in their structural project. Following the PowerPoint presentation, the students were given a survey including six structural questions, four multiple choice and two short answer. Next, the students began their structural design task. The objective of the project was to create a structure that could bear a wind load and a live [human] load without failing. However, the structures were tested under simulated wind load.

The procedure consisted of splitting students into teams of 2-4. Using their current knowledge of structures, they were given thirty minutes to gather supplies and materials. The material used could not be heavy wood, steel, heavy metal, or strong bonding glue. Students were then given thirty minutes to design and construct their project. Dimensions could be no bigger than three feet wide, three feet tall, and three feet long. Students selected their own groups and a total of 10 designs were created. After testing the structures, the final survey was given to the students.

The following is image of the students constructing their structures (Figure 3).

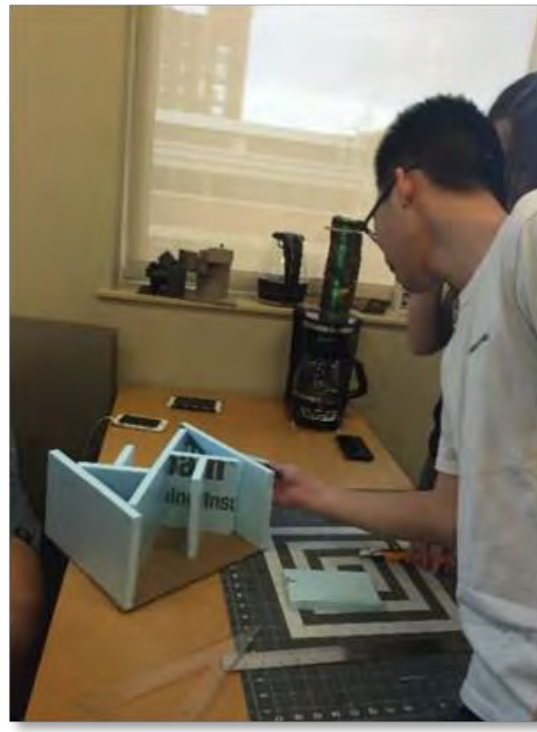


Figure 3: Students are working on their spring semester designs for part II of the research implementation.

Structural Design Results

Following completion of their designs, the testing of their structures ensued. First, the structures were placed on the floor with no attachments. Then, the wind blew from an inverted-vacuum to the structures. The heaver structures were shown more stability than the lighter ones as there were no attachments to the floor. Then, Mikey, a 205-pound student within the studio course appointed as the live load placed on top of each structure. In addition, two hand weights weighing 10 and 12 pounds were added to Mikey's weight during the testing. A total of 10 designs ranging from big to small were created. Many of the designs included bracing inside the structure; bracing was heavily emphasized throughout the second presentation that was shown to the students.

Of the 10 designs, three failed. These failures occurred from material choice, strength, and design. In this test, the lightest design also happened to be the strongest and sturdiest. The students who designed this structure exercised an understanding of bracing and the utilization of optimized materials. Safety precautions were taken in advance to ensure the student's safety when conducting the exercise.

Spring Pre and Post Survey Questions

Survey one and two both consisted of 6 questions; four multiple choice and two short answer. The questions and analysis are presented in the next section:

Question 1: What are structural systems in a building?

a. Beam
b. Partition
c. Column
d. Bracing
e. Ceiling
f. Shear wall
g. Mechanical pipes/ equipment
h. HVAC

Question 2: What do structural systems do in a building?

a. Supporting self-weight of building
b. Supporting wind loads
c. Supporting seismic loads
d. Supporting snow loads
e. For beauty of the building
f. Supporting mechanical and electrical loads
g. Supporting rain loads

Question 3: Do only complex buildings need structural systems?

a. Yes
b. No

Question 4: What are acceptable materials to use for column and beam construction?

a. Wood
b. Marble
c. Glass
d. Steel
e. Iron
f. Concrete
g. Copper

Spring Pre and Post Survey Analysis

Question 1: What are structural systems in a building?

In the survey completed prior to the structural activity, a high selection for beam, column, and bracing shown. HVAC systems received the least number of votes, with only 4 students selecting this as a structural system. This shows that students understand the difference between internal systems, and structural systems.

The survey conducted after the addition of more students to the class lecture. In comparison to question 1 from survey 1, beam, column and bracing still received the highest selections. The selection of shear wall went up by 21 votes, and mechanical pipes and HVAC selections decreased.

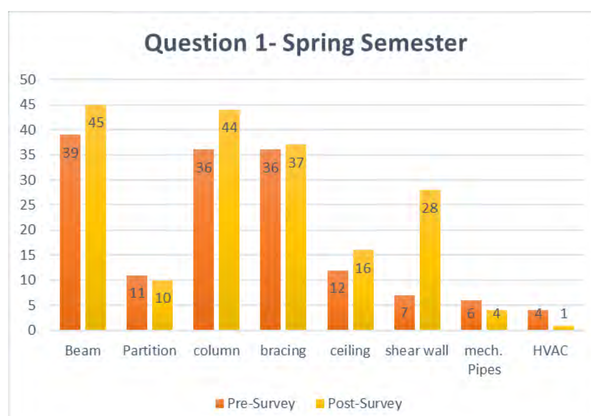


Figure 4 shows the results from pre-survey and post-survey.

Question 2: What do structural systems do in a building?

There was a high selection of self-weight, wind, seismic, snow, Mechanical pipes/equipment (ME) and rain loads in the first survey. The beauty of the building, choice E, had only 13 selections. Students were shown structural systems that contributed to building aesthetics in the PowerPoint prior to the testing. With the results of question two from survey one; it seems most students still do not associate structural systems with beauty and aesthetics.

For question 2, all answers increased in selection with the second survey. Students retained the information from presentation 2 as well as the understanding that structures support the entirety of the design and its loads.

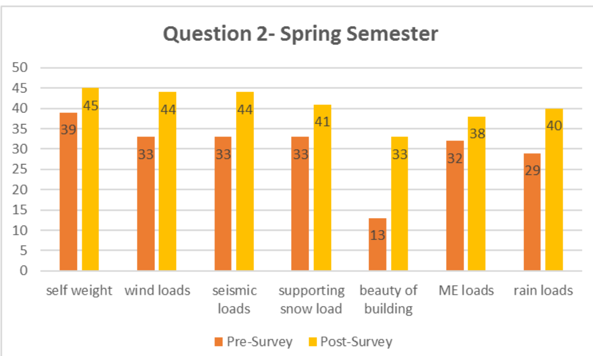


Figure 5 shows data for question 2 for pre-survey and post-survey.

Question 3: Do only complex buildings need structural systems?

-37 of the 39 responses properly assessed that complex buildings are not the only structures that need structural systems in the pre-survey.

The answers maintained nearly 100 percent of no votes, with only one student choosing yes in the survey after the workshop.

Question 4: What are acceptable materials to use for column and beam construction?

The pre-survey shows high selections for wood, steel, concrete, and iron when it comes to the selections for beam construction. Iron is not an acceptable material for this type of structural application; however, it seems students still associate all metals to be adequate for structural systems. Though iron had thirty-two votes, most students have not been able to distinguish the difference between iron and steel strength.

In survey two, the students' responses maintained a high selection of wood, steel, and concrete. Selections of iron and marble decreased while glass and copper had a slight increase. Some of the students have not yet associated certain strengths with materials not suitable for structures design.

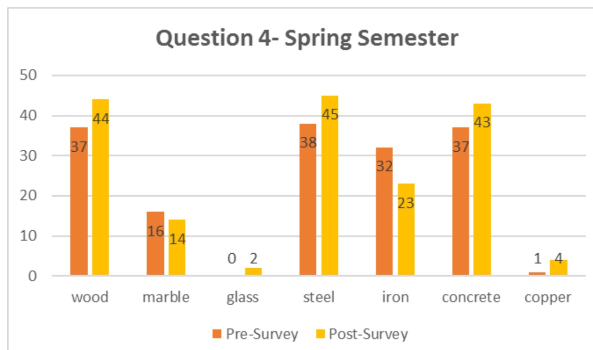
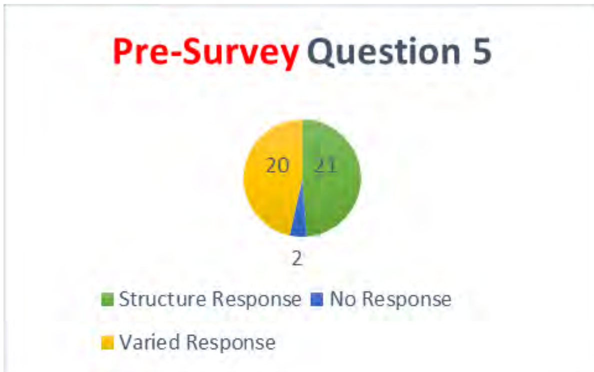
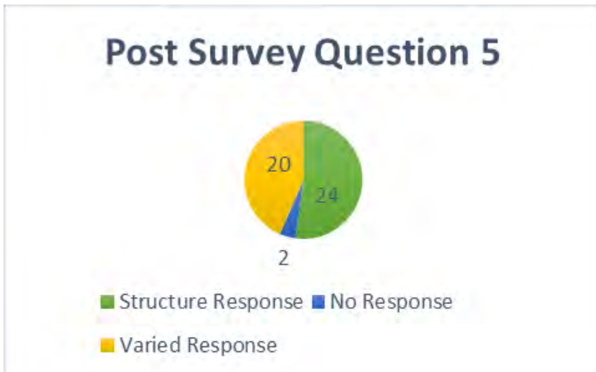


Figure 6: Students' answers to question four (left to right): pre-survey, and post-survey.

Question 5: What do you remember from last semester's introduction to structures course?

The answers varied. Nearly, half of the students answered with varied responses that showed a wide range of memory or lack thereof (this includes answers such as "a lot", "I'm not sure", "the egg drop", etc.). Over half of the students answered with a response that includes structures material/ terminology on both surveys.





Figures 7 & 8: Students' answers to question 5 pre-survey, and post-survey respectively.

Question 6 - Pre-Survey: What do you think you will learn from the structural activity you will complete today?

Nearly, half of the students answering with varied responses on what they anticipated to learn. Over half of the students answered with a response that includes structures material/terminology on survey 1.

Question 6 - Post Survey: What do you think you learned from the structural activity you will complete today?

After completing the lecture and activity, all students responded, with majority of students leaving a structure response.

Conclusions

The results were deemed effective, as students have retained much of the structural information presented to them in two lectures. The results from these lectures and tests proved to influence the students' knowledge and understanding of structures.

Many of the students have gained some type of structural understanding from these two workshops including lectures and activities. The activities provided the students with added reinforcement in understanding how these components work in design. With signs of improvement after activity completion, more sessions need to be conducted to see how much the students have actually retained.

Overall, the workshop method was a fairly successful structures introduction into architectural form. Likewise, the results prove integrating workshops and active-student learning techniques influence students' knowledge and understanding of structures.
However, further research is recommended to follow these freshmen students through their second year in the program. The study will examine if these same architect students: (1) retain and use structures in their designs - long before they actually take traditional structure curriculum coursework in their third year; and (2), if innovation with structural components appear in their work.

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Developing Evidence-based Tools and Resources for Material Selection

Erin Carraher and Luke Leither
University of Utah

Abstract

Building construction costs over a trillion dollars and accounts for half of the non-renewable resources consumed on an annual basis in the US, with materials and equipment comprising three-quarters of these costs. While not the final arbiters, architects play a critical role in determining what materials are specified for construction projects. Material selection in architecture has historically been taught through high-level lectures accompanied by empirical, evidence-based exercises and precedent studies during school followed by "in the field" experience for interns in practice. While there are many great resources that discuss material properties and analyze the use of specific materials in iconic projects through a case study approach, there is a significant gap in the literature and support materials when it comes to how and why materials are selected in the first place. With the rapidly evolving nature of digital tools, ever-expanding range of materials available on the market, and increasing standards for building performance, there has never been a greater need for comprehensive resources to support architects' and educators' understanding of the interconnected factors that influence and support informed decisions that are justifiable to all project stakeholders.

This paper presents the problem-setting process; findings from first-hand interviews with almost twenty practitioners at leading firms in New York City, Chicago, and San Francisco that have been recognized for their thoughtful use of materials; and plans for the next targeted phase of the work. University research seed funding supported the initial phase of this research, which was designed to validate assumptions about the unique nature of the material selection process. We plan that this study will serve as the first step toward developing codified resources to support a more evidence-based approach in education and practice.

Keywords: Materials and Construction, Professional Practice, Pedagogy

Introduction

The development of materials collections to support architecture and design programs is a growing trend in university libraries across the country. Architecture librarians, always searching for ways to engage with students and faculty, have leaped at the chance to acquire new collections and tackle the difficult task of cataloging, preserving, and displaying new materials. From the architecture educator's perspective, these collections are sought after to aid in materials instruction and to familiarize students with the diversity and depth material science has to offer. At least in theory.

The J. Willard Marriott Library at the University of Utah followed this trend in 2015 by acquiring a 1500-item materials collection from the New York firm, Material ConneXion. The library was encouraged to make this investment by faculty in the university's School of Architecture and its Multi-Disciplinary Design Program. Material ConneXion was chosen for a variety of reasons including the company's strategy to "select cutting-edge materials in collaboration with our research team" and their dedication to provide access to smaller, boutique manufacturers. The Material ConneXion subscription is accompanied by a database with descriptions of all the physical materials included in the Marriott's collection as well as those in the New York flagship collection. The Marriott rolled out its collection in 2016 and has been maintaining and promoting it ever since.

However, since the very beginning it was not entirely clear how to leverage the new acquisition to its fullest potential. Class visits from architecture and design students were often met with polite interest and little follow up. One-on-one consultations with librarians sometimes left the students frustrated with the limits of the collection in terms of the size of the samples, the focus on cutting-edge versus more foundational materials, and the limits of the Material ConneXion database in doing research on material properties. These setbacks forced a reexamination of the collection's intended use relative to its support needs.

Material Research and Selection Competency

The 2014 NAAB's Conditions for Student Performance in its Conditions for Accreditation require architecture students to have knowledge of the "technical aspects of design, systems and materials," as well as the ability to successfully select appropriate materials based on "their inherent performance, including environmental impact and reuse." Simply having the materials collection did not seem to be helping the students to a better understanding of how to perform material selection and research. In fact, the database sometimes seems to be a hindrance, as students viewed it as a one-stop website for all the information they needed about a material.

Librarians have also laid out competency standards for students, which help to drive the purchasing and programming decisions in the profession. The Art Libraries Society of North America, a professional association for art and architecture librarians, lists the "ability to collect information on specialized topics" like "sustainable and energy efficient materials" as an intermediate skill requirement for architecture students in its Information Competencies for Students in Design Disciplines. It goes on to suggest the use of handbooks, manuals, and catalogs as methods of discovery. The competency document does not specifically mention materials collections, but the advantage of having access to the physical objects for research seems to follow. Unfortunately, neither entity provides a standardized method to teach these skills or integrate various collections into the curriculum.

Framing the Question

It was these issues that prompted an initial, exploratory study into the current materials research and selection practices of architects in the United States. The study was designed to examine how materials research and selection are currently done in professional practice, what training practitioners identified as beneficial and/or lacking with respect to skills needed to do so, what resources were commonly used in the process, and if current methodologies were adequate for the needs of practitioners. The results of this study would then be applied in several ways within the university setting and help direct future research agendas. Below are several areas of inquiry the exploratory research hoped to address.

One of the study's main areas of focus was to determine how current practitioners were educated in the area of materials research and selection.[1] Do practitioners feel as if their education provided a systematic and rigorous approach to the research process? Did they have coursework in research methods? What did their materials education look like? Finally, how have they applied their education, or lack thereof, into their professional work? The hypothesis was that most practitioners would report very little formal education in this area, and that many rely on a non-systematic approach in their selection process.

The materials research and selection process is differentiated from knowledge about material properties and construction methods, which are clearly covered in the curricula of all architecture programs, by the incorporation of a rigorous, exploratory research process and the appropriateness of the architect's response to the complex environmental, cultural, aesthetic, performative, and budgetary requirements of a project. Beyond initial intuitive decisions by practitioners about the materiality and tectonic response appropriate to a project, the assumption was that much of architects' research and selection process was happenstantial, directed by products presented at firm lunch and learns, materials seen in other buildings, and those used by the firm in previous projects. The hypothesis here was that architecture practices may mirror the old physician/pharmaceutical-sales model, where the selection of a particular version of a drug is heavily influenced by vendor visits and the education provided therein.

The resources architects use in their exploratory research process was another area of interest. Determining if firms had materials collections and how they used them, as well as what other supporting material (e.g. manuals, journals, databases, etc.) were commonly used would help to determine current trends in practice. Additionally, whether or not firms evaluated the success/failure of materials used in previous jobs would be helpful in understanding how reflecting on past work informed future projects, effectively closing the loop of the traditional research process. A use of primary source information in addition to secondary sources seemed a logical approach to this type of research, which determined the need to interview practitioners in leading firms of varying types and sizes across the country.

Finally, the study was designed to uncover the wide array of experts around architects who assist with material research and selection. The relationship between architects and specification writers, engineers, and manufacturers was explored in an attempt to articulate the intricate back and forth that happens on every project. It was important to acknowledge the team approach common in architectural practice, and attempt to define its benefits and limitations. To this end, interviews were conducted as often as possible with multiple firm members who filled these roles within the practice.

Answers to some of these basic questions have provided the initial steps to improving student preparation for architectural practice and clarified areas where more in depth research will be conducted. From a library perspective, better information provides important feedback into how collections are managed and presented to students. From the architecture instructor perspective, it shines light on current strengths and deficiencies in education, and points toward where future focus and research needs to be applied.

Research Overview

Rigorous research practices in architecture education and practice have been identified as lacking by many despite initiatives as early as the late 1940s to promote these practices. Stephen Kieran outlined the need for more rigorous research processes to be taught in a 2007 article in JAE entitled, "Research in Design: Planning Doing Monitoring Learning," where he contrasts architecture and product design education. He states that architecture educators overemphasize the "planning" and "doing" stages of design without also insisting on measuring performance and learning to inform subsequent iterations like product designers do. "The bulk of our curriculum remains embedded in the nineteenth-century design studio where we plan, then we plan again and again, with little real growth in the quality and productivity of what we do either artistically or technically. While an ever-increasing number of schools have included ["doing" or building] in the curriculum, few schools of architecture teach research skills and fewer yet insist upon critical reflection and learning based upon research findings."2 Kieran goes on to outline the research culture intentionally fostered at KieranTimberlake as requiring the rigor to constantly interrogate projects and processes in order to learn and improve as well as the skills needed to "frame questions and seek out measurable data that we can act upon to improve what we have done."[3]

Since little research has been done on how material research and selection are taught and practiced by architects, it was determined that an exploratory research study was needed to refine base assumptions, vet survey and interview techniques, and determine if further exploration on the topic was in fact needed. The framework of an exploratory study was chosen to test foundational assumptions about larger issues within architecture education and practice and confirm that the right questions were being asked prior to embarking on larger-scale efforts. In his book, *Qualitative Research Design: An Interactive Approach*, Joseph A. Maxwell states that exploratory or pilot studies are valuable tools in any qualitative research project because they allow researchers to test, clarify, and shore up aspects of their research design and to identify features of the study that could only have been established through the study itself.[4]

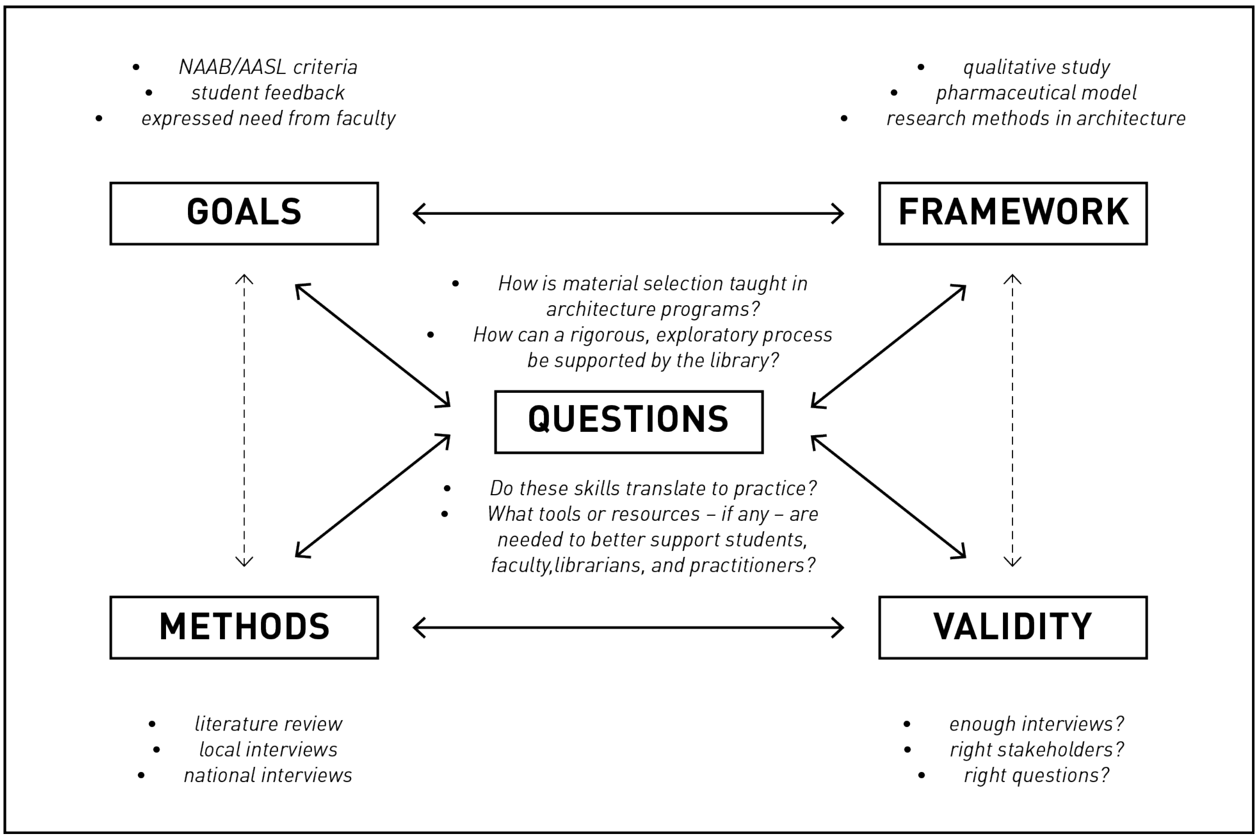

Fig. 1. Research Framework – (Based on "An Interactive Model of Research Design" From *Qualitative Research Design: An Interactive Approach*, by J. A. Maxwell, 2005. Copyright by SAGE.)

In parallel, the researchers intended to identify if any tools and resources are needed to better educate students and support practitioners in an evidence-based process of material selection that best achieves project objectives. Using the idea of scaffolding research funding as a strategy from past collaborations that has proven to lead to long-term success, the researchers applied for and were awarded a college seed grant to support these efforts. As with most exploratory research, the goal was to prepare the way for more targeted research in the future. A "beta" phase was performed locally through interviews of faculty, students, and practitioners connected to the university, attempting to ascertain how important they feel material selection is in practice and how prepared they feel to make informed design decisions about materials based on their education. Findings from this process informed the development of the questions for the field research conducted with leading national architecture firms.

In-person interviews were held with approximately twenty design professionals in San Francisco, New York, and Chicago at leading firms of various sizes and types of practice. It was critical to perform these interviews in person, not only to obtain the most complete answers to questions, but also to allow for the observation and documentation of materials collections in situ within the office environment. Recorded interviews were transcribed and are in the process of being comprehensively coded using qualitative research methods to identify common themes and specific examples. A number of initial findings–both general ones that inform the framework of the research itself and specific ones that help clarify assumptions and direct future work–are outlined in the following sections. The general will be discussed first, followed by the specific.

General Findings

General findings include the following: (1) neither the unique model of architecture education nor the more “artistic” elements of practice are clear to those outside the discipline; (2) the lack of codified research practices and the challenge of each project being seen as a prototype are indications of a discipline historically lacking a rigorous research ethic; and finally, (3) the term “research” is often used differently by architects and librarians, and thus needs to be clearly defined throughout this study. In compiling the findings of this initial research, it is necessarily to first take a step back and clarify broader issues before outlining specific findings.

Architecture Education’s Legacy

In his description of the curriculum for the first architecture program in the country, MIT’s founding director, William R. Ware, mentions two fundamental and unique challenges for formalized architectural studies that can be argued have not yet been reconciled to this day: that architecture education cannot, by the nature of the discipline, cover the entire body of knowledge that students will need in order to practice, leaving “much of the ordinary detail of work” to be learned in architecture offices; and that the structural shift to a formalized model of higher education for architects continued the apprenticeship model’s less formal methodologies of conveying information based on personal experience.[5]

Rather than seen as a continuum, the acquisition of knowledge in school versus the application of it in practice was seen as bifurcated by all of the practitioners interviewed as part of our study when asked how they learned to conduct research and select materials for buildings. Practitioners’ constant refrain was the common “nothing they were taught in school prepared them for the realities of practice.” While all agreed that materials and methods were covered in the core curriculum of their own education, their ability to conduct material research and selection in practice required a far different skill set – one that often had to be learned on the fly in practice. Said one senior practitioner with 40 years of experience, “We don't focus enough on [technical when compared to design] in school. I mean, it’s not that you can teach students everything about how buildings go together and all of the issues that you need to deal with as an architect, but certainly we can do much better at providing a foundation of understanding of these things. Materials research and understanding all the issues -- the code issues, the chemical issues, just understanding the basics about flame spread -- all these things. [When] you get out of school, you don't have any of this, so you're starting from ground zero. Unless you are lucky enough to have a good mentor or be in an office that understands the importance of mentoring and training young professionals on your own, it's a long road to figure it all out." Statements like this and many others also identified the internship phase as an important and previously overlooked component of the education process that will be added as part of future iterations of this study.

The "legacy teaching approach" in architecture studios reinforces the "rich legacy of principles and personalities that creates a common bond among veterans and novices alike"[6] and at the same time contributes to an insular culture that results in the profession struggling to communicate its value to those who have not experienced it. For this, the outside perspective of social scientists like Donald Schön and Ernest Boyer is helpful in describing the unique nature of architecture as an applied art.

Schön, a philosopher and urban planning professor at MIT, identified architecture education as occupying the "messy middle ground" between intuitive art processes and rational scientific ones. He stated: "I have become convinced that architectural designing is a prototype of the kind of artistry that other professionals need most to acquire; and the design studio, with its characteristic pattern of learning by doing and coaching, exemplifies the predicaments inherent in any reflective practicum and the conditions and processes essential to its success."[7] He equates learning the complex functions required to practice architecture to learning how to walk, speak, or ride a bike: one learns these skills by doing them, often with the aid of coaching. Once learned, a person may be able to perform such a skill–often at a level of mastery–but may not be able to explicitly verbalize how or why they are doing so.[8]

This does not mean that implicit knowledge cannot be taught; by observing and reflecting on the actions required to perform a task, Schön states that is possible to describe the tacit knowing implied within them. These descriptions need to be tested against the original actions and adjusted to the point where there is clear communication between parties. He goes on to differentiate design from other disciplines: "Designing in its broader sense involves complexity and synthesis. In contrast to analysts or critics, designers put things together and bring new things into being, dealing in the process with many variables and constraints, some initially knows and some discovered through designing. Almost always, designers' moves have consequences other than those intended for them. Designers juggle variables, reconcile conflicting values, and maneuver around constraints–a process in which, although some design products may be superior to others, there are no unique right answers."[9] Making this process explicit to those outside the discipline enables better collaboration on topics such as supporting the education of architecture students.

"Closing the Loop" on Architectural Research Practices

Design thinking is an iterative and syncretic practice, a way of operating within complex frameworks that translate across scales and responds to changing technological, cultural, social, and material conditions. Though it doesn't readily comply with more traditional research practices, many would argue that the design process is also a process of experimenting. However, the experimenting is often limited to establishing the parameters and doing the work with very little if any time spent on reflecting on the outcomes or comparing them against the intended goals to inform future direction.

Stephen Kieran identifies the need for architecture education to approach the research process more like products rather than one-off prototypes: "Architects tend to see most acts of design as unique. Site and program together give rise to circumstance. Circumstance inspires intention. Design organizes intention into instruction. Builders construct from what we instruct. And we all move on to the next set of circumstances and program, none the wiser. Architecture exists in a world where all we ever do is design and build prototypes, with little real reflection and informed improvement from act of design to the next."[10] Kieran describes the role of research as essential in architecture with the relationship between the two–architecture and research–as being divergent but complimentary.[11] Others argue against integrating the two and instead support the development of a "discipline-dependent scholarship" and that design itself is research.[12]

Defining Research as a Design Strategy

For librarians, research means a rigorous, systematic approach to investigation where hypotheses are developed, variables are identified and interrogated using a variety of research methods, and results are documented and compared to initial assumptions in order to validate or refute the hypothesis and direct future iterations. Architects, on the other hand, often conflate the overall research process with the methods used to conduct the research itself -- case studies, hands on experimentation, precedent analysis, etc. The lack of clarity within the discipline about the distinction between the two and their relative value is an ongoing debate.[13]

A fundamental distinction is in the type of problem being solved in architecture and design practices, which does not readily lend itself to isolating variables. Schön outlines the difference between "manageable problems" that lend themselves to solution through the application of research-based theory and technique and "confusing" or some might say "wicked problems" that defy a technical approach.[14] While linear processes can be defined to address problems that have clearly defined conditions, designers operate within indeterminate conditions, which often necessitates different approaches to both defining and then addressing the problem. "Design problems are 'indeterminate' and 'wicked' because design has no special subject matter of its own apart from what a designer conceives it to be. The subject matter of design is potentially universal in scope, because design thinking may be applied to any area of human experience."[15] For the purposes of this research study, the authors ascribe to Groat and Wang's definition of research as inclusive of "works of inquiry occurring across a range of disciplines (sciences, social sciences, the humanities) and professional fields."[16]

Research Findings

Three findings specific to the research on material research and selection include: (1) the need for more dialog among all parties seeking to support learning on this topic among studio and technical courses, architecture faculty and librarians, academics and practitioners, etc., especially where tools and resources are needed to conduct the work, (2) the need for architecture educators to collaboratively develop practicum for a reflective material research and selection process, including supporting tools and resources, to be addressed in school, and (3) the need for students, faculty, and practitioners to develop reflective communication skills in order to make explicit the oftentimes implicit aspects of practice.

The Need for More Communication among Stakeholders

Knowledge and application of materials and assemblies is clearly outlined in all aspects of architecture education, internship, licensure, and practice as a fundamental skill required to demonstrate competency. Students learn to intuitively choose materials in their studio projects to fulfill self-defined objectives regarding tectonics and materiality, but they do not often do so as part of a rigorous exploratory or investigative process. Materials and methods are taught in schools, with many courses incorporating hands on projects and visits to manufacturing plants and job sites. This approach provides an overall understanding of material properties by category (masonry, steel, wood, etc) and often is accompanied by hands on experiments with a material and/or projects that give students a more experiential understanding of how materials can be used. What is not taught as explicitly or rigorously is how to select materials for a project, particularly when using non-traditional materials or using traditional materials in non-traditional ways, based on not only visual criteria but also performative requirements.

A senior specification writer at one leading firm expressed his frustration with passing along his decades of expertise to the next generation. He explained that a junior architect working on a drawing set may specify a material based on aesthetic characteristics that needs to be modified in the specifications based on performance characteristics. Because there is no specific mechanism for feedback within his firm, the junior architect often isn't aware that such a change was made or doesn't know why it was made. The spec writer doesn't expect students to be able to learn the nuanced nature of material selection in school but also finds it challenging to contribute to their continued education in practice.

Interviews such as this as well as past research point to the need for dialog among all parties seeking to support learning in the area of material research and selection, especially where tools and resources are needed. This includes communication among studio and technical courses; faculty and librarians; academic and industry partners in order to understand the different types of tools needed and how best to align these with the intended learning outcomes. The collateral organizations do this internal to the profession through the development of NAAB's Conditions for Accreditation and the Architecture Experience Program and Architecture Registration Exams, which are informed by NCARB's Survey of Practice. However robust, these tools don't approximate the collaborative nature of practice, in which specification writers, material vendors, manufacturers, engineers, and others are an integral part of the process.

Many programs bring outside experts into the studio to work with students in a consultancy model, and many multi-disciplinary projects have been conducted that partner architecture students with those in other disciplines. The findings of our surveys indicate the need to extend this model into the curriculum development process by including not just academics, students, and practitioners but also the stakeholders mentioned above to holistically map the process across education, internship, licensure, and practice toward a more rigorous and innovative approach.

The Need for a Research-Based Practicum

While academia cannot–and should not–replicate practice, the model of a practicum allows students the opportunity to practice the skillsets that are being learned within an approximated context. Schön describes the process as follows: "Beginning with situations that are at least in part uncertain, ill defined, complex, and incoherent...designers construct and impose a coherence of their own. Subsequently they discover consequences and implications of their constructions–some unintended–which they appreciate and evaluate. Analysis and criticism play critical roles within their larger process. Their designing is a web of projected moves and discovered consequences and implications, sometimes leading to reconstruction of the initial coherence–a reflective conversation of the materials of a situation."[17] Tools and resources that support the investigation process need to also be developed, including in particular research methods.

One of the fundamental issues addressed through this research was how to better support the use of material libraries within architecture curricula. Through the interview process, the researchers discovered that while material collections developed in libraries and firms may look similar, they are used very differently in practice than in academic settings. From librarians' perspective, material collections are ideally used for discovery and supporting exploratory research practices. Material libraries in firms, however, are very rarely used for these purposes instead serving to aggregate physical samples in order to communicate design intent to clients. While all practitioners interviewed indicated the need for tools to help better select materials, it does not appear that a material library is the best place to do this. Rather, initial feedback was that a standardized format for materials themselves would be helpful in more broadly searching by aesthetic, performative, and cost qualities rather than by vendor collection or past experience.

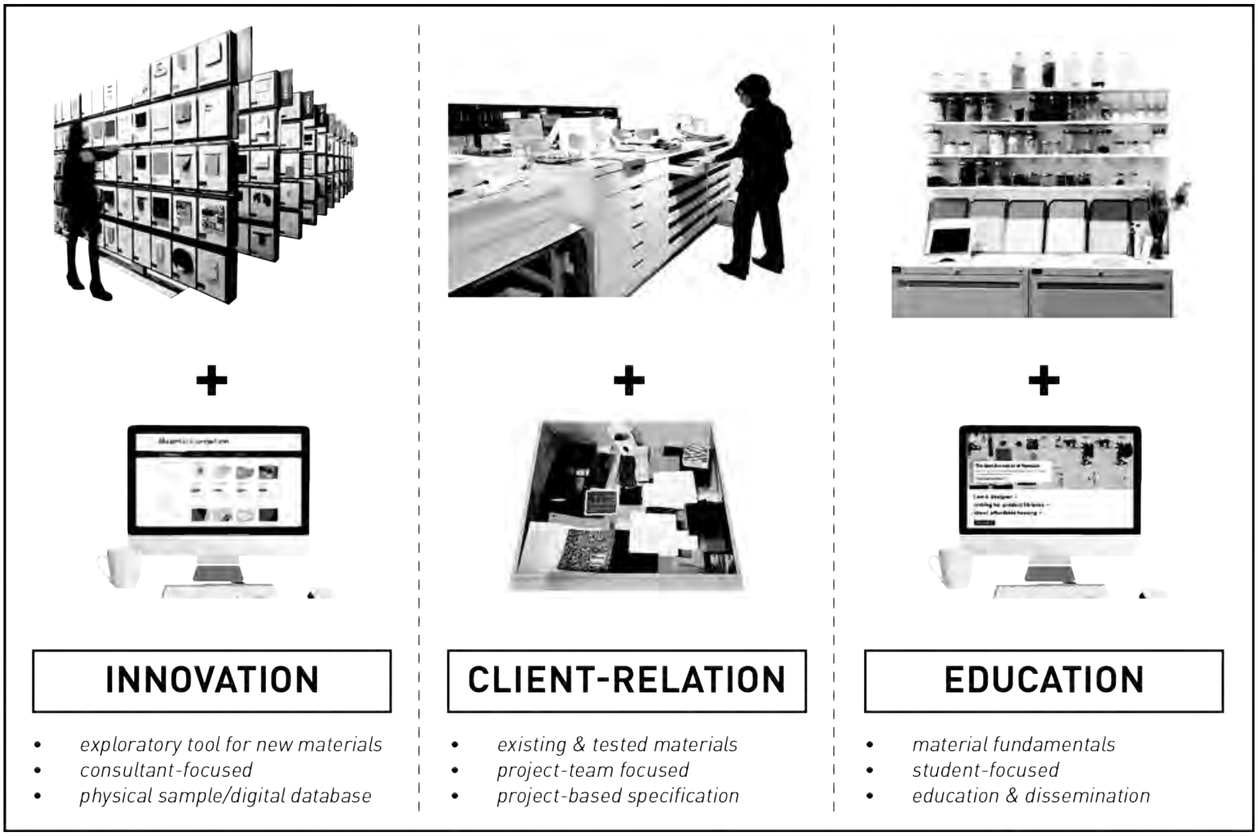

Fig. 2. Material Library Typologies

For new materials or materials that would be used for the first time in a firm, case studies and post-occupancy reports on how materials perform in application would be desired. Few firms interviewed had a formalized process for documenting material choices or following up on their success or failure beyond client presentation documents and submittals. One exception was a New York City-based firm where the librarian who manages the material collection and supports designers in the research and selection process documents each major project and observations about material performance in a series of binders for future reference.

In academic settings, having access to materials primarily for their qualitative characteristics or for preparing client boards is not a worthwhile objective for libraries when considering the cost, staffing, and space required to build and maintain a material collection. Instead, material collections are intended to serve as an educational tool that helps students understand materials at a more fundamental level and develop research skills–objectives that also align with the NAAB standards. The challenge for librarians then is to create a library that is useful for learning and research and provides hands on access to materials without duplicating the firm model. The library should have specific objectives (i.e. whether to focus on existing or innovative materials) that align with the needs of the academic program being supported.

One example of a collection that achieves this goal is the Healthy Materials Lab at Parsons, which is a living lab that collects and codifies information and examples of healthy materials. The lab houses not only products that meet the requirements of different rating systems such as LEED and Best, but it also has examples of the chemicals and materials that are used to create the products, giving students a holistic understanding of a material's lifecycle. This model is a good example of a material collection focused on supporting specific sustainability objectives within the academic program. Along with this focus on the full lifecycle of a material, other qualities that have been identified to supplement the current Material ConneXion collection of more innovative and emerging materials are basic architectural materials (glass, metal, wood, stone) as well as a series of "disposable" materials that can be used by students for personal experimentation and play.

Lastly, initial findings indicate that collections are best utilized–both in practice and academia–when managed by someone who is knowledgeable about both materials in application and collection management, indicating someone with a background in both design and library science as an ideal candidate. On the library side, this person should have a close relationship with faculty and students who are going to be using the collection; have a strategy for organizing, building, and weeding the collection; and most importantly devote a significant amount of time to cultivating relationships with manufacturers and material scientists so they can best direct designers who come to them with questions.

The Need for Reflective Communication Skills

As the discipline moves toward a more connected position within society, architecture, "by nature and tradition, holds vast potential as a model for integration and application of learning, largely because of its most distinctive feature—the design studio."[18] The design studio is central in architecture education as the site where each student's creative abilities and professional interests are fostered through the development of a strong connection with their studio professor and peers. During the exploration of increasingly complex architectural projects in studio courses, students work to holistically address program requirements, develop an artistic vision, and resolve technical issues within a broader social, environmental, and cultural context, aided by regular feedback. Education models like guided design, reflective practice, and active learning define the studio-based model. By providing transparency to educational practices and language to intuitive processes, design practice and design education can be demystified and strengthened.

Such an intervention may be especially useful during the internship stage where students or recent graduates are first asked to apply their skills in professional settings. Many practitioners interviewed described feeling like they were "thrown into the deep end" and had to figure out on their own how to accomplish prescribed tasks. They also indicated that much of a junior architect's success in this area was left to chance with regard to whether or not they worked under a project manager or had a mentor who was willing to teach them what they needed to know. While there may still be much a junior architect needs to learn when entering practice that can't be taught in school, they can learn how to ask the right questions and advocate to make sure they are getting the support and experiences needed to learn these skills.

Conclusions and Next Steps

This exploratory study has demonstrated the need for additional, targeted research in architecture and design schools. A more thorough understanding of how material research and selection is taught, what resources are provided to faculty and students, and how well prepared students feel is the next priority. Therefore, a survey for students, faculty, and support staff will be developed and distributed to address these issues. These data will help to inform recommendations for curriculum and supporting materials, including material collections.

Several interviewees expressed a desire to see a tool created to simplify the materials research process. One that would allow a user to input functional requirements as well as more extrinsic material qualities like aesthetics and sustainability ratings. The hypothetical tool would then list the materials and manufacturers that matched the specific query. This is an area being heavily scrutinized by businesses across the discipline, and will therefore not be a continued line of research from this study.

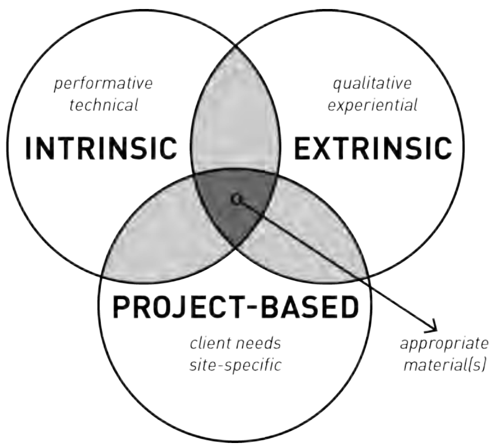

Fig. 3. Material Selection Framework

Architects are trained to think differently than most other professionals; they engage in reflective practice, which is an iterative, probing exploration of a complex project. As the architect works through design ideas, the project “talks back,” according to Schön. This process takes on a reflective conversation between the architect and the situation by re-framing the problem to address local and global issues. The designer uses tools unique to his or her profession during this process: a “metalanguage” that combines drawing and talking, an examination of the impact of choices on an interconnected system of variables, and a shifting stance toward the design that allows unbiased examination of various alternatives. This process is unique, in its ability to question “the problem of the problem” through an “inquiry in action” approach. Though architects are intuitively reflective in their process, they are not reflective about their reflectiveness.[19]

Stephen Kieran emphasizes the importance of reconciling research and practice for architects: “Research brings science to our art. Responses to place and program provide intuition to guide form. Research provides information and insight that enhances the performance of our intuitions. Architecture education rightly focuses on developing design intuition. To move the art of architecture forward, however, we need to supplement intuition with science. Research skills need to be brought to the center of the architectural curriculum, providing the basis for a cycle of continuous reflection, learning, and improvement. We need a deep research ethic to guide the art of intuition.”[20] By understanding the context in which faculty and supporting stakeholders like librarians are operating within, developments in fulfilling educational and practice-based objectives related to material research and selection can be thoughtfully addressed. This initial research study has confirmed the need for more work in this area discipline-wide and indicated several future research pathways in which to do so.

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1 ”Material” in this paper refers to the external cladding material(s) that define a building’s tectonic expression and primary enclosure.

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Steel Structures that Breathe: Two Extensively Glazed Buildings that Integrate Natural Ventilation within Structural Members

Patrick P. Charles
Roger Williams University

Abstract

The paper is a case study of two extensively-glazed steel-framed buildings, Jean Prouvé's 1957 temporary school in Villejuif, France, and, Müller Verdan Architekten's 2006 Sporthalle "Gotthelf" in Thun, Switzerland, that integrate natural ventilation within the building structure itself.

Practically, this unique approach enables the designers to provide usually mutually exclusive features, large glass formats and natural ventilation, without incurring the various penalties associated with operating such very heavy elements.

Conceptually, the idea of integrating the ventilation function within structural members goes against the standard orthodoxy consisting of the separation of enclosure systems from skeletal structural systems. This dichotomy has been one of the canonical rules of Modern Architecture ever since Le Corbusier enshrined it in his "Five Points". It remains today the prevailing paradigm in curtain wall-type envelopes.

These two projects deserve to be better known because of their integrative design intelligence, and, because they challenge the dominant paradigm of separation of structure and enclosure, and in doing so, they open interesting design perspectives regarding the sustainable integration of natural ventilation in buildings.

The method for researching Prouvé's building is archival research- and analysis-based. In the case of the Müller Verdan's Sporthalle, the analysis of drawings is complemented with direct on-site observations and conversations with the architects. The paper also compares and contrasts the two projects with special focus on their structural and natural ventilation aspects.

Keywords: Natural ventilation, Structure, Integration

Introduction

In many climatic contexts, natural ventilation is an important design approach to deliver comfortable and "delightful" thermal conditions while also achieving energy consumption-minimization sustainability goals. Letting air flow in and out of a building requires some sort of operable inlets and outlets to control the magnitude of the buoyancy-based (stack-effect ventilation) or pressure difference-based (cross-ventilation) natural ventilation. Typically, operable windows deliver this natural ventilation function along with daylighting and sight, among other functions.

Historically, such windows have been part of openings "punched" through the plane of, for example, heavy masonry or balloon-framed walls acting both as structure and enclosure. Throughout the 20th century, the separation of the building enclosure from the building structure was ushered by successive developments in iron, reinforced concrete, and steel skeletal frame structures. Le Corbusier enshrined the "ribbon window" as an icon of modernity, the undisturbed horizontal continuity of which resulted from the separation of the structural frame and the building envelope. The advent of commercial curtain walls after WWII made this paradigm of separation of enclosure from structure even more dominant and ubiquitous throughout the Western world.

Accompanying these evolutions were plate glass and, later on, float glass manufacturing advances that made large glass sheets more readily available. Large glass elements, however, are very heavy and thus, hard to operate. Their substantial weight predisposes them to remain as fixed glass elements within the façade, perfect for sight and transparency, but lacking in their ability to participate in the natural ventilation of the building. Operating large and heavy glass sheets usually comes at the aesthetic cost of a visually-heavy frame that appears incongruous with the appearance of lightweightness that we unconsciously associate with the transparency of glass. Alternate solutions to a heavy frame exist: centrally vertically pivoting windows that balance the weight of the glass, for example, or top-hung sliding windows such as those developed by Richard Neutra with very filigree frames. Subdividing the large glass so as to create a smaller, thus more easily operable opening, is another option. While this approach presents interesting compositional opportunities, it nonetheless contradicts the original design intention of employing exclusively large glass elements. For the designer, not compromising, i.e. keeping the large glass undivided, often results in abandoning the natural ventilation capability of the envelope and substituting it with a mechanical ventilation system.

The two cases examined below, Jean Prouvé's 1957 temporary school in Villejuif, France, and, müller verdan architekten's 2003 Sporthalle "Gotthelf" in Thun, Switzerland, are two rare instances in which the architectural designers achieve both the "large glass" and the natural ventilation by means of an ingenious and unorthodox move, namely, integrating the natural ventilation directly within building structure members.

The method used for investigating Prouvé's building is based on an analysis of various documentary, publication and archival documents. In the case of the project by müller verdan architekten, the analysis of published materials and plans obtained from the architects is complemented with direct on-site observations and conversations with the designers.

The paper contributes to the literature at the intersection between construction, structure and natural ventilation. It showcases the fertility of systems' integration-based design approaches that have yielded unusual design responses by revisiting the dominant and, arguably, usually unchallenged paradigm of separation of structure and enclosure.

Literature sketch

The topic of natural ventilation integrated into structural elements has received very little attention in the literature, perhaps because it is at the intersection—or arguably, the periphery—of several disciplines. It is absent from five BTES conference proceedings spanning the period 2009-2017, in which the terms "vent" is used only twice, and "venting" and "vented" are each used only once. The literature on natural ventilation [Allard, 1998], [Etheridge, 2012], [Santamouris and Wouters, 2006] tends to focus on general principles. Only the latter of the three references cited here venture into discussing, in its penultimate chapter, various kind of "advanced components for ventilation", none of which have anything to do with the structure. The literature on structure, unsurprisingly, focuses on structural issues, among which serviceability and wind loading, but without typically ever encompassing natural ventilation concerns. A notable exception is Peter Rice's discussion of Jean Prouvé's Maison Tropicale [Rice, 1994]. The contemporary literature on building enclosure typically has adopted the mantra of the separation of enclosure and structure systems. The growing concern with thermal performance favors warm inboard columns that keep thermal bridging issues easily under control. Historically, as illustrated by [Ehrenkrantz, 1989] or Banham's "well-tempered environment", the systems integration literature, has placed all its chips on mechanical systems. This has trickled down in all construction textbooks by Ed Allen, Ching and Iano, and others who discuss integration of mechanical services within trusses, castellated or composite cellular. While the approaches of draining rain water down inside a tubular structural column or forced air within box beams and columns are well known, the concept of letting air through a wide flange or other structural member appears to be a blind spot of the literature except for a few other projects by Prouvé [Huber & Steinegger, 1971], [Beeren, 1981], [Sulzer, 2008]. Ford, in the Detail of Modern Architecture, volume 2, page 383, shows a cut isometry through the structural member described in the next section, but without much context and mistakenly designated as an aluminum extrusion. The architects Sauerbruch & Hutton used holes in twin concrete columns within the double façade of their 1998 Berlin-Adlershof Photonics Center design. One would think that the versatility of casting technology and the ingenuity of 19th century engineers and other tinkerers would have yielded instances of integration of natural ventilation into structural beams or columns, but such examples have eluted us thus far; the catalogue published in 1865 by The Architectural Iron Works of the City of New York—a fac-simile of which was published by [Badger, 1981]—contains cast iron storefront façades that integrated tracks for shutters and other closure elements, but none apparently dedicated to ventilation.

Jean Prouvé's School in Villejuif, 1956

Jean Prouvé (1901 - 1984) designed a temporary school for Villejuif, a southern suburb of Paris, France, in 1956, after relocating in Paris from Nancy and setting up a new company, "Les Constructions Jean Prouvé". There, together with engineer Serge Kétoff, architect Jean Masson and collaborator R. Guidici, he worked on the modular design of the school erected in 1957. A masterful experiment in prefabricated architecture, the school was destined to be temporary—some call it rather hyperbolically "nomade" [nomadic]. The school was indeed dismantled three years only after its erection according to [Schein, 1964]. A positive in the unfortunate fate of this building was that some elements of the building's kit-of-parts were salvaged and re-erected in the form of an architecture office. More recently, thanks to the growing attention received by Prouvé's various creations, the structure was acquired by a gallery, restored, and put for sale. [Seguin, 2015]. A time-lapse video produced by the gallery responsible for the building's second reincarnation strikingly captures the ingenuous kit-of-part quality that infuses the building's exquisite aesthetic.

Prior literature on the school, as, for example, [Mannell, 2006] has mostly focused on its structure with little to none examination of the ventilation aspect of the building. This exposé draws from the writings of [Pascaud, 1957], [Huber & Steinegger, 1971], [Beeren, 1981], [Sulzer, 2008], as well as drawings from the Prouvé archive at the Centre Pompidou in Paris [MNAM-CCI, 2007].

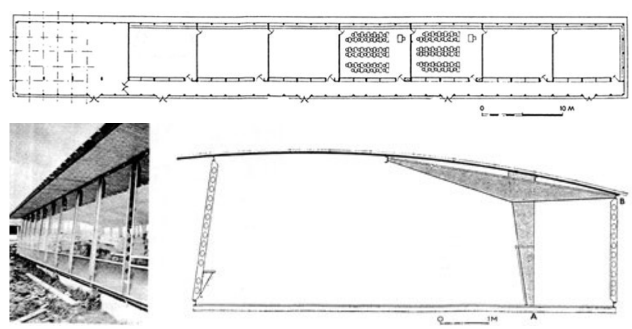

Fig. 1. Top: plan of the typical seven-classroom school with north-facing single loaded corridor. Bottom left: the slanted extensively-glazed south façade shaded by the roof cantilever. Bottom right: Building cross section with the corridor-side "poteau aérateur" tying the T-shaped "béquille" down, and the classroom-side slanted "poteau aérateur" tying the thin wood roof down, thus giving it a gentle curvature.

The temporary school for Villejuif was composed of three similar long bar buildings on an Est-West axis. The typical classroom bar was 75.25 meter long by 8.75 meter wide and was based on a 1.75 meter square grid module (fig.1 top). Along the building's length, seven South-facing classrooms, each five by four modules rectangles (8.75m x 7m) were distributed along a North-facing one-module wide (1.75m) single-loaded corridor terminating into an eight module-long indoor recreation area occupying the whole bar width.

The building iconic cross section visible in fig.1 shows the thin and gently-cambered roof made of wood with its cantilever shading the tilted glass South façade. Over the northern half of the building, the roof was resting on three purlins supported by a graceful asymmetrically T-shaped structural member that Prouvé called the "béquille" [crutch]. The béquilles, which were part of the boundary between the corridor and the classrooms were pin-jointed at their base, and were stabilized by 2.45m tall vertical V-shaped tie-down elements called "poteau aérateur" ("venting post") placed on the module. The tapered T-shaped béquille was made of custom brake-pressed steel plates. The lapping intersection of the twin cross bar elements and the twin leg elements ensured a rigid, moment-carrying connection between the two sets of elements. Structurally, the corridor-side poteau aérateur together with the béquille formed a three-pin half-portal frame that braced the building in the transverse direction. In the long direction, the béquilles were spaced 3.5m on center except for the one-module wide (1.75m) bay marking the entrance to each classroom.

The roof decking was constructed with flat 75cm-wide by 9.80m long and 40 mm thick, 3-ply "contrecollé" wood panels similar to today's cross laminated timber. A tongue-and-groove joint linked adjacent panels together. The roof curvature resulted from flexibly bending the flat wood panels down and bolting them onto a C-shape purlin resting on top of the inward-leaning South-facing poteaux aérateurs. While not the focus of this paper, it is nonetheless worth highlighting another unorthodox engineering move by Prouvé in the way the wood decking shifts position within the building's structural hierarchy. For instance, over the three purlins supported by the béquille, the roof wood panels are mere secondary structure, i.e. decking; in contrast, where they span 3.80m over the classroom, the roof wood panels are now primary structural components insofar that they "actively" connect the "free-standing" South façade's "poteau aérateur", a primary structure member, to the rest of the béquille+-tie-down primary structure. The roof was clad with aluminum panels resting on a layer of wood-fiber-based thermally and acoustically insulating board laid onto the contrecollé wood panels.

The "poteaux aérateurs" and the large fixed glass

All around the building's perimeter, all poteaux aérateurs—the 3.25m-tall ones along the South façade, and the 2.45m-tall ones along the North facade, as well as those of varying heights of the East and West narrow end facades— were located on the 1.75m grid module. Each V-shaped poteau aérateur appear to have been 300mm wide by 150mm deep with a 50mm-wide central flat-bottom and with 37.5mm flanges on each sides onto which the large glazing elements were fastened (see figure 2). The angle between the two legs of the V appear to have been 60 degrees. Radii between the different planes of the profile indicate that they were custom brake-pressed from a blank flat steel sheet probably 450mm wide and possibly as thin as 3 or 4mm-thick.

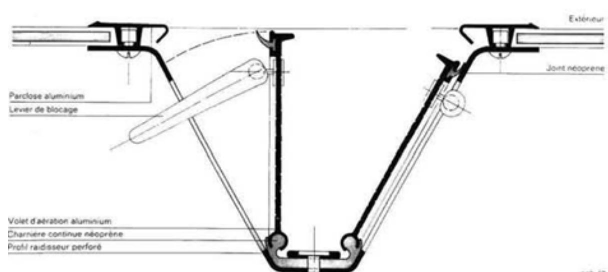

Fig. 2. Horizontal /perpendicular section through the flanged V-shaped "poteau aérateur" [venting post] with the flap on the left in open position.

The facades' single, approximately 147cm-wide clear plate glass elements were continuously edge-clamped to the poteaux aérateurs' flanges by means of an aluminum extrusion and gasket, held into place by small screws exposed to the inside. According to [Beeren, 1981], the glass participated to the in-plane bracing of the façade. The upper edge of the glass elements was discontinuously edge-held by means of two clamping plates bolted into the roof purlin. The 2.45m-tall corridor-side glass façade was vertically subdivided in three equal size glazing lites. Fig.1 shows that the classroom façade was fitted with a continuous shelf-table, the level of which was an estimated 50mm below the level of the horizontal rail that separated the upper, approx. 240cm-tall clear glass panel from the lower, approx. 75cm-tall wired glass panel.

The ventilation function of the poteau aérateur was implemented via a series of circular cutouts—120mm-diameter according to [Pascaud, 1957]— spaced an estimated 205mm on center of both flanges (legs) and slightly off-center of the centerline of each of the V-shape profile legs. This configuration resulted in two sets of nine cutouts (one set per leg/flange) over the height of each corridor façade posts (13 for the classroom-side façade poteaux aérateurs). The drawing number 4N24297 in the Prouvé archive at the Centre Pompidou [MNAM-CCI, 2007] shows an earlier design version of the façade kit-of-parts that included the poteau aérateur alternating with another simpler post without ventilation capability. This design also included a horizontal infill metal panel with a line of round vents located directly under the roof, above the glass, which was subdivided and comprised an operable window.

As visible in fig.2 and fig.3, two outward-opening extruded aluminum flaps, one for each leg of the V, shut the series of venting cutouts close independently from each other. A handle was provided to operate the shutter and let the air in by unlocking it and pushing the shutter open through one of the circular vents.

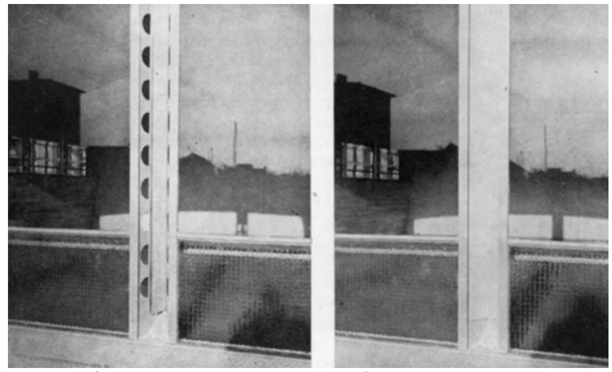

Fig. 3 (left) the poteau aérateur seen from outside with the flaps in open position. (right) flaps in close position.

These shutters were hinged via a fish-mouth profile along one long edge of the extruded flap that "bit" onto a continuous bulbous neoprene extrusion affixed on the flat bottom of the poteau aérateur. On the inside, this flat feature of the venting posts also served as a surface against which the interior partition elements separating adjacent classrooms could abut.

Besides the continuous hinge on inner vertical edge fo the flap, a snap-on gasket along the outer vertical edge provided air and water tightness. The solution at the shorts ends of the flap is not known. It is possible that these were left ungasketted, which would have allowed condensation water on the inside face of the flap to flush out unimpeded.

Müller Verdan's Sporthalle Gotthelf, Thun, 2006

The Zürich-based architecture firm "müller verdan architekten" lead by Rafael Müller and Dominique Verdan completed the award-winning Sporthalle "Gotthelf" on the ground of the school of the same name in Thun, in the canton of Bern, Switzerland in 2006. The sport facility is used by both the school pupils and local sport clubs. Programmatically, it is a "dreifach-Turnhalle", a type of gym space commonly found in Switzerland, that is configurable either as three side-by-side basketball courts separated by hanging nets, or as one handball court along the building's long axis. The rectangular building dimensions are 50 x 40 meters. The sporthalle is sunken into the ground by 3.5 meter below grade level. The height of the volume above grade is 7.50-meter as visible in fig.4. In plan, a continuous ring of circulation runs along the entire rectangular perimeter at grade level and overlooks the court below Its WSW-facing portion is wider and serves as an entrance. It is screened from the sunken court space by a one-story bar volume housing various ancillary spaces and two staircases.

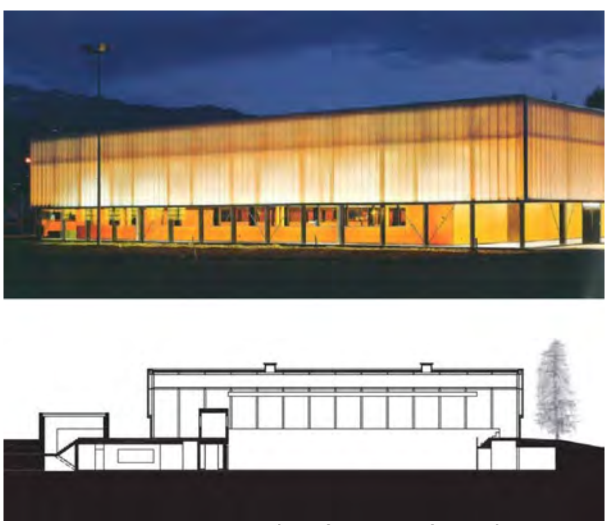

Fig. 4. Top: A view at dusk of the Sporthalle Gotthelf in Thun, Switzerland, by müller verdan Architekten showing the consistent treatment of the two-tiered horizontal composition of its facades. (pho: Alexander Henz). Bottom: Transverse section showing the approx. 5.30-meter clear headroom sunken practice space flanked with the changing rooms with independent stairwell access on one side and the sport equipment storage space on the other side. Two twin exhaust vents are visible at the roof level.

The primary structure of the roof is composed of ten 40-meter span, 1.47meter-deep welded plate girders that rest on HEA240 columns spaced 4.56 meters on-center. As fig 4. shows, in order to achieve a glowing lantern effect consistent across all four facades, the spans immediately adjacent to the two short facades have been designed without the girders but, instead, with beams—identical to those running along the long facades—supported by HEA180 columns spaced 2.83m on-center. The lateral bracing of the building occurs similarly on all four facades via diagonal steel rods terminated by end-fork fittings.

Figure 5 is a section through the WSW-facing long façade. All four facades are similarly composed based on two horizontal bands with minimized vertical joints and HEA 240 (or 180) columns positioned 10 cm inboard of the grade-level 2.2m-tall glass band. This lower transparent band is made of 10/14/6+6 thick insulated glazing units ("IGU") separated by vertical silicone joints aligned with the columns beneath. The upper band is 5.20-meter tall and projects 30 centimeters outward beyond the lower glass band plane. It is composed of 50cm-wide, 40mm-thick, six-cell vertical translucent polycarbonate panels stiffened by means of a polycarbonate stiffener aligned with the proprietary vertical tongue-and-groove joint on the inside.

As indicated in fig.5, wind loads are taken at four locations over the height of the façade. These are, from bottom to top: A) at the grade floor level, B) at the top of the glass band which is also the bottom of the polycarbonate band, C) at the level aligned with the roof girders' lower flange, and, D) along the roof curb edge.

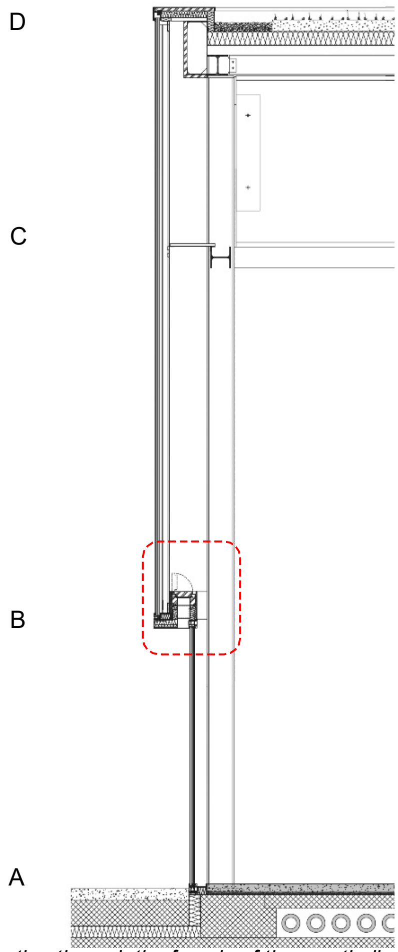

Fig.5. Section through the façade of the sporthalle with A through D wind bracing levels.

Conditions “A”, “B”, and “D” are conditions in which either the glazing units or the polycarbonate panels are continuously supported by means of U-shaped edge profiles. At condition “C”, which is slightly above the middle of the upper polycarbonate band, wind loads on the panels are transmitted via brackets connecting the polycarbonate stiffening profile to the upper flange of rotated horizontal HEA240 (“H”) shapes centered on the primary columns.

Figure 6 shows condition “B” where the air inlets are integrated in the web of the horizontal rotated HEA240 (“H”) girts that are fastened eccentrically 33cm (centerline to centerline) away from the columns.

The thermally-broken horizontal glass framing rail at the top of the IGU is located below the horizontal “H” wind girt and flush with its inside-facing flange. The polycarbonate panels are positioned approx. 85mm in front of the outside-facing flange of the “H” girt, thus concealing it from view from the outside. The panels’ lower edge is housed in a shallow thermally-broken aluminum extrusion.

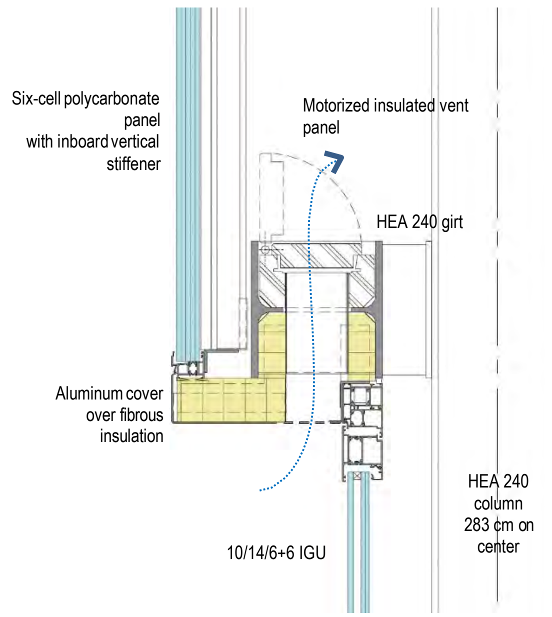

Fig. 6. Detail vertical section of the air inlet cut in the flange of a HEA240 profile at condition “B”. The setback between the lower glass band and the upper translucent polycarbonate band provides a pathway for air to flow into the building.

Flush with the outside vertical face of the panel, a custom brake-pressed 2mm-thick anodized aluminum L-angle covers the 80mm-thick insulation. The portion of this closure angle’s horizontal leg aligned with the web cutouts in the “H” girt above is perforated in order to allow for air passage. An insect screen is also provided. Spray foam insulation fills the voids between the H profile and short stubs of vertical PVC ducts through which the air enters the building. The opening of the air passage is controlled via motorized upward swinging insulated flaps visible on figures 6 and 7.

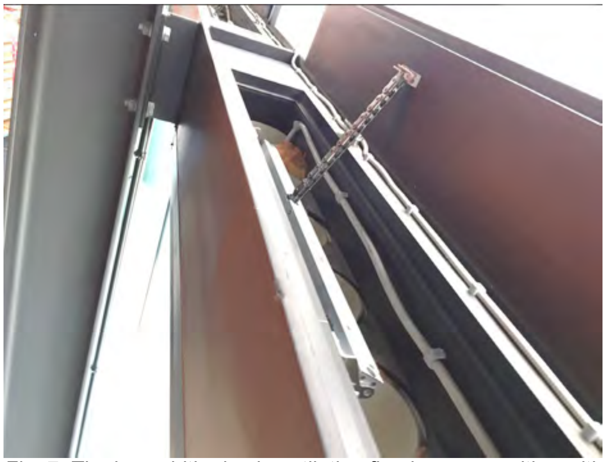

Fig. 7. The bay-width-sized ventilation flap in open position with one of its two 24V motor.

Seventeen 121mm-diameter cutouts, spaced 150 mm on-center are thus created per 2.83m-wide bay along the building's short sides. Each cut out is fitted with a section of a PVC tube with clear 105mm interior diameter. All vents within one bay are capped with a single concealed 201mm-wide by 2556mm-long motorized flap. Similarly twenty seven circular vents are provided per 4.56m bay along the building's long sides. Six pairs of insulated outlet vents are provided at the roof level. Each motorized awning-type vent is 4.32m-long by 42 cm-high, and is protected from rain by a 20cm overhang.

Fig. 8. View from above of two air inlets lined with short PVC stub. The slightly larger diameter cutout in the HEA240 is visible as is some sprayed-in foam insulation filling the lower cavity beneath the shape's web. The perforated closure angle is visible, but the insect screen resting directly only it is washed out in this photo by the author.

Compare and contrast

The integration of natural ventilation within the structure is a very seldom seen design move. For both the projects presented here, this approach was conceived and implemented by the architects themselves without the help of façade consultants.

Prouvé integrated the vents within the primary structure of the school. Mueller and Verdan integrated the vents within the sporthalle's secondary structure that supports the enclosure and braces it against the wind. Both designs, however, approach the provision of openings for ventilation via an analysis of where superfluous material is located within a structural member. Removing material along the neutral fiber of the web of the hot-rolled H-shape girt in the Sporthalle does not hamper the shape's ability to perform as a simply supported horizontal beam resisting wind loads. Similarly, the cutouts along the brake-pressed flanged V-profile of the poteaux aérateurs in Prouvé's school are also positioned along their neutral fiber. This position is optimum when analyzing the poteau aérateur as a slanted beam-column resisting wind loads. The presence of cutouts at the neutral fiber is inconsequential in the poteau aérateur subjected to axial tensile forces. In this case, of course, only the net cross section of material left in the poteau aérateur around a cutout is taken into account to evaluate tensile stresses. For what regards axially compressive forces in the poteau aérateur resulting from an exceptional wind and/or snow loading case, the position of the cutouts along the profile's neutral fiber only very marginally impacted its moment of inertia and radius of gyration, hence its ability to resist buckling.

In the sporthalle, the glass, as most often is the case, plays no structural role. In contrast, as noted by [Beeren, 1981], the glass panels in the temporary school are conceptualized in terms of flat shear planes contributing to the stabilization of the poteaux aérateurs.

Some differences between the two projects reflect differences in design preoccupations at the time of their design. The manually-operated and uninsulated poteau aérateurs of the school is crude compared to the motorized and insulated vent assembly of the sporthalle; similarly, so, the insect screen absent in the school vs. placed directly onto the perforations of the L-shaped aluminum closure element in the sporthalle.

The type of natural ventilation involved in both project is a little bit different. When the door between the classroom and the corridor was closed, the ventilation of the classroom in Villejuif was single-sided ventilation based on stack effect with bidirectional flow. On a cool day, warm indoor air would have flowed out of the vents located above the neutral plane—approximately above the mid-height of the room—and been replaced by incoming fresh outside air entering the room via the cutouts in the lower half of the poteau aérateur. In the case where the classroom door was left open, two ventilation regimes would have occurred. On a windless day, a stack-effect-based ventilation would have resulted due to the asymmetrical cross-section of the building and/or the temperature difference between the South and North façade. Alternatively, on a windy day, a cross-ventilation could have developed, with possibly a jet region in the part of the classroom directly aligned with the classroom door, as well as a recirculation region off of it. With its inlets in the façade and its outlets at the roof level, the sporthalle is naturally ventilated by stack-effect on a windless day. While this has neither been experimentally verified nor computationally modeled, one can hypothesize that there probably are particular temperature, wind direction and velocity conditions under which some of some inlets—tentatively, those near downwind corners—that occasionally act as air outlets due to their being temporarily within regions with lower negative pressures than those near the middle of the roof where the roof outlets are located.

In the temporary school, the classroom occupants would have been quite directly exposed to the incoming air. Conversely, in the sporthalle, the inlet vents are positioned slightly above the occupied level and therefore impact the building first and foremost. Its occupants are only indirectly affected. There are both advantages and disadvantages in terms of occupants' thermal comfort with both configurations throughout the seasons. While direct exposure to cold drafts would be undesirable, conversely, increased convective cooling via air drafts would be welcome to help offset an elevated interior air temperature, the solar radiation transmitted through the glass and the inward radiation of heat absorbed by the sunlit glass. In the school, opening the south-facing vents let the sun penetrate directly into the room around noon time. In the sporthalle, the glass band is shaded somewhat due to its setback. At lower sun angles on windless days, it is likely that the convection resulting from the heating up of the outermost pane of glass can be "sucked in" the inlets, thus tapping into a pre-heating effect potentially beneficial during cool days.

Both designs took into consideration the possibility of ventilating under light rain conditions. The façade inlets and roof outlets in the sporthalle are shielded locally by the façade setback and a bespoke overhang, respectively. In the temporary school, the wood roof projecting out over the tilted south façade provided a global protection of the vents against rain, arguably more efficiently so for the upper ones than the lower ones.

Visually, in the sporthalle, the air inlets, which are inserted flush between the upper edges of the HEA240 flanges, are completely concealed. The flaps, when in their open position, are also quite inconspicuous. In the temporary school, the ventilation scheme was also very discreet when looking at the façade tangentially from outside. In contrast, the experience of the opened vents from inside the classroom would have been quite striking with its two sets of "spots" of light dotting the height of the poteaux aérateurs.

Conclusion

What makes Prouvé's temporary school in Villejuif and Müller Verdan Architekten's sporthalle "Gotthelf" remarkable is not only the rarity of their approach to integrating natural ventilation within structural members, but also how they, in doing so, challenge the prevailing paradigm of separation between structure and enclosure. As such they are representatives of a unique "species" within the broader genre encompassing facades of buildings with skeletal structure.

These two projects point to a unique approach to natural ventilation that opens new design possibilities. They are a reminder that the dichotomy between structure and enclosure underlying generic curtain wall construction, if instituted into a dogma, ought to be questioned. The argument in favor of the separation between structure and enclosure typically has to do with the issue of the different of tolerance of construction of structure and building enclosure. In the two cases presented here, however, the designers overcome this otherwise valid constraint by simply associating the precision demanded in terms of air- and water-tightness of an operable vent system with that of easily achievable precise cutouts along the web of a structural member, itself manufactured with precision.

Jean Prouvé's integration of natural ventilation within the *primary* structure of the school seems like a heroic move made possible by the more lax thermal insulation requirements at the time. müller verdan architekten integrate the natural ventilation of the sporthalle in its *secondary* structure with great elegance. The column remains inboard and warm. This architect-driven design inspiringly navigates the conflicting demands placed on contemporary building enclosures. Its ingenuity sends an hopeful message in an age of BIM-powered off-the-shelf product-picking.

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Writing-in-Action: Teaching Technical Writing through the Lens of the Reflective Practitioner

Christopher L. Cosper
Ferris State University

Introduction

Although architects are known as visual thinkers, they also need to be effective writers. Architecture programs have struggled to find effective ways to teach future architects how to write well. This paper is the first step in a proposed research project built on the research of Donald Schön, who developed the concept of the "reflective practitioner." This paper proposes a pedagogical approach in which students are introduced to substantial, professional reflection in writing, deploying what this author calls the "writing-in-action" process.

Writing: A critical skill for architects

For many established practitioners or academics, the need to write well is obvious. Practitioners know the merit of a well-written letter to a client, the need for elegantly written marketing materials, or perhaps the lawsuit-preventing value of a clear and complete field report. For those of us in academe, quality writing is essential for our scholarship and our tenure and promotion applications.

Surveys of employers in myriad fields demonstrate that businesses need employees who can communicate well. In most fields, this means speaking and writing well.[1]

Architects, of course, must be able to communicate visually, but the ability to communicate visually does not allow architects to abdicate their responsibility to speak and write well. In fact, some have argued that the relationship between architectural images and the written word is critical to architects realizing the full potential of their designs.[2]

Looking toward the future—a time of growing population, diminishing resources, and increasingly disruptive climate change—the practice of architecture will be increasingly difficult, requiring a level of mastery significantly advanced from 20th century standards. How will architects of the future address these difficulties? According to Oklahoma State University professors Tom Spector and Rebecca Damron, architects of the future will practice architecture in a fundamentally different way. They wrote, "The concept of the architect as Master Builder is disappearing, transforming into that of the architect as Master of Information."[3] This critical information will be gathered, analyzed, and disseminated largely through the writing process.

Writing manuals for architects

How are the architects of today being taught to write? This author started his research with an examination of some of the most popular writing manuals created specifically for architects and others in the design and construction industries. He examined the purpose and organization of the writing manuals, looking specifically for examples of reflective thinking that mirror Donald Schön's ideas of reflective practice.

Writing for Design Professionals

Stephen A. Kliment's *Writing for Design Professionals* is a scenario-based writing manual organized primarily by writing genre (e.g. "Marketing Correspondence," "Proposals," and "Writing in Academe").[4]

Writing for Design Professionals begins with a chapter on eight writing principles (with two additional sections). The final principle, "When to Break the Rules," is the closest the book comes to describing a writer's process. In that section, Kliment wrote:

> [W]hen writing, do not let rules or guidelines get in the way of **spontaneous expression**. If a snappy word, turn of phrase, or rearrangement of material strikes your fancy and in your view adds to the strength or sparkle of your message, trust your **intuition** and go for it.[5]

Both "spontaneous expression" and "intuition" echo Schön's concept of knowing-in-action, which will be explored later in this paper.

The Architect's Guide to Writing

Bill Schmalz's *The Architect's Guide to Writing* is a grammar and style manual, something of a Strunk and White for the designer.[6] Schmalz's book is basically arranged in two parts: grammar (e.g. chapters titled "The Slippery Sidewalks of Grammar," "Words and Their Meanings," and "The Punctuation Toolbox: Terminators") and style (e.g. chapters titled "Writing Numbers," "Names and Titles," and "Developing a Lean Writing Style).[7]

Although Schmalz's book is well organized and full of useful tips, *The Architect's Guide to Writing* is not very reflective in approach. Even the chapter titled "Editing Your Draft," which begs for a component of reflection, is a step-by-step set of instructions devoid of any sense of meta-thinking.

Writing Architecture

Yale University professor Carter Wiseman's *Writing Architecture* is primarily organized around six writing genres (persuasion, criticism, scholarship, literature, presentation, and professional communication).[8]

Perhaps the most interesting chapter is the first, titled "Structure: Getting Your Thoughts in a Row." In this chapter, Wiseman discussed process with some intriguing hints of a reflective process. For example, Wiseman argued for the use of notecards to organize ideas, which he admitted was "old-fashioned."[9] However, Wiseman suggested that the physical quality of the cards helps a writer to organize a series of ideas.[10] Wiseman also discussed word processing software and noted, "One disadvantage of the process is that we no longer have paper records to show how a piece of writing developed."[11] This prevents, in Schönian terms, reflecting on reflection-in-action, which will be discussed later.

Thinking more broadly, Wiseman also discussed the role of writing in architectural education. Echoing Spector and Damron, Wiseman argued, "Writing on architecture should be inseparable from the design process itself."[12] Assuming Wiseman is correct, and writing is an inseparable part of the design process, one should be able to teach writing as design is taught—that is. by engaging the reflective practitioner.

How Architects Write

Spector and Damron's *How Architects Write* starts with a chapter titled "How (and Why) Architects Write" followed by a series of chapters devoted to specific writing genres (e.g. "Design Journals," "History Term Papers," and "Business Documents").[13]

Of the writing manuals for architects cited in this paper, *How Architects Write* is the only one that directly references Schön. The reference, which appears at the beginning of "Chapter 2: Design Journals," is brief. Spector and Damron wrote, "Donald Schön calls design a 'reflective conversation with the situation.'"[14]

Given the direct reference to Schön, it is not surprising that Spector and Damron devote four pages to "Critical Reflection" in a chapter devoted to "Design Journals."[15] In this section, Spector and Damron argue that architects have much to learn from what they observe and from their reflections on those observations

Like the previously mentioned authors, Spector and Damron primarily organize their book by writing genres. Germane to this paper, Spector and Damron devote a chapter to "Research Reports and Analyses," but the chapter is disappointing from a Schönian perspective. Rather than instructing students how to write a report, the authors catalog a series of report types, starting with architectural programs, and describe what content may be appropriate for each report.

Summary of writing manuals

The above-referenced writing manuals provide much good advice (students and weaker writers would be well advised to purchase one and follow it). However, they are incomplete. Just as a book of architectural detailing is helpful but cannot teach one how to design a building, the writing manuals provide detail-level advice but critically little help with the process of writing "in the moment," or what Schön calls "knowing-in-action."

Teaching writing to architecture students

As part of an ongoing research project, this author will continue to examine past research on how architecture students are taught to write. At this point, however, a couple of points are warranted, based on preliminary research.

First, many of the articles addressing writing in architecture school appear to be a "one and done"—that is, a single published article (maybe two) that discuss writing in studio and/or a support class. This suggests that improving writing education in architecture schools may be a lonely, fatiguing, and often unrewarding battle. The exception appears to be a series of articles by Peter Medway, a professor of linguistics who studied how professionals communicate (among other subjects).

Second, considering the importance of Schön in the field of writing education and Schön's enthusiasm for studio-based education, it strikes this author as ironic that no one appears to have put the two ideas together—that is, using Schön's ideas to teach writing to architecture students.

How are architecture students currently taught writing? In 2010, Damron and Spector16 examined writing programs at various architecture schools. Efforts to improve writing in architecture schools have faltered, Damron and Spector argued, because "architectural education…has long held the role of the written word in design thinking at a certain reserve."17 Looking at writing programs across design fields (including architecture), Damron and Spector found the following efforts:

• Ball State University—the College of Architecture and Planning, led by Dean Robert Fisher, participated in a Writing Across the Curriculum (WAC) program.

• Oklahoma State University—faculty in Design, Housing, and Merchandising worked with the English Department to add writing assignments to discipline-specific courses.

• Oregon State University—graphic design students take a 4000-level class that "draws parallels between the writing process and the design process."

• University of Minnesota—the landscape architecture program worked with the Center for Writing to determine if writing assignments should be part of design studio.

• Virginia Tech—participated in a WAC program.[18]

Examining the above-listed programs, Damron and Spector observed:

> All of the programs we investigated had two things in common. First, they were paired with and/or co-taught by English departments and Writing Centers. Second, their emphasis was on "writing to enhance the design process" rather than to enhance job prospects after graduation.[19]

Efforts to improve writing in architecture schools are taking place in schools beyond those listed by Damron and Spector. Some of the most provocative research occurred at Iowa State University, where professors Thomas Leslie and Ann Munson experimented with a workshop designed specifically to improve architecture students' writing. Looking at the consistently poor writing quality of architecture students at their institution, Leslie and Munson wrote, "Both of us believed that the lack of writing ability in our department was not due to the students, but was instead a shortcoming in the curricular structure and philosophical aims of the program itself."[20]

Leslie and Munson started their exploration of writing in architecture schools by arguing that, as a group, architects are not the strongest writers. They argued, "Usually, architects are by definition visual thinkers, a group that has well-known problems with the linear nature of thought required by writing."[21] This is a point explored in more depth in an earlier paper by Gerald Grow.[22]

How, then, to address the problem? Leslie and Munson looked to the core of architectural education, the design studio. They wrote, "[W]e realized that writing could be taught in a format similar to studio, with time for one-on-one critiques, peer discussions, and a focus on development in addition to product."[23] This decision was anchored in their belief that "The craft of editing is remarkably similar to the discipline of re-designing."[24]

Leslie and Munson performed screen editing for all students to review, using the "track changes" function of the word processing software.[25] This form of live coaching is very similar to the coaching provided by a studio mentor to his student in Schön's narrative of a studio crit session. In both cases, students and teachers are engaging in what Leslie and Munson call the "process-rich realm of design."[26]

Donald Schön and the reflective practitioner[27]

Schön's research into the reflective practitioner stemmed from his belief that traditional research lacked relevance while traditional practice lacked rigor. According to Schön, the addition of professional schools to the traditional university, with its liberal arts and hard science focus, led to a "radical separation between research and practice" because research in the traditional university courses was isolated from the messiness inherent in professional practice.[28] Looking at the idea of addressing problems that are either (A) narrow, focused, but manageable or (B) broad, realistic, but uncontrollable, Schön wrote:

> The dilemma depends, I believe, upon a particular epistemology built into the modern research university, and, along with this, on our discovery of the increasing salience of certain "indeterminate zones" of practice—uncertainty, complexity, uniqueness, conflict—which fall outside the categories of that epistemology.[29]

The messiness—the "uncertainty, complexity, uniqueness, conflict"—of practice stands in stark contrast to the precision of what Schön calls "technical rationality," a kind of process that is "instrumental, consisting in adjusting technical means to ends that are clear, fixed, and internally consistent."[30]

Schön argues that technical rationality works in clean, laboratory conditions but has limited value in messy, complex, real-world scenarios. For example, civil engineers can use the technical rationality of their education to figure out how to build, but they are less well-equipped to argue with absolute certainty about why or even if something should be built.[31] The latter two questions involve "a complex and ill-defined mélange of topographical, financial, economic, environmental, and political factors" that technical rationality is poorly situated to address.[32]

Technical rationality certainly has its place, however. Schön argues that technical rationality "becomes professional when it is based on the science or systematic knowledge produced by the schools of higher learning."[33] Many in the architecture, including architect Stephen Kieran, argue that more, not less, technical rationality is needed—specifically new knowledge in the field known broadly as "building science." As concerns about global climate change mount and client expectations of performance increase, architects will face an increasing number of measurable markers of performance. Likewise, the emergence of big data—the ability to see formerly invisible trends with the use of massive data sets—promises to change the design and management of future facilities.

For the reasons discussed above, architecture programs occupy a disadvantaged position in the modern research university. Although university architecture programs are more than 150 years old—the department of architecture at MIT was founded in 1868—architectural scholarship is not generally well-respected in the university community. The discipline of architecture, save the field of building science, is not terribly close to basic science, which is often considered the raison d'être of the modern research university. As Donald Schön observed, "The greater one's proximity to basic science, as a rule, the higher one's academic status."[34] Summarizing architecture's position, Schön wrote:

> Architecture is an established profession charged with important social functions, but it is also a fine art; and the arts tend to sit uneasily in the contemporary research university. Although some schools of architecture are free-standing institutions, most exist within a university, where they tend to be marginal, isolated, and of dubious status.[35]

Despite the less-than-sterling reputation of architectural scholarship, architectural education is often considered first rate. In Educating the Reflective Practitioner, Donald Schön argued that architectural education is the paragon of professional education and is well-suited for teaching students about the messiness of professional practice.

Schön's Reflective Practitioner

To understand Schön's concept of the reflective practitioner, one must understand key terms including "knowing-in-action," "reflection-in-action," and "reflecting on reflection-in-action."

Knowing-in-action is the "spontaneous, skillful execution of [a] performance" where "the knowing is in the action."[36] A bicyclist who makes countless instantaneous adjustments to keep the bicycle upright is demonstrating knowing-in-action.[37] Likewise, an architect who assembles a series of spaces on a floor plan—rotating, stretching, and re-assembling them so they work together—is demonstrating knowing-in-action.

Reflection-in-action occurs when the "familiar routine" of knowing-in-action is interrupted by a "surprise" moment—whether that surprise is good, ill, or neutral.[38] For example, a bicyclist hits a pothole—a new experience—and either stays on course or crashes the bicycle. Either way, the bicyclist has an opportunity for reflection-in-action to determine what was done correctly (or incorrectly) and, more importantly, what needs to happen the next time a pothole is encountered. Similarly, an architect working on a floor plan may discover that a single-loaded corridor provides an opportunity to provide daylight and fresh air to the corridor. This "surprise" enables the architect to consider space planning in a new way.

Reflecting on reflection-in-action is Schön's term for meta-thinking, or thinking about one's thinking. The bicyclist who is surprised by the pothole might consider other potential road hazards and how they could be addressed even before they are encountered. The architect who "discovers" the single-loaded corridor may want to revise his or her design process so other obvious (after the fact) opportunities are not missed on future projects.

Reflecting on reflection-in-action has the potential to be the epistemological basis of inquiry in a broad range of fields, including not only design fields such as architecture, but also other practice-based fields as diverse as counseling and music education, where the artistry of the professional is critical to success.[39]

Writing is one such practice-based field. The process of writing results in a definitive product—a text which can be analyzed and critiqued. Because of this, teaching writing should mirror teaching studio closely enough that the processes Schön observed in the studio crit should work for a writing crit.

Some thoughts on the limits of "reflection"

Reflection in its myriad forms (reflective essays, reflective journals, etc.) became trendy in educational circles, as Schön himself acknowledged in the introduction to his book The Reflective Turn, which is a series of case

studies from a wide range of scholars who follow Schön's philosophy.[40]

As often occurs in education circles, many educators bought into the hype surrounding reflection, but fewer understood the substance. The now ubiquitous reflective essay is a case-in-point. Assigned outside the context of professional practice—or some other meaningful intellectual construction—the reflective essay often becomes a vapid exercise in which a student of limited experience explores that limited experience instead of engaging deeply with a difficult concept.[41]

In his article "Schooling Heidegger: on being in teaching," education professor J.F. Donnelly explored the limits of Schön's framework of the reflective practitioner, specifically in relationship to education. Concerning the activities of many educators, including the "design" of curricula, Donnelly wrote:

> But it is questionable whether such activity has much in common with the Schönian design studio, or even musical performance. These practices involve immediate feedback and direct, almost sensuous, immersion in the act of design.[42]

Building his argument that reflective practice may not be meaningful for teachers, Donnelly excerpted the following from Educating the Reflective Practitioner.

> [The] designer [is] one who converts indeterminate situations to determinate ones. Beginning with situations that are at least in part uncertain, ill defined, and incoherent…

> designers construct and impose a coherence of their own.[43]

While the abovementioned quote suggests that reflective practice may not be right for curriculum design, it may be well aligned with writing. Although Donnelly is a critic of Schön, the framework of his criticism tends to confirm, rather than contradict, the potential for substantive reflective practice in the teaching of writing.

Research proposal

The proposed research project has three parts.

Part I: Teach writing-in-action skills to design studio students

This author plans an immediate intervention with a fourth-year design studio course during which the writing-in-action process will be introduced. The process will work as follows:

1. Students will be asked to justify their capstone project in writing.

2. Students will be asked to bring a partially completed draft to the studio (much like a progress print of a current design).

3. Using a carefully developed script, the instructor will explain the writing-in-action process to each student.

4. Working individually with each student, the instructor will coach the student through the composition process, asking questions and making comments as the students refine and expand their essays.

In future years, writing samples from the beginning of the semester (before the writing-in-action process is introduced) will be compared to papers produced at the end of the semester, providing evidence of pre- and post-intervention conditions.

Part II: Teach writing-in-action skills to design studio students

Following Carter Wiseman, and Tom Spector and Rebecca Damron, this author believes that writing is an integral part of the design process. Base on the actions discussed in Part I above, students will be required to submit progress writings as part of their capstone design. The author hopes that these writings will improve the quality of the design projects while leading to more substantive discussions during final reviews.

Part III: Test the writing-in-action process in a general education English course

Because the architecture program at Ferris State University is small, the number of potential test subjects is small. Furthermore, the author believes, based on the literature review, that it is imperative to immediately reframe the capstone design studio to integrate writing into the capstone design experience. Given the importance of the material, the author believes that the use of a control group would be unethical.

However, the author is less sure about the Writing-in-Action approach for a more general audience. Thus, the author is working with a faculty member in the English Department to develop a writing-in-action intervention for a general education English course. Such an approach would allow for the ethical creation of subject and control groups.

Conclusion

Writing is as critical skill for architects, but it is a skill that has been taught haphazardly across our architecture schools. Fortunately, architecture schools are well versed in studio teaching, the epitome of Donald Schön's concept of the reflective practitioner. Thus, a Schönian approach to teaching writing would seem like a logical approach. The research plan proposed in this paper is designed to test that concept.

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Reducing Building Water Use Intensity (WUI): Tools for Academia and Practice

Courtney Crosson
University of Arizona

Abstract

Recent prolonged droughts have increased water awareness worldwide, yet limited progress has been made to expand integrated building solutions. This paper investigates the critical tools needed by architectural practice and academia to support water efficient pedagogy and design. A water auditing protocol was developed, tested, and standardized during an undergraduate/graduate architecture water efficiency course over 2017-19. This paper presents the case study implementation of this tool for water use reduction in a commercial building in Tucson, Arizona. The paper ultimately evaluates the success of this new tool through four outcomes from the case study. First, a cutting-edge, service-learning pedagogical model was developed to teach water efficient design to architecture students. Second, the local water service provider was given a new tool for future commercial building owner compliance in the case of a Level 2 Drought declaration. Third, the water audit provided the building owner with cost-effective strategies to accomplish use reduction. Finally, the architectural professional community received a new tool for water efficient design and retrofit. The paper presents a tool for architecture students and professionals to expand integrated water efficient design for commercial buildings.

Introduction

Water awareness has increased with prolonged droughts in arid regions worldwide. Yet, the building profession has limited post-occupancy protocols and tools to evaluate advancements in integrated building solutions. Unlike energy, there are no certified, comprehensive auditing protocols for water. The apparent barrier had been expensive and invasive water metering technology. Using new, inexpensive electromagnetic metering technology, this research developed, tested, and standardized a water auditing protocol for commercial buildings. This study was conducted in Tucson, Arizona, a desert city in the Southwestern United States that has been under drought advisories since 1990. The city's water utility, Tucson Water, currently uses national use percentages to estimate fixture-level water use. This study provides a protocol and tool for architecture students to collect and analyze data to evaluate local water use at the fixture-level. Auditing and analysis is particularly important in drought prone cities to provide the data to determine the most efficacious water efficient building strategies for municipal investments.

In order to successfully understand and implement water efficient design and retrofit, the architectural profession needs standardized and accessible protocols and tools. To address this critical academic and professional need, a partnership was formed in 2017 between a regional architecture and engineering firm, a district member of a national energy and water efficiency organization (the 2030 District), local building owners signatories of that organization, and a undergraduate/graduate architecture water efficiency course. This public-private-academic partnership mobilized unique and complementary skills toward developing, testing, and disseminating a water auditing protocol. The district partner identified building owners and oversaw final efficiency measure implementation. The professional partners provided critical, detailed feedback to ensure usability of the protocol for national practice. The architecture course developed and tested the auditing process during 2017-19. Research findings were analyzed by the author with the integral involvement of professional partners.

This paper examines this new water auditing protocol through four goals: educate the next generation of architects to address water efficiency through design, expand community capacity, reduce commercial building water use, and increase professional tools. The paper begins with a discussion of past obstacles and new promising technology for water auditing. Next, the context of Southwestern drought and commercial building use is provided. Then, the methodology of the four module water auditing protocol is outlined. A case study audit of the Community Food Bank of Southern Arizona is provided to illustrate to auditing process. Findings from the testing of the protocol are analyzed. Finally, conclusions are shared for the new auditing tool to be used by the architectural profession and academy.

Past Obstacles and New Promise in Water Auditing Technology

The Need for Fixture-Level Auditing to Determine Regional Use Behavior

Currently, building water consumption by type of use is almost exclusively examined through self-reporting behavior methods, most commonly in residential settings.[1 2 3 4 5] Several pragmatic barriers have made the more precise method of fixture-level data collection costly, invasive, and rare. Unlike energy, water infrastructure is difficult to access and modify once a building is constructed. Water sub-metering technology has required in-pipe installation, usually during construction when pipes are exposed and empty. Today, most buildings have one water meter with no differentiation between indoor/outdoor use or fixtures. As a result of this technology barrier and scant data, no comprehensive, standardize auditing protocol exists for water.[6]

A new suite of inexpensive electromagnetic water metering technology has recently provided new promise for fixture data collection. The FLUID Water Meter clamps onto pipes and reads individual fixtures through flow signatures (e.g. a toilet flush registers as a different flow velocity and amount than handwashing). This project used this new technology to develop, test, and standardize a water auditing protocol for commercial buildings through an undergraduate / graduate architecture water efficiency course.

Existing Water Assessment Programs: National and Local

Programs like Architecture 2030 and the 2030 District set goals for water (and energy) reduction. However, few tools are provided to support subscribers to reach these targets. The Environmental Protection Agency (EPA) created an “Energy Portfolio Manager” with a short section on overall water consumption.[7] The United States Green Building Council (USGBC)’s Leadership in Energy and Environmental Design (LEED) provides water reduction goals broken into indoor, outdoor, and process water use. The required calculations to obtain “Water Efficiency” points in the LEED system, are based on projected national averages and occupancy numbers under the Environmental Protection Act (EPAct).[8 9] Greater precision in average water use by the variations of building type and regional climate is needed.

In Tucson, the water utility, Tucson Water, conducts self-reporting audits with residential customers whose water bills have experienced unexpected spikes. During these audits, no fixture-level data is collected – rather estimates are made on national averages. Tucson does not currently have data specific to regional use by fixture.[10]

The Challenge: Decreasing Commercial Building Potable Water Use in the Face of Increasing Drought

The United States Southwest is experiencing what some believe to be the worst drought in 500 years.[11] Studies have projected a more arid climate and higher risk of water shortages in the region over the coming century.[12] While water resources become scarce, population in the region has grown considerably in the past decades and the growth is expected to continue. In Arizona, the population is anticipated to increase by 25% between the years 2012 and 2030, with a 30% growth in Phoenix Metro region and a 17% increase in Tucson Metro. The Arizona Department of Water Resources (ADWR) determined that in 25 years Arizona will need an additional 900k acre feet of water to meet projected shortages. In 100 years, Arizona's water demand will outpace supply by about 3.2 million acre feet.[13] Having a reliable source of water is key for enabling sustainable and equitable development. In this context, this study seeks to standardize a method to evaluate success in building water efficiency implementations.

In response to these water realities Tucson Water devised a 2012 Drought Preparedness and Response Plan.[14] The plan is structured in four drought responsive levels beginning with Stage 1 and increasing in severity to Stage 4. Currently, Tucson is at a Stage 1 drought and has been at this rating for several years. Declaration of Stage 2 drought depends on Colorado River conditions and is made by the Tucson City Manager with advice by the Director of Tucson Water.

The plan states that if Stage 2 is declared, all commercial and industrial customers using an average of over 325 centrum cubic feet per month (or 2.5 million gallons per year) need to conduct a self-audit of water use at the facility and develop a conservation plan. Nationally, commercial buildings represent 29% of water use compared with a slightly lower 25% in Tucson.[15] [16] Overall, commercial buildings rank as the highest single users of water in Tucson. Although numerous studies exist at the scale of broad urban water management and narrow residential behavior, little research has examined water use at a fixture-level, particularly for commercial buildings.[17] [18] Due to their large occupancy and square footage, thus usage, these buildings provide one of the greatest opportunities for water reductions.

Tucson Water has begun to offer free commercial water audits in preparation for the Stage 2 declaration.[19] Currently, these audits estimate fixture-level use by using national estimated ratios. This project worked with Tucson Water to enhance this program through a systematic water auditing procedure that measures fixture-level use. Students worked with volunteer commercial buildings to hone the process and technological use by lay people. The water auditing protocol discussed in this article was planned with Tucson Water to be one piece of Tucson's ongoing efforts to ensure that the growing metropolitan area has a long-term reliable source of water for its expanding populations.

Methods: A Comprehensive Water Auditing Protocol for Commercial Buildings in Four Modules

The water auditing protocol has four modules: (1) conservation, (2) passive systems, (3) active systems, and (4) integrated strategy implementation (*Figure 1*). Each of the first three modules are composed of a baseline assessment, a quantitative and qualitative auditing process, and strategy recommendations. In the fourth module, a comprehensive strategy implementation plan is provided to the building owner. All steps were carried out through the Water Efficiency in Buildings course (ARCH 461/561) at University of Arizona. In the process of testing and refining this water auditing protocol, students learned the building fixtures with the greatest average demands, daily and seasonal variations in these fixtures use, regional variations in use, and building owner and users' perception of their use. Students devised comprehensive strategies to reduce indoor and outdoor building water use together. They then worked with owners and occupants to create a feasible and measureable plan for immediate implementation. Before the project began, the professor conducted a one month pilot study to ensure that the water meters were appropriately placed and correctly transmitting data. Additionally, written consent from the commercial building owner was acquired to release their hourly water meter data from Tucson Water to the professor for educational purposes. The four modules are outlined below using the case study audit of the Community Food Bank of Southern Arizona.

	TIME	FOCUS OF AUDIT	DESIGN APPLICATION
Module 1	Month 1	Indoor Water Use	Conservation Design
Module 2	Month 2	Outdoor Water Use	Passive Design
Module 3	Month 3	Process Water Use	Active Design
Module 4	Month 4	Integrated Strategies	Technology and Energy-Water Nexus

Fig. 1. Water Auditing Protocol with Four Modules

Module 1: Indoor Water Audit / Conservation Design

The first step of the water auditing protocol is to establish a baseline use by which future efficiency gains can be measured. The baseline contains both quantitative numbers and qualitative behaviors. In the first month of the course, students visit the commercial building to interview owners and users on occupancy patterns and use behavior and count and obtain flow rate specifications for all building fixtures. The main learning objective during the baseline step is for students to understand how to measure each type of fixture use, average user behaviors by fixture use, and the impact of basic conservation measures.

Demand Calculation: Students hold an interview with the building manager and key occupants. During this interview, occupancy hours are recorded for the average workday and over a year with holidays and seasonal use patterns. A fulltime occupancy equivalent (FTE) and visitor occupancy hours are computed with this information. During this interview, floor plans are used by the building manager to identify all indoor fixtures for the students. Students then record the installed flow rates of these fixtures either through time testing or through written specifications. With this information, the LEED indoor water prerequisite procedures are followed to calculate baseline water demand for the building (indoor) based on the national averages under the Environmental Protection Act (EPAct).[20]

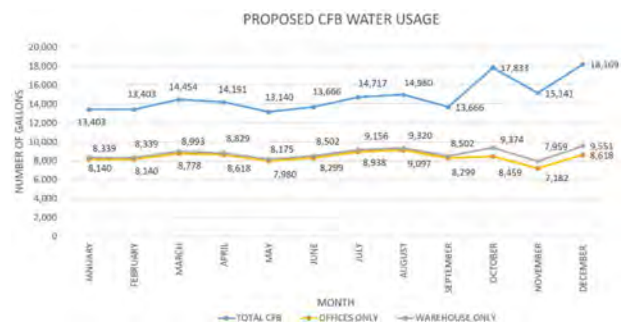

Fig. 2. Module 1: Indoor Water Budget (Credit students: T. Alaqtum, S. Ghaemi, M. Wilke, K. Chaikunpon, M. Torres)

Strategy Formation: The calculated LEED and EPAct baseline is then compared with current fixtures and then higher efficiency fixtures to project total baseline, current, and potential potable water use reduction. Total percentage reductions are calculated between baseline, current use, and potential reduction. In the case study example of the Community Food Bank of Southern Arizona (*Figure 2)*, students recommend that compost toilets be built for visitors to the garden. Other suggested conservation measures included installing more efficient-fixtures and using the Tucson Water rebate to exchange the current inefficient top-loading washing machine for a front loading machine. The strategies led to an overall 67% baseline reduction.

Module 2: Outdoor Water Audit / Passive Systems Design

In the second month of the course, students completed a site water audit for outdoor uses and consider passive measures to decrease potable water use. Passive rainwater harvesting systems are designed to retain water until it can be naturally absorbed into the land (swales and pervious pavers are common passive strategies). Water harvested passively offsets irrigation demands, whereas the water harvested through active systems can be stored and employed to meet non-potable and potable demands, depending on the treatment level achieved.

Demand Calculation: For this module, students complete a site plan, locating various vegetation species throughout the site. To calculate outdoor water demand, the students then use species factors, microclimate factors, and density factors to project vegetation demand. Students fill out LEED credits for outdoor water use with these numbers.

Fig. 3. Module 2: Passive Water Design Baseline and New (Credit students: T. Alaqtum, S. Ghaemi, M. Wilke, K. Chaikunpon, M. Torres)

Strategy Formation: To calculate potential new sources of water (through passive strategies), students then use the site plan, average monthly precipitation, and impervious and pervious material run-off coefficients to calculate possible water collection volumes. Students consider both rainwater harvesting and native and adaptive species as strategies to passively reduce water use outdoors. Students complete a water budget for outside supply and demand to determine water reduction percentage. In the case study, student used the water budget to maximize passive water harvesting via a retrofit to the existing parking lot for flood mitigation and heat island reduction (*Figure 3)*.

Module 3: Process Water Audit / Active Systems Design

In the third month of the course, students complete a process water audit with qualitative and quantitative tools. Active measures were considered as means to reduce water use. Active systems to decrease potable water use include rainwater harvesting, gray water use, and condensate recovery. Active rainwater harvesting collects, cleans, and stores rainwater for reuse (tanks and cisterns are prevalent elements of active harvesting). In this module, student build on their knowledge of indoor fixture use and outdoor use by adding a specific understanding of process water and determining how active systems can address these potable water demands.

Demand Calculation: The students examine process water systems. The students create a water budget based on this data. Students also complete calculations to determine the amount of water that can be actively harvested from the process water systems for reuse (e.g. condensate recovery from air handling units and bleed-off from evaporative coolers).

Strategy Formation: Then, students identify the indoor, outdoor, and process water demands (calculations form Module 1, 2, and 3) where active systems could be employed to replace potable water use. Active measures, along with the previously applied passive and conservation measures are applied. From this water budget, a total potential reduction is calculated.

Students compare the FLUID real-time water meter fixture-level data, the Tucson Water hourly water meter data, and their demand calculations from module 1, 2, and 3. Students reflect on the discrepancies and accuracies of these datasets. Student reflect on the challenges of designing a building to preform in a predictive manner and what they can do as designers to decrease this uncertainty. Disparities between total predicted use and actual use are usually found. This comparison gives students an important first-hand lesson in the margin of error between predicted use and operational use over time – a pitfall in designing sustainable buildings to perform for average populations in average situations.

In the case study, students aimed to size the active harvesting system so that the garden survived on rainwater only (*Figure 4)*. They recommended both expanding the roof catchment given their analysis that the cistern was never full. Students also recommended both turning garden beds fallow in the summer and reducing the number of beds so that the garden demand matched the available active system rainwater supply.

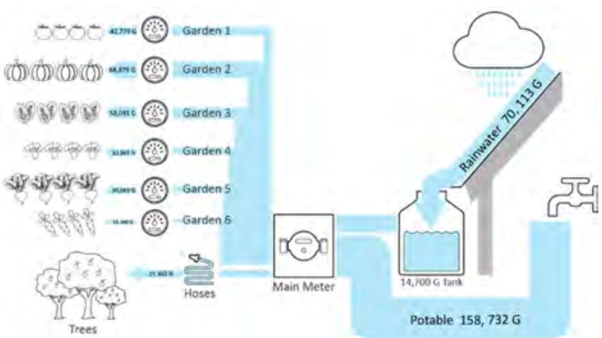

Fig. 4. Module 3: Baseline Active Water System Calculation (Credit students: T. Alaqtum, S. Ghaemi, M. Wilke, K. Chaikunpon, M. Torres)

Module 4: Final Report / Strategy Implementation

In the final month of the audit, students look holistically at data and recommendations from Module 1, 2, and 3. In Module 4 students add research on new technologies that had also been shown to be successful – particularly at the nexus of energy and water. Students meet with the building owner and manager to go over the complete water budget and the conservation, passive, and active strategy recommendations. Building owners and managers provide students with feedback on the feasibility of the selected measures and which are financially and operationally practical for short and long-term implementation plans. Students complete a full report for final presentation to the building owner, manager, and key occupants. In the case study, the owner plans to adopt composting toilets, parking lot modifications, and garden bad reduction with gutter expansion.

Discussion: Analysis, Applications, and Impact of Protocol

This section analyzes real and potential outcomes from the use of the water auditing protocol based on the testing that occurred from 2017-19. The protocol outlined in this article has the potential to directly impact four populations: (1) architecture students, (2) water service providers in drought prone areas, (3) commercial building owners, and (4) the professional architecture community. The analyses, applications, and impacts of the auditing protocol for each of the four populations are discussed below.

Pedagogical Learning Outcomes: the Next Generation of Architects

A model service-learning pedagogy was developed to teach future architects water efficient design – and push the boundaries of the former understanding of architect's responsibility in integrating water savings through design. The author's Water Efficiency in Buildings (ARCH 461/561) course engages undergraduate (Bachelors of Architecture) and graduate (Masters of Architecture, Masters of Science in Architecture, and Masters in Water, Society, and Policy) students each spring semester. Students enrolled in ARCH 461/561 learned water auditing, water budgeting, and key trends in use by occupant, fixture, and program type. Education promoting water efficiency is a key priority for federal funding institutions and programs such as the EPA and DOE due to increasing professional importance. Students will enter the profession with this new, marketable skill. Through the case study, students gained confidence as future professionals able to take on the growing water challenges in the built environment.

Local Community Outcomes: Tucson Water Commercial Water Auditing for Level 2 Drought for Building Owners

Unlike energy, no national, standardized water auditing protocol exists. The absence of these tools presents a major barrier to municipalities and water utilities seeking to successfully reduce community water use. This is particularly pertinent in drought prone areas, like Tucson. Under Tucson Water's 2012 Drought Contingency Plan, all commercial and industrial customers using an average of over 325 centrum cubic feet per month (or 2.5 million gallons per year) need to conduct a self-audit of water use at the facility and develop a conservation plan once a Level 2 drought is declared. However, no standardized protocol exists to guide commercial building owners and managers through a self-auditing process to comply with this requirement. The protocol outlined in this article was planned with Tucson Water for this ultimate purpose. Now that the protocol has been piloted form 2017-19, the intension is for Tucson Water to use the four module spreadsheets as a platform and tool for commercial self-audits when Level 2 drought is declared. In the case study, the Community Food Bank of Southern Arizona was projected to decrease overall potable water use if the auditing recommendations were adopted.

National Outcomes: 2030 District National Application

Nationwide, the 2030 District organization has the goal to reduce energy and water consumption by 50% by 2030.[21] Over fifteen national districts have successfully pursued the energy goal through the Energy Star portfolio manager tool, the national Commercial Building Energy Consumption Survey (CBECS) database, and ASHRAE standardized auditing protocols. However, an integrative approach to the water goal has been largely unaddressed due to the absence of protocols and tools for professionals. The new water auditing protocol supports the community partners to reduce water use in current district signatory buildings by 50% by 2030. The auditing tool provides greater clarity to building owners and managers on the actual impact of implementations on their volume of use and financial payback of water savings investments.

Professional Outcomes: Changing Architecture's Approach to Water Efficient Design

Finally, the created water auditing protocol serves the architectural professional community through the creation of new, currently unavailable, critical tools for water efficient design and retrofit. Unlike energy, no national standardized water auditing protocol or database currently exists. The discipline will be served with a cutting-edge, service-learning pedagogical model to teach water efficiency. With further testing, an online platform will be created. On this platform, the new standardized water auditing protocol will be easily accessible to building owners in the fifteen other efficiency district cities.

Conclusion

This paper argues that building water efficient design will advance if accessible, fixture-level tools are made available to professionals, building owners and operators, and students. Ultimately, to address this resource gap, a standardize auditing protocol was developed and evaluated for commercial buildings. The protocol is composed of four modules: (1) conservation / indoor use, (2) passive design / outdoor use, (3) active design / process use, and (4) holistic strategy implementation. Qualitative and quantitative research methods are used throughout all four modules. The protocol was developed and then tested from 2017-19 in an undergraduate and graduate co-convened architecture course in collaboration with the local public and private sectors in Tucson, Arizona.

In future work, the developed protocol will be placed on an assessable online platform for use by the 2030 districts across the county. Architects need to receive training in school to design for a water efficient future. The auditing protocol provides architecture students with a systematic tool to apply to each future building they design. The real world experience of auditing the presented commercial building case study developed student s' confidence to take on current and future challenges of water with an integrated process of measurement, analysis, and design.

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Timber 4.0: Open Source Systems as a Democratic Tool for Designing and Building

Ulrich Dangel
The University of Texas at Austin

Abstract

Architecture, as it exists today, is deeply rooted in perceptions that were established during the Renaissance, which credited the architect as the sole author of creative thinking processes and the resultant design ideas. Since then, the architectural profession has desired to develop new and innovative ways of building, often without being bound by traditions, the environment, or any other constraints and limitations. This approach has frequently failed to address the needs and concerns of many. As a result, architects have not been successful in imparting significant social change that is valuable to large portions of the population. In contrast, however, many other industries have adopted shared design and production practices for the benefit of the masses, warranting further exploration into how architectural practice might evolve its current modes of operation.

Wood as a building material has many beneficial characteristics–specifically its widespread availability, versatility, and ease of workability–which make it particularly suitable for investigating shared authorship and collective production methodologies. As an alternative to steel and concrete for mid-rise and high-rise buildings, mass timber construction, in particular, has experienced significant advancements in recent years, resulting in the development of entirely new building processes that rely on innovative engineered wood products, digital manufacturing, and prefabrication techniques. However, this has frequently led to expensive one-off proprietary solutions that are limited in their application. To foster innovation and disseminate knowledge, an open source culture of designing and sharing is necessary. To this end, this paper will present approaches for open source mass timber construction systems that can be applied to a wide range of scenarios and settings, with the aim of ultimately increasing the acceptance and market share of wood construction for the benefit of society at large.

Keywords: Materials + Construction Techniques, Shared Authorship, Open Source Architecture, Timber Building Systems, Prefabrication

Authorship in Architecture

The artistic ownership of a single author has been praised in the discipline of architecture as far back as Giorgio Vasari.[1] Much like Prometheus, the Titan who stole fire from the Gods at Mount Olympus and gave it to humankind, architects considered themselves charged with enlightening humanity by singularly committing great acts of creation. The notion of an individual as the sole originator of iconic design ideas has continued today, fostering the image of the Starchitect. Thus, a small group of elite architects has emerged, which is responsible for designing a majority of high-profile contemporary buildings, from airport terminals to headquarters of global corporations, to museums. However, in their noble quest to change society, architects have increasingly ignored the needs and desires of a considerable portion of the world's population. They focus on buildings as iconic, singularly authored objects while often failing to respond to social concerns. Formal explorations and expressions frequently take precedence over human scale and functional needs. As a result, it is estimated that architects are involved in no more than two percent of global construction efforts today. Architecture has been unsuccessful at becoming a democratic tool that imparts significant change beneficial to large portions of society.[2]

The origins of architecture, however, are intrinsically tied to the nameless contributions of many. Vernacular architecture was developed collectively in an anonymous fashion, carefully responding to the local climate, environment, and cultural values (Figure 1). Designs were modified, adapted, and optimized in response to the experiences and tried and tested methods of others, while slowly contributing to a large body of knowledge over time. Form and function were seamlessly combined into anonymous buildings, which were instrumental in shaping most of the world's great cities.

Fig. 1. Vernacular architecture: Europe, Africa, and Asia

Open Source Architecture

To recognize the premise and potential of shared authorship architecture, one needs to understand the origins of open source models and their development throughout history. *Open source* as a term originated in the context of software development to designate computer software that had its source code made publicly available with a copyright license providing the rights to study, modify, and distribute the software to anyone and for any purpose.[3] Today, the term *open source* describes a broader approach for projects, products, or initiatives that "embrace and celebrate principles of open exchange, collaborative participation, rapid prototyping, transparency, meritocracy, and community-oriented development."[4]

While contemporary architecture still operates under the sole authorship model established during the Renaissance, many other industries have embraced the shared design and production practices of the information age for the benefit of the masses, which includes joint efforts such as Linux, Wikipedia, and Creative Commons Licensing. Considering the multitude of challenges facing society—climate change, an exploding world population, and increasing economic inequality—it is timely to question current modes of operation within architectural practice.

Several open source initiatives have emerged over time in the discipline of architecture. The *Open Architecture Network,* for example, was developed by the US-based charitable organization Architecture for Humanity and launched in 2007. Discontinued in 2015, it was an online, open source community dedicated to improving global living conditions through innovative and sustainable design.[5] More recently, *WikiHouse* was initiated as an open source project to reinvent the way houses are made (Figure 2). It is being developed by architects, designers, engineers, inventors, manufacturers, and builders who are all collaborating to create the best, most straightforward and sustainable high-performance building technologies that anyone can use and improve.[6]

Fig. 2. WikiHouse open source project

Some industry organizations offer free databases related explicitly to timber construction. Holzforschung Austria, the Austrian Forest Products Research Society, maintains an extensive technical online library of structural and non-structural wood products, components, assemblies, and details at *dataholz.eu*.[7] Lignum Holzwirtschaft Schweiz, the umbrella organization of the Swiss forestry and timber industry, provides a building component catalog focused on the acoustic properties of assemblies at *lignumdata.ch*. [8] Furthermore, MetsäWood, a Finnish wood products manufacturer, has recently launched its *Open Source Wood* initiative (Figure 3). As an open ideas platform, it focuses on sharing innovative knowledge to foster modular wood construction. Architects and engineers can submit modular building elements using Creative Commons license type CC-BY 4.0, which allows content creators to grant someone else permission to use their work. [9]

Fig. 3. MetsäWood's Open Source Wood Initiative

Sharing information and disseminating knowledge through the development and promotion of open source design strategies is a logical next step for democratizing architecture. This approach has the potential to broaden the reach of the architectural profession while simultaneously making its impact on humankind more meaningful. Most importantly, however, it could provide large swaths of the world's population easy access to thoughtfully designed and carefully constructed buildings, satisfying their need for adequate places for living and working. Open source design methodologies also remove control that relatively few might be able to exert over many by inviting contributions from all. Rather than a small group of creators providing deterministic design solutions for large portions of society, design becomes a fluid and participatory process.

Systems in Architecture

Due to the many authors involved, open source design can only be successful if a common language is employed by all participants to coordinate processes and methods. Thinking in systems has long been utilized in architecture as a holistic approach to establish how individual components interrelate with each other in the context of larger and more complex constructs. Early vernacular construction techniques unitized buildings through the use of modular stones, brick, and timber members. However, it was the ability to manufacture identical building elements in large quantities and to exact standards during the industrialization that laid the foundation for the development of building systems. Prefabricated iron–and later steel–components were essential in enabling the construction of large and systematic infrastructure projects such as bridges and train stations. [10] In the late 19th and early 20th century, new industrialized production methods were hailed as a solution for many economic and social issues at the time. Most importantly, it was hoped that relying on these technological advancements would resolve the housing shortage that was caused by the migration of working-class laborers to the urban industrial centers in search of employment.

Closed Systems

The continued development of prefabricated construction systems was interrupted by the economic crisis of the 1920s as well as the outbreak of World War II, which shifted the focus of industrial production to armaments manufacturing. [11] The need for rebuilding in the post-war years ushered in a new era for industrial fabrication. New prefabricated building systems were conceived, ranging from solutions for affordable housing to large span structures for commercial and industrial applications. System building became synonymous with progress in the 1950s and 1960s. The rationalization and standardization of design and construction processes resulted in the repetitive use of identical elements, which led to a new aesthetic and redefined the concept of beauty in architecture. Many architects and designers employed construction systems as a vehicle to propose bold visions for the future of buildings and even entire cities. In the end, this blind reliance on technology to solve the social and economic issues of the time was rejected. Substandard quality of construction, poor urban planning strategies, and the relentless uniform appearance of buildings– among many other concerns– meant that the general public increasingly grew disillusioned with building systems.[12] This was in part due to the fact that the self-contained, deterministic nature of the concepts conceived in the 1960s did not provide enough flexibility to respond to individual needs. Within these so-called *closed building systems*, nothing could be easily removed or added, significantly reducing the ability to respond to users' changing demands over time.

Open Systems

While serial production with identical components seems to have gained widespread acceptance in many other industries such as automobile and aircraft manufacturing, a comparable approach in architecture has not been well received by society.[13] Additionally, the more common development of *closed building systems* has imposed even greater limitations since they use proprietary components or subsystems that are designed and developed exclusively for use within the system, eliminating the ability to integrate third-party building elements or products. In contrast, an *open building system* concept consists of exchangeable components or subsystems that often come from different manufacturers, thus increasing choice and flexibility for both the designer and user (Figure 4).[14] Open systems can provide overarching order while still allowing freedom for individual customization. They also facilitate alterations that might occur due to a change of use or shifting user needs. This approach has the potential to make a structure significantly more resilient than its less adaptable neighbors since repurposing increases a building's acceptance by its occupants, thereby extending its lifespan over time. Through their flexibility, open systems are also able to respond more readily to localized conditions, whether they are cultural, social, environmental, or economic in nature.

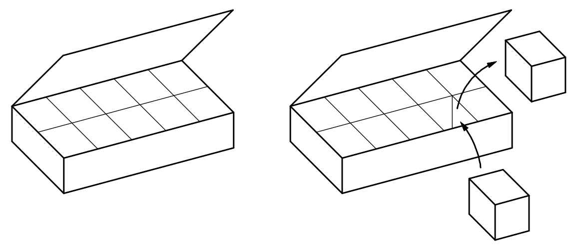

Fig. 4. Closed system: proprietary components or subsystems (left) vs. open system: exchangeable components or subsystems (right)

Few successful examples of open, system-based buildings exist in contemporary architecture. The School Construction Systems Development (SCSD) project initiated by architect Ezra Ehrenkrantz can be considered one of the first convincing demonstrations of the efficiency of open building systems. From 1961 to 1967, this program created an innovative, flexible, and prefabricated architectural building system for the construction of schools in Southern California. Rather than a single contractor providing a comprehensive building solution, independent manufacturers bid on individual subsystems that were to be compatible and integrated with components from other suppliers. Notably, the kit-of-parts did not include the exterior facade, which was to be designed based on the context of each school and the preferences of the architect. This cooperative approach provided a number of universal subsystems that could be combined into a wide range of building configurations which were then easily adapted and customized to local circumstances, ensuring the widespread success of the system.[15]

Open Source, Open Systems in Timber

Light Frame Construction

Within the context of building with wood, the nowadays ubiquitous platform framing method, which emerged as an improvement to balloon framing in the early 20th century, can be considered the ultimate open source, open building system. It is a construction system that is based on the use of standardized 2x structural members that are assembled with standard, mass-produced nails. Rules of thumb are employed for member spacings of 16” or 24” on center, and standard connection details are common knowledge or readily accessible through freely available reference literature. The use of minimal structural material allows the enclosure of large areas at minimal cost while allowing a wide variety of architectural styles. Originally conceived as a technique that facilitated assembly by unskilled or untrained labor, it is possible to create an entire building without the involvement of a designer, architect, or engineer by merely following the established rules. The method’s ease of adjustability in the field is one of its major advantages but also leads to its most significant disadvantages, in particular, its inefficiency of on-site assembly and the potential to generate substantial amounts of construction site waste compared to prefabrication. Due to its flexibility, low cost, and ease of assembly, platform framing continues to dominate residential and small-scale commercial construction in North America.[16]

Panel Construction

Inspired by North American platform framing, panel construction emerged in Europe as a technique that offered significant advancements in timber construction, most importantly higher levels of prefabrication and improved quality of craftsmanship. While the structural logic of panel construction is the same as for platform framing–a framework of load-bearing members that is laterally braced through sheathing–entire wall, floor, and roof panels are prefabricated and then transported to the site for final assembly.[17] As an open source, open system, panel construction takes advantage of wood’s many beneficial characteristics–in particular, its lightness and ease of workability–by shifting design and production processes into the shop. This allows the designer and fabricator to exert more control over the final product, which ensures consistency and precision while simultaneously facilitating quality assurance. Shop fabrication also provides more efficient use of material and significantly decreases the amount of on-site construction waste, which would otherwise have to be disposed of as landfill. One major advantage of panel construction is that fact that it does not require highly specialized equipment, which means that any qualified carpentry business can easily perform the necessary tasks for production.[18]

Solid Timber Construction

Recent technological innovations have led to the development of load-bearing, large-format components that far exceed the structural limitations of more common timber building products. With its ability to resist both gravity loads and lateral forces, cross-laminated timber (CLT) in particular has revolutionized the construction sector. Increased load-bearing capacities have opened up possibilities to construct taller multi-story structures, allowing timber to compete with more energy-intensive building materials such as steel and concrete.[19] These new solid timber–or mass timber–building systems not only have the potential to provide an affordable, low-carbon solution to the housing crisis in urban areas around the world. They also offer improved quality of construction, thermal mass for increased comfort, enhanced fire performance compared to frame or panel construction, as well as exposed interior wood surfaces that have shown to improve physical and mental health for occupants.

Mainly conceived in Western Europe and North America, mass timber systems have led to the development of entire new building processes for timber construction, but at the same time rely heavily on high-level engineering expertise and specialized production technologies. The wide range of production equipment and processes has also resulted in each manufacturer developing their own proprietary cross-laminated timber elements, which is reflected in the large variety of layups and dimensions available on the market today. This lack of standardization may force a design team to settle on a specific product from a particular supplier early on for design and planning purposes, effectively eliminating any competition at the very onset of a project. Due to a concentration of know-how as well as significant start-up costs, the location of fabrication facilities is currently limited to industrialized nations, frequently requiring the distribution and shipment of products over long distances and even overseas. Since they have had the opportunity to streamline production processes over time, larger well-established manufacturers are often able to offer more competitive pricing than start-up suppliers that might be more local.

Toward an Open Source, Open Hybrid Timber System

Classifying timber construction into discrete techniques such as light frame, panel, or solid timber construction no longer seems reasonable since combining building components that employ different systems has mostly become standard practice. Each building element is selected for a particular application based on its unique properties, which results in optimized hybrid structures. This approach offers designers a large amount of freedom during the planning process to arrive at highly tailored solutions.[20]

To this end, this paper proposes the implementation of a low-tech open source, open timber system that can be applied to a wide range of building scales, socio-economic scenarios, and markets. The primary objective is to establish strategies that enable the provision of sufficient sustainable and affordable housing in urban areas, particularly in emerging economies that struggle to meet the growing demands while simultaneously satisfying economic, ecological, and social concerns. These countries might possess vast forest stocks, but likely neither have a well-established or sophisticated timber products industry nor have traditionally focused on building with wood. The promotion of timber construction has the potential to offer alternatives to more carbon-intensive construction methods by introducing more sustainable building practices.

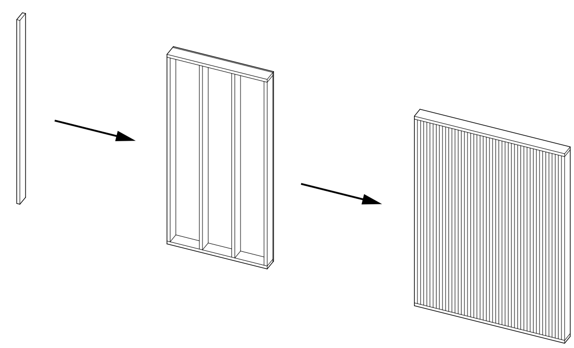

Fig. 5. Gradient from platform framing, to panel construction, to mass timber construction

Conceived as a hybrid system, the proposed solution is intended to operate across a gradient of construction methods. By employing this strategy, it takes advantage of the flexibility and cost efficiency of platform framing, the prefabrication benefits and quality control inherent to panel construction, and the improved structural performance and thermal properties of mass timber (Figure 5). Reliance on (locally) readily available commodity products allows the system to respond to localized conditions–whether they are cultural, environmental, or economic. Rather than promoting a universal formal language, it emphasizes architecture as a product of place, material, and function.

Where a particular design solution falls within the spectrum depends heavily on several factors: Building height, required load-carrying capacities, local building and fire codes, availability of raw materials, and skill set of the local workforce. Rather than relying on the fabrication of laminated components such as cross-laminated timber and glulam that might require specialized equipment, this method proposes an additive approach to handle increasing gravity loads for floors and walls that is similarly found in platform framing: Heavier loads are therefore accommodated by combining several smaller structural members together into larger cross sections. Joining individual boards together can be accomplished with mechanical fasteners such as nails (nail-laminated timber or NLT) or hardwood dowels (dowel-laminated timber or DLT).

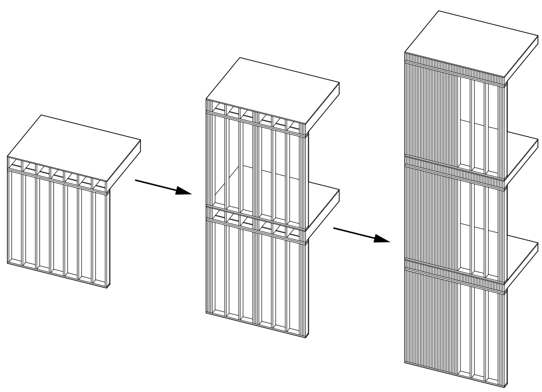

Fig. 6. Seamless transition between construction methods

The appropriate bonding technique can be selected based on local construction practices and availability of equipment. Nailing is undoubtedly considered the simplest method, but the presence of non-wood fasteners in the final product may pose limitations on workability and recyclability. While the use of hardwood dowels requires an increased level of craftsmanship, an all-wood product greatly facilitates processing as well as end-of-life material recovery and repurposing. This configuration of members allows the wood to be primarily loaded parallel to the grain, which offers exceptional strength to resist vertical gravity loads. However, the addition of lateral load-resisting components such as structural sheathing or diagonal bracing is required to transfer lateral loads successfully. [21] By allowing the structural system to readily respond to both specific load patterns and local conditions, the transition from lightweight wood framing to solid timber construction becomes seamless (Figure 6).

Crucial for the successful dissemination of the proposed open timber strategy is an online portal that allows free access to technical information as well as the sharing of knowledge. Using Creative Commons licensing, any user can propose and distribute new building components within a defined set of rules, but they can also freely copy and make derivatives of the work of others. Rather than a single entity possessing ownership and control over proprietary and static information, this participatory, open source process allows the development of tailored, localized design solutions that can respond to a variety of economic, environmental, cultural, and social scenarios with the intention of satisfying the housing needs for many.

Conclusion

This paper summarizes the genesis of the research project and serves as an interim report that lays the foundation for an open source, open timber system while proposing an overall conceptual framework for its implementation.

The next stage of the project will include the following steps:

1. Systematic research and analysis of open source building methodologies and current timber construction systems
2. Design and development of building components based on the findings from step 1, establishment of a component classification matrix

3. Proof of concept: Prototyping and testing of key building components to evaluate feasibility and compatibility
4. Establishment of an online database of tried and tested building components for distribution and sharing

Valuable feedback from anyone involved in the built environment and the general public is currently being solicited and will be incorporated into the concept as the research development continues.

Acknowledgments

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Open Pedagogy for Teaching Structures

Robert J. Dermody
Roger Williams University

Abstract

There is great potential to improve student engagement and retention by using open resources and pedagogies to teach structures. Open Educational Resources, OER, as defined by OER Commons are "…teaching and learning materials that you may freely use and reuse at no cost, and without needing to ask permission". Open Pedagogy is more difficult to define, but Wiley states that "Open pedagogy is that set of teaching and learning practices only possible in the context of the free access and 5R permissions characteristic of open educational resources."[2] The "5R permissions" refers to the fundamental basis of sharing open content that allows anyone to Retain, Reuse, Revise, Remix, or Redistribute the content of the resource in question.

After teaching structures for many years, using several different textbooks, with varying results in student engagement and learning outcomes, the author decided to investigate/develop open pedagogies to use in teaching fundamental structural concepts. This paper will focus on the author's recent experiences in introducing open pedagogies into an existing, second-year, introductory structures course. The primary goal of this experiment was to improve students' retention of course content and engage them more directly in their coursework by challenging them to find, create and share open content. Another goal was to guide students in creating documents containing pertinent structural design information that they could maintain for use in their future structures courses and design studios. Students were required to create their own websites to store and share their work in the course. This exercise exposed students to the "5R's" of open content, at a relatively small scale. The course goals and context in which open resources and pedagogy were used will be explained and described. Future potentials for using open pedagogies to teach structures will also be discussed.

Keywords: Pedagogy, Open, Structures

OER - Open Educational Resources

Open Educational Resources (OER) are now being used much more frequently in higher education for many disciplines. Reasons for this influx of open approaches include reducing, or even eliminating textbook costs for students, and more pedagogically driven initiatives to engage students directly in the creation/sharing of content to improve the achievement of learning outcomes. Many open pedagogies and initiatives focus on more constructionist approaches to teaching, wherein students are challenged to create shareable content and come up with the questions they want, or think, need to be answered to master a particular subject. Content creation by students is also a main tenant of open teaching practices, in an effort to have students take ownership of the material they are learning. As a relatively young field, recent articles on open pedagogy discuss how the field is being defined and how open approaches are being implemented and evaluated.

	Student creates an artifact	The artifact has value beyond supporting its creator's learning	The artifact is made public	The artifact is openly licensed
Disposable assignments	X			
Authentic assignments	X	X		
Constructionist assignments	X	X	X	
Renewable assignments	X	X	X	X

Fig. 1. Criteria distinguishing different kinds of assignments.

Wiley and Hilton also discuss, "OER–enabled pedagogy", while clearly noting that traditional (or disposable) assignments can have learning value, but suggest that more open assignments offer myriad opportunities for increased retention and other possible benefits.[3] (See Fig. 1.)[4] Seraphin et al explore NDA's, "Non-disposable assignments", wherein they "…endeavor to promote a launching ground for empirical research focused on effective practices and learning outcomes for NDA's", and to provide "…support for open pedagogy."[5] Much of the recent literature in this rapidly growing field indicates that open teaching practices offer viable pedagogical approaches in many different subjects. While many courses within NAAB accredited curricula have been utilizing open pedagogies for years, in courses such as community engaged design studios or environmental research courses, there is little evidence so far of open practices being used in structures courses.

Genesis of the experiment

In the last academic year, the author participated in an OER Fellows Program on their campus for a cohort of faculty from any department who were interested in learning more about open resources and how to incorporate them into their courses. Based on that experience and reflecting on the content of the recent literature on open educational practices, the author decided to try using more open pedagogical practices to teach architectural structures. A second year introductory course in structures seemed to be a good course in which to implement open teaching practices.

Course Context

ARCH 335, Structure Form and Order, is a required second year structures course. It is the first course in a three course sequence for the NAAB accredited MArch degree. The catalog description states in part that, the course "…introduces the fundamental concepts of structural form and behavior through a combination of lectures and studio exercises." The course objectives outlined in the syllabus are:

1. To develop a strong structural vocabulary.
2. To understand basic structural forms.
3. To understand the relationship between structural form and behavior.
4. To understand the evolution of structural developments over time.
5. To identify important historical structures, and their designers.
6. To understand the behavior of basic structural elements and materials.
7. To analyze basic structural systems behavior through models and first order calculations.
8. To understand structural load tracing.
9. To understand vector based force representation and manipulation.
10. To model and develop an understanding of basic structural systems to be used in studio design projects.
11. To explore the possibilities of Open Educational Resources.

Not every course goal was specifically targeted to be achieved through open teaching methods, but several key objectives were chosen to be explored through the creation of open education resources by the students. In the first attempt to open the structures course efforts were focused on engaging students in thoughtfully reflecting upon and documenting what they had learned in the course in a medium that could be easily maintained, shared with other audiences, and easily referenced in the future.

First Open Iteration

In the first iteration of the "open" version of the course, in Fall 2018, students were asked to create "digital notebooks" that summarized the content they learned in the course throughout the semester. The notebooks were created and curated by the students using Google sites. They were instructed to write for different audiences; themselves, their classmates, and other students in the School of Architecture, with the intention of possibly sharing their sites in the future. The goal for this exercise was to challenge students to reflect on what they had learned and then to present that information in a clear accessible manner suitable for future reference. Longer term goals for this project included developing sites with course information that they could use in advanced structures courses or in design studio. Additionally, they were asked to consider the possibility that they could share their sites with other students in the architecture program, perhaps first year mentees. Many students approached the project by organizing their digital notebooks by assignments, while others organized content by themes. Good graphical layout of their sites and clear presentation of information was also emphasized throughout the project. The key objectives of the digital notebook project were:

1. To review and reflect upon course content and course learning objectives.
2. To summarize key terms and concepts from the lecture throughout the semester.
3. To create a resource for future reference in structures courses, studio and practice.

The assignment prompt also required them to include a written reflection on what they had learned during the semester considering the course goals listed in the syllabus. They were also encouraged to populate their web-pages with a variety of media, written passages, lists, images, sketches, drawings, links, webpages, journal articles, current events, images of models, and a bibliography. The creation of new content/documentation about architectural structures was also required for this project, to challenge the students to build upon what they learned, and avoid merely cataloging their assignments submitted throughout the semester. (See Fig. 2)

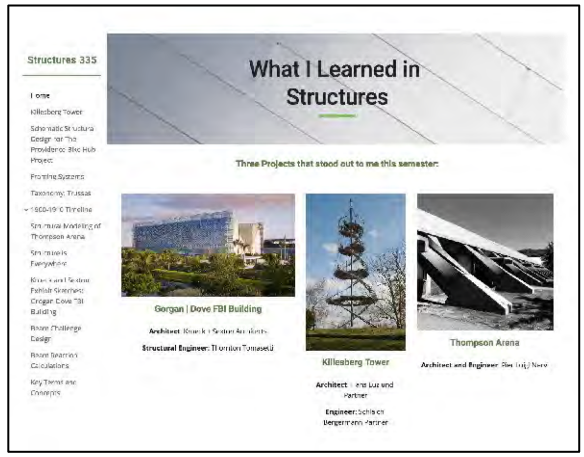

Fig. 2. Student Digital Notebook front-page, Evelyn Chambers.

In place of a traditional written final exam (perhaps the quintessential example of a disposable assignment), the last class meeting of the semester was devoted to a two-hour session for the students to present their websites to a public audience. The session was held in a multimedia room in the campus Learning Commons. Multiple large format touch screens were available for all the students to take turns displaying their websites to an audience from all over campus. The public presentation proved to be an important learning experience for the students as they were required to explain the both the project and the content they created, to an audience of non-architects. Verbally explaining the project's genesis and parameters forced students to think carefully about their audience. It was an opportunity for the students to share their newly acquired knowledge about structures and practice their oral presentation skills.

Current Initiatives

Based on the positive experience in the Fall 2018 version of ARCH 335, a second iteration of the course, with additional open assignments, was launched in Spring 2019. Student feedback regarding process and content was incorporated into this version of the course. Some of the most valuable comments from students suggested providing more assistance in understanding proper attribution protocols for citing "open" sources. The students also recommended, quite perceptively, that the digital notebook project should be introduced earlier in the semester, allowing them to build up the website gradually. With these recommendations and other student feedback in mind the author endeavored to "open" up the course even further, by incorporating more opportunities for students to create and share content about architectural structures. The course began with a guest lecture from our University Scholarly Communications Librarian, who introduced the students to the basic concepts of copyright laws and how they relate to academic work. A second class session was offered by the librarian, who specializes in open content issues, is planned for this semester. The second meeting with the librarian will focus on developing students' skills for in finding open source materials and the proper citation or attribution of these open sources.

Opening Up Assignments

For several years, the author has typically started each class with a "Structure du Jour", one slide of an important, or cutting edge building with an elegant structural system. This is done to grab students' attention and to get them excited about the informative possibilities of well integrated structure in building projects and to develop their ability to identify structural systems by name and materials used. Additionally, it often provides a good segue to the topic of the that day's class. After students began suggesting ideas for, or requesting a specific Structure du Jour, the author realized the potential benefits of having all students participate in selecting and presenting their own Structures du Jour. To facilitate the process, the instructor's graduate assistant created a Google slide show with a formatting template that was shared with the class. Students were encouraged to find a structure of distinction to discuss at the start of each class. Several pedagogical outcomes were achieved by doing this. It as an effective way to develop their structural vocabulary as well as their critical thinking skills by challenging them to find efficient, elegant structures. An unexpected, but positive benefit to this approach is that students can see what their classmates are researching as the site grows with entries throughout the semester. Students are often excited to share their own photographs of buildings they have visited or to present a structure they may have learned about in their design studio or history class. (See Fig. 3.)

Fig. 3. Sample Structure du Jour, Alexis Violet.

The second assignment adapted to be more open from previous versions of the course is a short biographical sketch of a significant structural engineer. Students were asked to research a structural designer of their choice and create a small poster presentation on their life and major works. Again, the collection and sharing of the information between classmates provided a broader range of learning opportunities for all students. In prior semesters, this assignment would be shared between just the student and the professor. Having a digital collection of all the students' posters (60+) allowed the instructor to easily display the slide show in class and have the students to see the rich legacy of structural engineers and make connections between the different eras covered, which ranged from 18th century to present day. (See Fig. 4.)

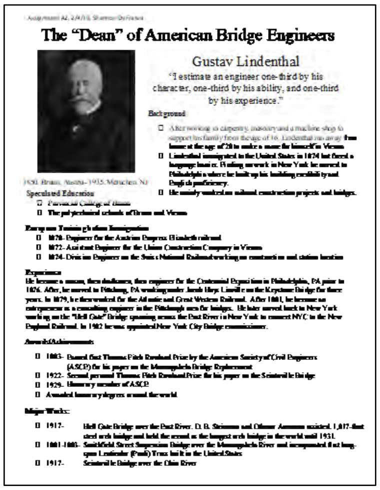

Fig. 4. Sample Designer Biography, Shannon Defranza.

The designer biography assignment led directly into a class project that is ideally suited for the collective efforts of students researching a topic individually and then sharing their results communally. Two of the course goals achieved in this assignment included developing students' understanding of the relationship between structural form and behavior, and the evolution of structural developments over time. In a little more than a week, the class collectively assembled a comprehensive slide show showing the historical development of structures over the past 10,000 years. Each student was assigned a specific time period to research. They were each asked to create a few slides with text and images covering the important structures, designers, and structural or material innovations from their specific time period. The next step in this project will be an in-class workshop where students will work together in small groups to evaluate and edit the content of the timeline slides. Ultimately, the information will be incorporated into an online searchable timeline, that can be expanded, updated and/or revised by future classes. It will also serve as a good reference for students in studio and other future courses. (See Fig. 5)

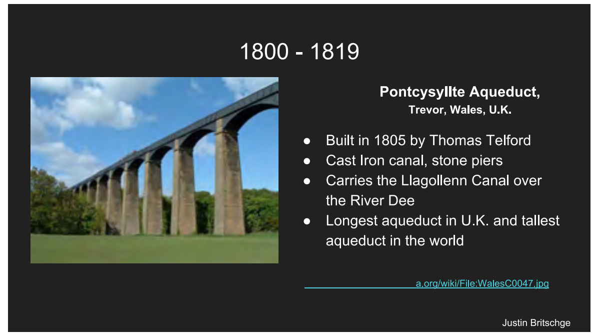

Fig. 5. Sample slide from Timeline of Structural Developments through History, Justin Britschge.

Reflections and Challenges

Several benefits have been found in these first few attempts at "opening" up the structures course. In previous versions of the course, most assignments were "disposable"; produced by individuals or small groups of students, and shared only with the instructor for grading purposes. After the graded assignments are returned, they are rarely seen again. The digital notebook project was an attempt to create a non-disposable assignment that would be useful for students in future courses, even if only for the creator of the notebook. Other assignments that involved communal research and content creation allow students access to much more information that they and their classmates have collected in completing their assignments, and sharing the results. For this to be effective, it is essential that quality control of the accuracy and efficacy of the content be ensured by the instructor. Another goal of the digital notebook is for students to refer to it in their future design studios. It remains to be see how effective it would be to share with a wider audience such as the wider student body of the school of architecture. Additionally, when students share the methods and resources they use in completing assignments, their classmates are exposed to many information references that they can also utilize. The instructor has also found it very helpful during lectures to show slides created by students to review the content and provide feedback to the entire class. This method also fosters more in class discussion when students see their work displayed on the screen. Students have also been encouraged to research and use "open sources" such as Creative Commons licensed content and images for all their assignments. However, more class time needs to be devoted to instructing students on how to find and properly document open content. This has proven to be one of the biggest challenges in ensuring the student created content is both correct and properly attributed. An in-class workshop with our university librarian is scheduled for the current semester to review best citation practices and to provide the students with a better understanding of the underlying philosophy of creating and sharing open content.

Future Directions

Future initiatives for incorporating OER-enabled pedagogy in the structures course will investigate ways of actually sharing more student created content to wider audiences. Evidence from Seraphin et al suggests that, "Student generated instructional materials represent some of the best examples of culturally rich and effective learning objects." [6] The "pay-it-forward" philosophy has great potential for increased learning and retention for the student authors and their shared audience. Efforts to assess the realized benefits of sharing student produced learning materials will be conducted in future versions of the course, perhaps with past students returning to visit the course to discuss their experiences with their digital notebooks and other non-disposable assignments. Furthermore, the author should also have the opportunity to work with many of the students from the first two "open" versions ARCH 335, as they also teach the second and third structures courses.

Conclusions

While open pedagogies can be incorporated into a course in any discipline, they have been used with great success in the social and natural sciences among other fields. It is not yet apparent that they have been widely introduced into architectural structures courses. It is evident, even from limited recent experiments in using OER, that a NAAB accredited architecture curriculum is ripe with opportunities to leverage many positive benefits for retention and learning outcomes that these methods offer. Given that many of the required courses in architecture curricula rely heavily on precedents from the built environment, OER-enabled pedagogies, such as non-disposable assignments certainly have the potential to play an effective role in helping students achieve different learning objectives in various courses, not just in structures.

Notes:

1 "Getting Started with OER." OERcommons.org. https://www.oercommons.org/about (Accessed Oct. 10, 2018).

2 Wiley, David. "What is Open Pedagogy," Iterating Toward Openness (blog), October 21, 2013. https://opencontent.org/blog/archives/2975. Creative Commons Attribution license version 4.0.

3 Wiley, David, and John Hilton III. 2018. "Defining OER-Enabled Pedagogy". The International Review of Research in Open and Distributed Learning 19 (4). p.136 https://doi.org/10.19173/irrodl.v19i4.3601.

4 Wiley and Hilton, p. 137.

5 Seraphin, Sally B., J. Alex Grizzell, Anastasia Kerr-German, Marjorie A. Perkins, Patrick R. Grzanka, and Erin E. Hardin. "A Conceptual Framework for Non-Disposable Assignments: Inspiring Implementation, Innovation, and Research." Psychology Learning & Teaching, (November 2018). doi:10.1177/1475725718811711.

6 Seraphin et al. p. 11

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Water and Land in Flux: Pedagogy for Design Innovations that Inhabit Water

Niloufar Emami
Louisiana State University

Abstract

The Float'n'rise Design Studio encourages a paradigm shift in design by speculating how a partially submerged building can be designed along the Southern Louisiana coast. As the erosion and submersion of terra firma continues, what might the future of a community's existence look like? If the fact that once-inhabitable ground slowly submerges is assumed, why not construct buildings designed to float on water in the first place? Instead of holding firm to past ground/water conditions, and only raising buildings according to the hundred-year flood level principle, why not embrace a relationship with water as a new design opportunity? Located at the intersection of architecture, ecology, and advanced technology, this studio is a step forward in navigating the fraught/complex relationship between terra-firma/aqua-firma and its environmental settings, using advanced computational and fabrication techniques to rethink modes of habitation in the coastal areas of Southern Louisiana.

This paper first provides an overview of the environmental conditions of the Southern Louisiana region in general and New Orleans in particular. Then, a review of the existing research and practice in the field of floating architecture is presented. Next, the specifics of the Float'n'rise Design Studio are introduced, followed by an overview of the CAD/CAM techniques employed throughout the process. Finally, students' projects are presented with a discussion of how they aligned with the pedagogical goals.

Employing CAD/CAM methods was found to be an inspiring source for design thinking that offers innovative design solutions to multi-faceted complex problems. It can also act as an aid in prototyping and to verify the feasibility of proposed design scenarios. In fact, an interesting improvement to the studio, if repeated, will involve using CAD/CAM techniques paired with material explorations to fabricate small-scale prototypes that can actually be tested on water. The iterative nature of prototyping and testing can synergize the iterative nature of design towards better contextualizing it.

Keywords: Materials + Construction Techniques, Floating buildings, Buoyancy, Digital fabrication, Technology Pedagogy

Introduction

Human settlement is an aggregation of properties grounded in the static character of terra firma. Humans have developed a false sense of ownership and authority over land and its associated ecological networks, including water. The space between land and water, however, is best considered amphibious. The word amphibian derives from a Greek root meaning 'to live a double life.' As a result, a dynamic reading of a potential amphibious space can be related to both land and water, while implying a tenuous relationship between the two: "An amphibian is a transitional figure inhabiting a space not just where land and water meet, but where they overlap and claim each other" [1].

According to Barker and Coutts, "Approximately, 40% of the world's population currently live within 100 km of the coast and 20% of the Earth's population live in river basin areas at risk of frequent flooding" [2]. The duality of water, at times our friend, at others a threat, must be examined in order to redefine our relationship with water. In fact, how we respond to the thread of flooding will shape our cities as much as our need for water. Many past civilizations have demonstrated ingenuity in designing with water, such as floating housing in Tonle' Sap in Cambodia. Barker & Coutts (2016) introduce and define *aquatecture* as a "water centric approach to design in which flood-risk management, development pressure, and adaptation to climate change are simultaneously reconciled to allow buildings and cities live and work with water."[2]

Humans' sense of authority over land is shaken after a flood. The relationship between land and water is particularly complicated in lower Louisiana, where the coastline is in a constant state of change as the site shifts between terra firma and aqua firma: this occurs both slowly, over time, and also abruptly, during natural disasters such as hurricanes or rising floodwaters. The lands along the Louisiana Gulf Coast are subject to the risks of fluctuating environmental conditions, which can be as harsh as 2005's Hurricane Katrina in New Orleans, or the 2016 flood in Baton Rouge.

Focusing on flooding as a threat, it can occur from various natural sources including rivers (fluvial), coastal and tidal sources, and surface water (pluvial) flooding. Other possible sources of flood include sewer, groundwater, or artificial structures. As flood risk increases, traditional approaches to defending land from flooding become more costly and less effective. A paradigm shift is needed to embrace the natural water cycle and to begin designing *with* water, rather than against it. Considering these approaches to tackle flood risk on a building site, how can designers get past a focus on design strategies of flood avoidance, flood resistance, and flood resilience, moving toward strategies where a building floats on water or, more dramatically, where the building is amphibious?

Previous studios at the Louisiana State University (LSU) School of Architecture have examined and speculated on this fragile relationship, including Ursula McClure's amphibious constructions for LUMCON [3] and Shelby Doyle's Losing Ground Studio [4].

This paper summarizes research and speculations conducted in the Float'n'rise Studio on the design of floating buildings in Southern Louisiana, New Orleans. This options studio was offered at LSU during Fall 2018. The studio takes *architecture* as its first focal point by considering a program that works both with and on the water. The second focal point of the studio, *ecology*, explores/interrogates habitation and settlement patterns that are isolated from ecological systems in an unsustainable manner. In other words, when a building shares the space of the water's edge with the native inhabitants of the water, ecology becomes a key concern. Thus, design and construction features that encourage cohabitation with marine and avian life were considered. The third and final focus is on *technology*, which shapes the means and methods of investigating a complex problem. Computational design and simulation tools are employed to explore the center of gravity and of buoyancy of a submerged object. Composite materials, as well as ship design technologies, add to the collective studio's examining of the materiality of a buoyant object. In addition, digital fabrication techniques, such as 3D printing and CNC cutting/routing are employed for prototyping complex, non-Euclidian surfaces, all in service of tackling a complex multi-faceted problem. This paper includes explanations of the context, the educational methodologies employed, and the final design projects interventions developed by students.

Context: Southern Louisiana and New Orleans

For better or worse, the history and livelihood of New Orleans are inextricably associated with the city's relationship to water. Water has been a boon for New Orleans, as the Mississippi River and Lake Pontchartrain provided ample support during the fledgling years of the city. Transport, recreation, scientific exploration, and sustenance have all been a part of this critical relationship. However, the city also has faced an eternal struggle against water, as the very forces that keep the city alive also threaten its existence. In addition to the ceaseless job of pumping water out of the city, New Orleans is faced with catastrophic weather and climatic events that could potentially inundate the entire city.

To better understand the context, site analysis is conducted considering the *physical* (and material), *political* (and managerial), and *cultural* (and symbolic) aspects of the site at the architectural, urban, and regional scales. The results of site studies at the regional scale, commercial and recreational fishing describe an important part of Southern Louisiana's political aspects (Fig. 1).

Fig. 1. Analysis of political aspects at the regional scale developed by a student (developed by Annan Wang)

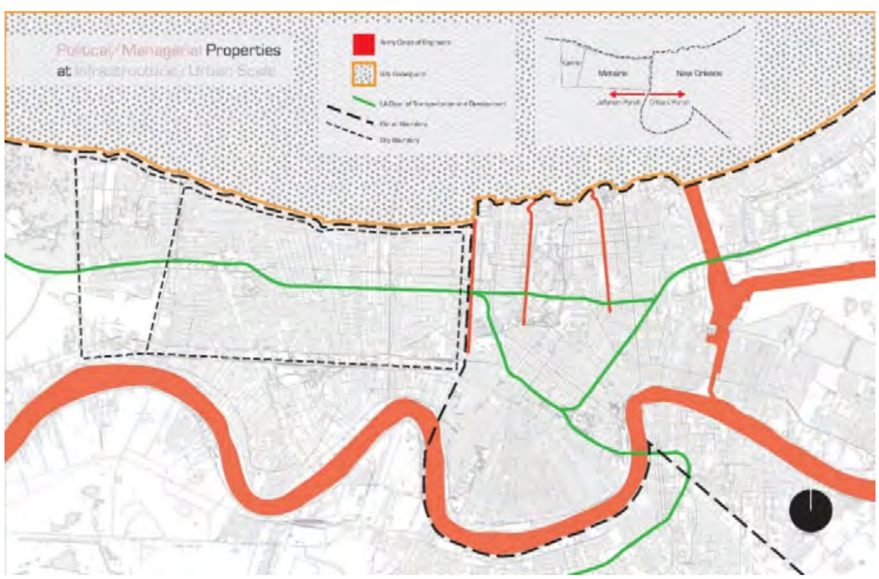

Fig. 2. Political (and managerial) aspects at the urban scale, showing the New Orleans–Metairie divide, as well as the areas overseen by the Army Corps of Engineers versus the U.S. Coast Guard developed by a student (developed by Jordan Farho).

Looking at Fig. 2, water sources that affect flooding and flood management in New Orleans, namely Lake Pontchartrain and the city canals, are overseen by two different institutions. The Army Corps of Engineers oversees the Mississippi River and canals within the two cities, whereas Lake Pontchartrain is overseen by the U.S. Coast Guard. Despite the differences in oversight, these two systems are interconnected; the water in the canals is pumped into Lake Pontchartrain to control canals' water levels and prevent the city from flooding. Therefore, the water level of the lake is subject to constant fluctuations. Among these canals, the 17th street canal functions not only as a water management system, but also as a dividing line between New Orleans and Metairie, two cities with social and economic differences. This region of the lake was chosen as the studio's site for designing a floating building due to its many interesting dimensions. The next section briefly overviews precedents of floating architecture and prototypes before reviewing the details of the studio in the following section.

Floating architecture

In architecture, "a floating building is usually a lightweight structure that rests on a buoyant base or foundation designed to rise and fall with the level of the water" [2] . Thus, for it to float, the buoyancy of the platform must exceed the weight of the building. The floating building is usually tethered to mooring posts that allow it to move up and down (with changes in water level) but prevent it from floating away.

As Barker & Coutts, (2016) explain, floating architecture is feasible where water depths exceed 1 meter (or about 3 feet) [2]. Taller floating buildings require greater water depths, or *draft* (a term used in naval architecture) to provide sufficient buoyancy for the weight. It should also be noted that floating buildings are best suited for static bodies of water, such as purpose-built docks and inland lakes, where water level variations are predictable, and flows are usually low. Therefore, for implementation, robust planning guidelines and building codes are required.

From a different perspective, some legal issues have proven to be complex and problematic. The traditional bureaucracy surrounding the construction industry and its financing are based on the assumption that the results of the construction is real estate property, which is inherently immobile. It is true that houses on the water are not intended to move to as great an extent as mobile homes, but towing them to another site or location, is certainly possible in principle [5].

Knowing that many types of floating structures are used in construction, natural materials such as straw, bamboo, and wood have been used historically by indigenous populations to make lightweight buildings designed to rest on raft structures. Timber, fiberglass, steel, and aluminum hulls are often found in houseboat design due to their structural and material efficiencies. More recently, alternative construction methods have been explored for higher levels of stability, durability, and minimal long-term maintenance. Modern materials employed in such construction include composites, such as polystyrene and concrete rafts.

The use of platforms to design floating buildings has many precedents. A well-known project is the Makoko school, a floating prototype. Its structure is built like a pontoon, on a series of plastic drums or barrels, making it less vulnerable than regular construction to flooding and extreme weather. It also harvests rainwater, recycle waste, and use renewable energy [6]. Its use of hollow plastic drums encourages questions related to material density and its relationship with buoyancy. Another example includes the floating pavilion in Rotterdam's city port, [7] with a total floor area of 1,104 square meters. The pontoon is made of expanded polystyrene (EPS) combined with a grid of concrete beams. Its geodesic domes are covered with lightweight ethylenetetrafluoroethylene (ETFE) foils [8]. Its combination of concrete and polystyrene creates buoyant platforms that offer greater durability and strength than the plastic barrels used in the Makoko school. Another example is Project Waterbuurt West, the largest floating house community in the Netherlands, consisting of houses constructed on piles and houses floating on the water [9]. The outline of each house is 70 m^2 (about 753 ft^2), with an immersion of 1.5 m (about 5 ft), while the maximum weight calculated for the house is just above 100 tons (about 200,000 pounds). The limitation on the depth of the water on which the apartments float encourages questions around not only material combinations but also on finding geometric configurations that can float in shallow waters. Finally, Seoul's floating islands are an example of very large floating structures (VLFS) consisting of three inter-connected islands [10]. The buoy on which the islands float is secured by 28 mooring chains to ensure it can withstand changing river levels and bad weather. This precedent encourages questions around how to prevent a buoyant artifact from floating away while allowing it to rise and fall with changes in water level.

Floating systems, artifacts, and ecosystems have also been explored by architects and researchers in an academic setting. Roger Hubeli and Julie Larsen of Aptum Architecture prototyped Isla Rhizolith, a floating concrete breakwater intended to revitalize Colombian shorelines [11]. Coleman Coker of the Gulf Coast DesignLab designed and built a floating camping site in Sea Rim State Park in Louisiana [12]. Moreover, Adam Marcus designed a prototype of a resilient coastal infrastructure [13]. The curved geometry of this prototype paired with the detailed curvilinear patterns on its surface encourages questions around how a designer can create freeform surfaces, and how to then realize these forms. Therefore, the CAD environment for creating these forms, followed by CAM methods for fabrication, is highlighted. There are many methods for implementing CAM, including 3D printing—an additive method—and CNC routing—a subtractive method.

Float'n'rise Studio

Float'n'rise is an Option Studio at the Louisiana State University (LSU) School of Architecture comprising fourth and fifth-year undergraduate students as well as third-year graduate students. The Bachelor of Architecture Program at LSU is a ten-studio sequence, while the Master of Architecture Program is a six-studio sequence. Rather than advocating for a traditional notion of building in South Louisiana, one that aims to protect buildings "against" water, this studio explores the concept of designing "with" water. Designing buildings that freely float on water to better respond to sea level changes, while attempting to enhance the natural ecosystem of the lake forms the core of this studio.

In the Fall 2018 studio, studying floating building precedents studio led students to consider two important design strategies that affect buoyancy: the geometric form and material of the buoyant platform. Investigating form and material in an abstract way was a key part of the studio even before the intervention design stage. Regarding form, students were taught the concept of buoyancy via exploration of the center of gravity and of buoyancy of different geometric shapes using CAD.

Following CAD, two methods of fabricating free forms, 3D printing and CNC routing, were explored. Students were encouraged to create patterns to enhance habitation by marine life. Creating the same surface using two different fabrication methods enabled students to compare the processes as well as the quality of the surfaces. From a different perspective, some students took an interest in exploring materials by conducting hands-on experiments with plaster, concrete, and foam to understand how composite materials with different densities can be employed to design a buoyant platform. The next three sections describe how each of these initial studies was implemented.

Computational studies: Center of buoyancy simulations

Understanding the concept of buoyancy is key for designing a floating building. Geometry and material choice both play a role in designing the buoyant surfaces. A small-scale project was defined to explore geometry's effect on buoyancy in floating structures. Rhinoceros, modeling software developed by McNeal, is capable of calculating center of gravity and center of buoyancy with an assumed water line elevation. Students were asked to explore how changing the geometry shifts these two centers in different geometrical shapes (Fig. 3). Students explored how the buoyancy in the z-axis decreases when the base thickness increases (Fig. 3- top row), how the center of buoyancy leans towards the bottom of the surface when a mass is added to a flat bottom surface (Fig. 3- middle row), and how creating a void or removing material pushes the center of buoyancy away (Fig. 3, bottom row).

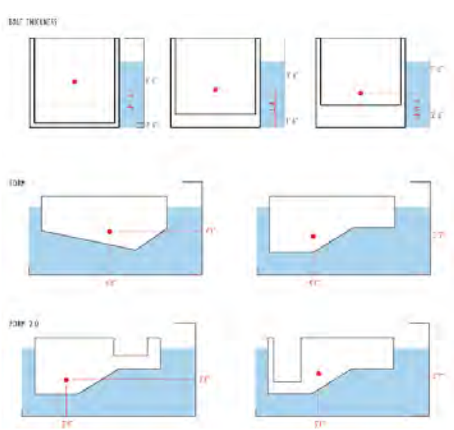

Fig. 3. center of gravity and center of buoyancy studies by Anne Kellerman, Julia Scheuermann.

Process studies: CNC milling and 3D printing

One of the technology education sections of the studio includes education on computer-aided design (CAD) and computer aided manufacturing (CAM) production. The additive and subtractive CAM methods—namely 3D printing and CNC routing, were introduced respectively. The students were asked to design forms, surfaces, and textures using CAD methods, and explored production using additive and subtractive techniques. Surface textures were a subject of study in employing different techniques, as the designed surfaces can be textured either through design or through CNC tool-pathing (Fig. 4). Learning to work with these methods while comparing the texture of the outcome was one of the learning goals.

Fig. 4. Surface studies of 3D printing versus CNC milling developed by Amir Hussain, Bristie Smith & Jeremy Gremillion

Material studies: Composite buoyant materials

With respect to material investigations, students were asked to research the materials and construction techniques used in precedents of floating architecture. A group of students took an interest in hands-on material experimentation, building composites of foam and plaster and testing how these would float. The experiment was an exciting moment for them, as they experienced the feasibility of floating architecture, and how composite material comprised of two materials with different densities can float on water. Later, they used mold-making techniques to create a pattern for the floating portion of their structure (Fig. 5).

Fig. 5. Material studies conducted by Amir Hussain, Bristie Smith & Jeremy Gremillion

Design projects

Working in groups of two or three, students studied a section of Lake Pontchartrain's shoreline on the north side of New Orleans. They then identified a problem in the site and proposed a location for intervention to help ameliorate the identified problem. Finally, they imagined a possible future floating project based on this imagined intervention. As the instructor, I summarize some of my higher-level pedagogical findings:

Program: Students were free to develop the program of the design interventions. On one hand, this opportunity allowed them to focus on the CAD/CAM aspects of the studio. On the other hand, some were carried away in developing the program. Although there were square footage limitations, some proposed programs operated in two phases (normal vs. disaster). The increased complexity of these programs distracted students from the main thrust of the studio. The scale and complexity of the *program* must be controlled so that it does distract from the learning goals.

Buoyancy: Exploring center of buoyancy using CAD was effective. However, when students reached the point of designing an intervention, many students had difficulty implementing it, and used columns in their initial sketches. I believe making a floating object/geometry paired with CAD exploration could have enhanced CAD integration at the design phase.

Access: The section of Lake Pontchartrain chosen as the project site introduced more complexities (and design opportunities). One of the challenges of the project was the limited depth of the lake along the shoreline. Therefore, to design a floating building, students needed to move further into the lake to reach a minimum depth of eight feet. This condition challenged them to design (or to ignore) the access paths from New Orleans and Metairie shoreline to the entry point of their intervention. Therefore, *access* became critical and pushed some projects to have a landscape scale. Also, upon moving into the lake, I noticed that a *breakwater* needs to be designed for the design interventions. Therefore, a research project on infrastructures and breakwater structures was added to the curriculum to prepare students.

Surface patterns: Exploring design patterns using additive and manufacturing CAM techniques was fascinating to the students, and the scale and freedom of the defined project worked very well. However, not many of those patterns were carried forward to the design interventions. Perhaps scaling up the patterns understood as the building envelope would have a stronger pedagogical effect for later implementation in the design interventions.

Material composite: Exploration of composite materials was not part of the studio curriculum. However, after seeing its positive effect on students' learning when a group voluntarily conducted it, I believe it should form a key part of studio, enhancing both the design of the buoyant platform and surface patterns.

Here, the students' projects are analyzed regarding their proposed program, buoyancy, access, and surface patterns, to discuss how the learning methods led to their implementation in the design interventions.

Weathervane (Jordan Farho, Chryshanna Williams):

As presented in Fig. 6-top-left, a floating amorphous form covered with glass and high-tech engineering plastics acts as a scientific and quantitative method of observing nature. This form is nested inside the vernacular decking, allowing for qualitative observation of the visually and physically changing environment. The proposed *program* had the right scale. The amorphous form created using CAD is a direct result of working with free-form surfaces and understanding how they can be fabricated. Designed as a *buoyant* blob, the compartments at the bottom of the intervention are designed to reduce density, while increasing the mass against the buoyant force of the water to make it float. The design intervention is *accessible* only by boat. *Surface patterns* were not translated to this design intervention, which fit the concept. This project met the studio's goals.

Bird Up: The Lake Pontchartrain Bird Haven (Henry Bein, Josh Nicols): This project (Fig. 6-top-right) provides habitat for migrating birds and a rehabilitation program for injured or oiled birds, while providing education and recreation for people. The *program* was the right size, aligning with the context. Regarding *buoyancy*, the principles of boat hull design were implemented to conceptualize a floating platform made of steel, hollow pockets, and wood. This design decision was based on students' understanding of materials and their effect on floating. The project resolved *access* by distancing itself from human society and becoming a floating island attached to the existing Breakwater park peninsula breakwater. *Surface patterns* were not translated to this design intervention, a missed opportunity, especially given the program focuses on birds. This project successfully met the studio's goals.

Communal Archetype (Anne Kellerman, Julia Scheuermann): The Communal Archetype aims to provide a location for cross-disciplinary education, communication, and decision-making open to all people. The vision is that it will host leading officials from the neighboring parishes of Orleans and Jefferson (otherwise separated by the 17th Street Canal). The main meeting room is responsive to the occupation of the center by the public, descending in the water as more people are present in the center, demonstrating people's power to affect the decision and make a change (Fig. 6-center). The *program* had the right scale and was well-contextualized. The students successfully combined the concept of *buoyancy*, by designing the hollow compartments and using materials with low density such as wood, as well as by integrating the concept of buoyancy to their core design concept: designing a room for policy makers that sinks in water as more people attend. From a different perspective, designing a freeform shell surface to cover the space was affected by their understanding of CAD/CAM exercises conducted at the beginning of the studio. *Surface patterns* were not translated to this design intervention. To resolve *access*, they used an existing breakwater along the lake with appropriate water depth for their site. This project successfully met the studio's goals.

Floating Nexus (Annan Wang, Cory Natal): Defining the *program* as a center for circulating knowledge and people, the structure is a passageway that meshes both architectural and landscape design to make the floating building connected to the city. Implementing *buoyancy* was a challenge in this project. However, *surface patterns* were successfully integrated into the design intervention; the surface curvatures on the top and bottom of were designed to attract birds and marine creators, respectively. The curvatures were combined with the access pathways to the intervention, starting from the shoreline, then going underneath the intervention, before wrapping around the intervention. *Access* was designed through the same pathway. The effect of CAD/CAM exercises was obvious in the development of this project, which met the studio goals to a good degree.

Bucktown Reef (Amir Hussain, Bristie Smith, Jeremy Gremillion): The *program* of this project revolved around fishing, boating, and cuisine, features vital to the cultural identity and traditions of Lake Pontchartrain. It is a floating fish market that allows the fishermen to sell fish off of their boats, combined with a restaurant that is sourced by the market's vendors (Fig. 6-bottom). The *buoyant* platform was combined with *surface curvatures* investigated earlier using CAD/CAM techniques. A breakwater attached to an existing breakwater was designed to provide *access* for pedestrians while also providing boat access for fishermen. This project exceeded the studio's goals.

H.E.R.C. Hurricane Education + Response Center (David Oliver, Brendan Bailey): The *program* was defined as educating about the dangers that hurricanes pose, while functioning as a search and rescue center following storms. The program was complex, as it needed to be designed for two phases of operation. This project employed the concept of *buoyancy* for designing the hull of the intervention—inspired by buoyancy studies—however, it did not implement *surface patterns*. *Access* was not also fully resolved. This project met some of the studio's goals.

Fig. 6. Weathervane (top-left); Bird Up (top-right); Communal Archetype (center); Bucktown Reef (bottom)

Discussion

This studio took a non-traditional approach in speculating on design possibilities in Southern Louisiana. When levees, canals, and pump stations fail to protect already elevated buildings from the water inundation, it might be time to consider what else can be done to mitigate this problem. Students conducted in-depth site analysis, identified a site, and formulated a program around the identified problem. Afterward, they experimented with CAD and CAM processes and materials before designing a floating intervention.

The course evaluations indicate that the subject of the studio was challenging but interesting for the students. One student stated "I highly appreciate the professor's enthusiasm and interest in exposing the students to new programs and pushing our abilities. The challenge was both exciting and rewarding." Another student spoke more to the ambiguity and struggles in the studio by stating: "Overall, I am pleased with the results, but it was a definite struggle to wrap my talents and mind around something so big and undefined." From a different perspective, the education process seems to have been effective, as a student stated: "the process of this class has been very successful. I believe the teacher held students to a high level."

Upon reading the course evaluations I noticed that many students who took this "option studio" were interested in its material exploration and fabrication aspect. They believed the scope was wide, and some of them viewed the extensive site investigations as an element that could have been minimized. As the instructor, I believe the extensive site analysis resulted in rich and diverse problem identification followed by interesting program proposals. However, fitting an extensive site investigation and material/fabrication process investigation into one semester does not seems feasible, and I would seek to modify the studio in future semesters

Conclusion

This studio explored innovative design practice for designing with water in Southern Louisiana using advanced CAD/CAM techniques and composite material studies. The use of CAD/CAM methods facilitated exploration of complex problems, as well as validation of the feasibility of proposed solutions. However, mastering many of these techniques has a deep learning curve, meaning that for students to flourish, they should either have some level of understanding of the methods before enrolling in the studio; experiment further with these techniques in a parallel course; or focus more on the material exploration and digital design and fabrication aspect of the studio rather than conducting extensive site investigations or working with complex programs. By focusing on material explorations using CAD/CAM techniques, and by reducing the scale of the design intervention, small-scale prototypes can be made that can actually be tested on water. This will be an interesting improvement in future studios. This approach can also highlight how experiments translate into a prototype through an iterative design process.

Acknowledgments

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Integration of Building Energy Modeling (BEM) and Building Information Modeling (BIM): Workflows and Case Study

Mahsa Farid Mohajer, Ajla Aksamija
University of Massachusetts, Amherst, MA, United States

Abstract

Building Energy Modeling (BEM) intends to quantify buildings' energy performance to help designers and architects better understand the environmental impacts of their decisions. Building Information Modeling (BIM) refers to a digital, model-based representation, where information about building design can be shared among different stakeholders and used during all stages of buildings' lifecycle. The purpose of this research was to investigate integration of BEM and BIM, using one modeling and two analysis tools. Green Building Studio (GBS) and Sefaira are two performance analysis software programs, which can be used both in the form of BIM plug-in/built-in tools, as well as web applications to analyze and quantify energy performance of buildings. To capture their level of integration with BIM, an existing Campus Recreation Building on UMass Amherst campus was used as a case study to evaluate modeling processes, requirements, and workflows. Comparative analysis between modeled and actual energy consumption data was also performed to analyze accuracy of the different simulation programs. This paper discusses each tool capabilities and drawbacks in providing accurate energy analysis procedures and results.

Introduction

Understanding buildings' energy performance and the environmental impact has been a central theme in building technology research, education and professional work over the past two decades. However, integration of Building Information Modeling (BIM) and Building Energy Modeling (BEM) is a new concept, requiring significant research and development (Augenbroe et al. 2004; Senave and Boeykens 2015). BIM process creates a digital prototype of a building in 3D format, including integrated information about the design, materials, specifications and construction methods. BIM offers significant advantages throughout every step of buildings' lifecycle. Design issues can be addressed and improved earlier in the design phases. Its 3D modeling capabilities allow improvement in construction planning, and easy access for facility managers to detailed information about building systems, thus supporting building operation and maintenance. BEM, on the other hand, is a process of creating buildings' energy models in order to capture and evaluate their energy performance and to quantify the impacts of design decisions on energy consumption. Integration of BIM and BEM tools has the potential to streamline design, documentation, and building performance analysis. However, integration not only requires streamlined incorporation of BIM and BEM tools, accuracy of analysis results is also crucial.

Literature Review

Energy consumption analysis and simulations are necessary for various building sustainability rating systems, such as Leadership in Energy and Environmental Design (LEED), developed by the U.S. Green Building Council (USGBC) (Kim and Anderson 2013). BIM-BEM integration from the early stages of architectural design is a crucial step towards energy conservation and high-performance buildings (Aksamija 2013). With the integration of parametric design capabilities and BEM, multiple design scenarios can be rapidly and cohesively tested. BEM and parametric design have been integrated in a study to design a building facade (Aksamija 2018). This research investigated the workflow between Rhino as a 3D modeling tool, Grasshopper plugin as a parametric design program, Honeybee and Ladybug plugins as parametric performance simulation tools. Ladybug connects Grasshopper to the EnergyPlus engine and Honeybee connects with different performance simulation engines: EnergyPlus, Radiance, and Daysim. Various geometry and performance parameters were tested, which allowed for numerous analyses and result comparisons (Aksamija 2018). In another study, energy performance simulation results from two BEM tools (Green Building Studio and EnergyPlus) were compared against the results of a proposed framework (Kim and Anderson 2013). The framework included: 1) BIM creation in ArchiCAD, 2) extracting geometrical and spatial data through IFC file format, 3) 3D remodeling for a quick visual check using Google SketchUp, which has built-in Ruby programming language and can read the IFC input files, and 4) running DOE-2.2 simulation engine to compare results from this framework and results from GBS and EnergyPlus simulations. The results were comparable, considering various energy simulation engines, and also geometry/spatial information being reconstructed for the proposed framework (Kim and Anderson 2013). Therefore, interoperability capabilities of the tools, as well as ability to comprehensively represent buildings in a way that they really exist or will be built are paramount.

BEM Engines and Tools

Accuracy of BEM tools and their level of integration with BIM varies depending on their capabilities in providing an array of input options (Kim and Anderson 2013). There has been ongoing research on BEM tools and engines aiming to develop and enhance more comprehensive simulation programs. DOE and EnergyPlus are the two widely used energy simulation engines. DOE was first developed by the U.S. Department of Energy in 1976, and the commonly used version of it, DOE-2.2, was last released in 2009 (Maile et al. 2007; Birdsall et al. 1990). EnergyPlus, the U.S. Department of Energy successor to DOE-2, was developed in 2001 aiming to incorporate DOE-2 features and heat transfer calculation capabilities (Kim and Anderson 2013).

Some of the predominant BEM tools are RIUSKA, GBS, eQuest, and DesignBuilder (Kim and Anderson 2013). RIUSKA was first developed in 1996 as a Graphical User Interface (GUI) for DOE-2.1 (Maile et al. 2007). GBS was first launched in 2004, and it later became an Autodesk-affiliated program that runs on DOE-2 engine (Autodesk n.d.). eQuest was developed by James J. Hirsch in 2005, and DOE-2.2 has been its analysis engine. However, recently, DOE-2.3 simulation engine has been introduced as the latest version, which will be a full replacement to DOE-2.2 in the future (Hirsch n.d.). This tool only supports DWG and gbXML input files, which each has its own limitations. DWG inputs enable importing of building's footprint into eQuest, however, various floors cannot be distinguished. In addition, gbXML input files for complex geometries may result in simulation errors and issues (Maile et al. 2007). DesignBuilder, on the other hand, is an interface for EnergyPlus engine that allows for gbXML input files and was first introduced in 2005 (Thermal Energy System Specialists n.d.).

BIM-BEM Data Exchange Methods

Data exchange between BIM and BEM applications is not a seamless task and usually requires manual intervention and data transformation. The two predominant data exchange options are; Industry Foundation Class Extensible Markup Language (ifcXML) and green building Extensible Markup Language (gbXML), both supported by major BIM software developers.

Nevertheless, because of the interoperability shortages and energy analysis procedure being time-consuming, designers often leave it to electrical and mechanical engineers later in the design process. This results in less energy conscious and non-optimized designs (Kim and Anderson 2013; BuildingSMART n.d.).

Research Objectives and Methods

The purpose of this research was to investigate integration of BEM and BIM tools, specifically Green Building Studio (GBS) and Sefaira, as two different BEM programs that are compatible with Revit as a BIM application. The following objectives were addressed:

1. To investigate the two tested BEM tools by comparing their modeling and simulation procedures and results.
2. To investigate GBS as a Revit built-in and as a web application.
3. To investigate Sefaira as a Revit plug-in and as a web application.
4. To investigate Revit in assigning thermal properties to its BIM model.

The research methods included data collection, modeling, simulations and comparative analysis of results. Research workflow is shown in Figure 1.

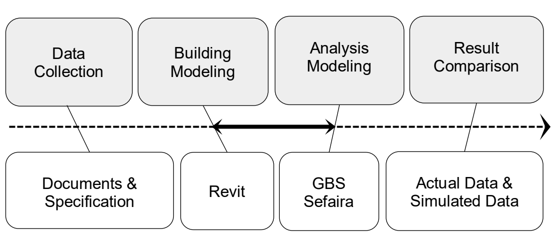

Fig. 1. Research workflow.

Case Study Introduction

For the purpose of this research, Campus Recreation Building on UMASS Amherst campus was selected as an existing case study building. Monthly electricity and steam consumption data was collected for a year-round operation cycle in the year 2017. Results from each analysis software program were then compared to the actual energy consumption data, used as the baseline. In order to provide a valid data comparison, all units were converted to kBtu. And, given the building area, Energy Usage Intensity (EUI) of the building was calculated.

Building Information Modeling (BIM)-Autodesk Revit

The original construction documentation for the case study building was collected and reviewed in order to create a 3D model in Autodesk Revit (as a BIM application), as shown in Figure 2.

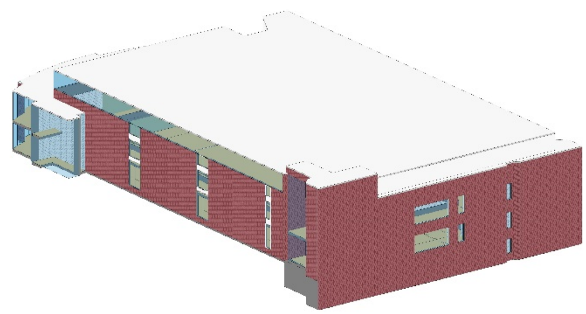

Fig. 2. Case study building BIM model created in Revit.

Following the building specifications, glazing types were assigned to windows and curtain walls as shown in Table 1.

Table 1. Case study building glazing types used in the BIM model.

Glazing Type	VT	U-Value (Btu/h.ft^2.°F)	SHGC
Double Glazing Low-E Clear Glass	0.7	0.3	0.38
Double Glazing Low-E Fritted Glass	0.39	0.3	0.24

In order to properly define building envelope thermal properties in Revit, thermal conductivity (λ) of some of the materials were extracted from ASHRAE Handbook

(ASHRAE 2013b). For other materials, based on their thicknesses (from the collected documents) and/or their R-values (from ASHRAE 90.1, and collected documents), thermal conductivity was determined as shown in Table 2 (ASHRAE 2016).

Table 2. Material thermal conductivity used in the BIM model.

Material	λ[1] Btu/h.ft.°F	λ[2] Btu.in/h.ft^2°F	Thickness (inch)	R-value h.ft^2.°F/Btu
GWB	0.09	1.12	0.63	0.56
EPS	0.02	0.20	2	10
Metal Plate	0.02	0.20	0.37	1.82
Cast in Place Concrete	0.64	7.69	6	0.78
Batt Insulation	0.03	0.32	6	19
Semi-rigid Fiberglass	0.02	0.24	4	17
Steel Deck	16	192	4	0.02
Grout	1.73	20.76	2	0.10

λ[1]: Thermal conductivity applied in Revit
λ[2]: Thermal conductivity extracted form ASHRAE Handbook (ASHRAE 2013b)

Building envelope R-values in BIM was automatically calculated based on materials' thermal conductivity and thickness inputs. These R-values were different from the add-up of layers' R-values, which were calculated based on the following equation:

Equation 1. R-value calculation equation.

$$R - value = \frac{Thickness}{Themal\ Conductivity}$$

This discrepancy between Revit-calculated/assigned R-values and add-up R-values for the building envelope is shown in Table 3. It is one of the BIM drawbacks since R-values are automatically assigned without providing the opportunity for users to edit values.

Table 3. Building envelope Revit-calculated and add-up R-values.

Building Envelope	Add-up R-value (h.ft^2.°F/Btu)	Revit R-value (h.ft^2.°F/Btu)
Brick Cavity Wall on Metal Stud Framing	19.66	17.96
Metal Deck Roof	18.84	18.06

Building Energy Modeling (BEM) Tools-GBS and Sefaira

The focus of this research was on the application of two BEM tools: Green Building Studio (GBS) and Sefaira. GBS is a Revit built-in whole building energy analysis tool that runs on DOE.2 engine. Sefaira, on the other hand, runs on EnergyPlus analysis engine, and it is a plug-in program that needs to be installed within the BIM environment. Inputs for the BEM tools were collected from documents and building standard codes, as shown in Table 4 (ASHRAE 2016, 2013b, 2013a).

Table 4. BEM inputs taken from the building standard codes.

Variables	BEM Inputs
Operation Hours[1]	9am-9pm
Ventilation[2]	20 (cfm/person) or 0.18 (cfm/ft^2)
Occupancy Heat Gain[1] (Sensible-Latent)	710-1090 (Btu/h-person)
Occupancy Density[1]	33 ft^2/person
Plug Loads Density[1]	0.95 (W/ft^2)
Light Power Density[1]	0.68 (W/ft^2)
Setpoint Temperature[1] (Cooling-Heating)	75-70 (°F)
Setback Temperature[1] (Cooling-Heating)	85-60 (°F)
HVAC[3]	VAV

1. ASHRAE 90.1
2. ASHRAE 62.1
3. Building documents/specification

Simulation and Analysis Results

GBS as a built-in application in BIM allows for energy analysis within Revit without a need for data transferring. It is necessary to define energy settings and create an energy model directly in BIM, as shown in Figure 3, in order to run GBS analysis.

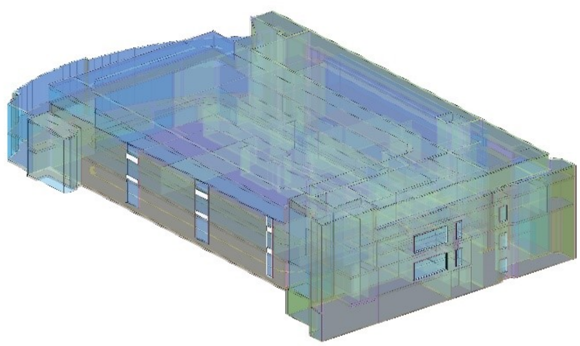

Figure 3. Green Building Studio (GBS) energy model created in Revit.

However, this built-in tool does not allow to assign detailed BEM inputs as indicated in Table 4. In addition, although the building typology was selected to be gymnasium in Revit's energy setting, built-in GBS assigned it as an office. This indicated that the built-in GBS could not properly read data presented in BIM, which affected monthly/annual energy consumption data and EUI of the building.

In order to assign necessary BEM inputs and to select the right building typology, BIM model had to be exported in gbXML file format from Revit, and imported into GBS web application. Results and comparison between the two energy analyses are shown in Table 5. As shown in the table, electricity usage did not change dramatically. However, gas consumption was significantly higher when simulated in GBS web application.

The case study building's heating system used district steam, provided from the Central Heating Plant (CHP) distributed to various buildings on campus. Considering that CHP gas consumption data for the steam production purposes was not available, simulated-gas was compared against actual-steam consumption in this research. This steam vs. gas comparison is one of the deficiencies of the BEM tools since they do not provide a variety of possible heating sources and systems. Since energy efficiency of district steam-based HVAC systems is higher than the local gas-based system, it was expected that simulated monthly and annual gas consumption data to be higher than the actual steam usage (Rezaie and Rosen 2012). However, in the built-in GBS analysis, gas consumption was either close or lower than the steam usage, as shown in Table 6.

This confirmed that the built-in tool did not provide valid simulation results. As shown in Table 6, the overall monthly and annual gas consumption in GBS web application was higher than the actual steam usage. Given that the web application allowed for building typology selection, BEM inputs procedure, and it provided more precise gas consumption data, it was concluded that GBS web-based simulation is more valid than the built-in version.

Table 5. Energy consumption comparison between GBS Revit built-in and GBS web-application.

	Electricity Use (MBtu)		Gas Use (MBtu)	
Month	**Built-in**	**Web Application**	**Built-in**	**Web Application**
Jan	406	420	1000	2311
Feb	338	285	618	1444
Mar	358	294	450	1015
Apr	317	314	255	577
May	365	432	100	249
Jun	392	497	35	192
Jul	443	586	15	166
Au	450	591	20	163
Sep	382	480	35	174
Oct	324	326	150	384
Nov	324	281	300	751
Dec	361	314	615	1505
	Annual (MBtu)			
	4500	**4800**	**3600**	**8900**

Table 6. Actual steam usage vs. gas consumption data from GBS (built-in and web application).

Month	Monthly Steam/Gas Use (MBtu)		
	Actual (Steam)	Built-in (Gas)	Web Application (Gas)
Jan	967	1000	2311
Feb	663	618	1444
Mar	821	450	1015
Apr	465	255	577
May	386	100	249
Jun	236	35	192
Jul	163	15	166
Aug	160	20	163
Sep	333	35	174
Oct	430	150	384
Nov	502	300	751
Dec	869	615	1505
	Annual (MBtu)		
	6000	**3600**	**8900**

Similarly, for Sefaira as a Revit plug-in application, input data can only be adjusted through the *Real Time Analysis* slider rather than assigning certain numbers. However, with Sefaira web-based application, exact input values can be inserted. For the purpose of this research and to apply certain BEM inputs, Sefaira was used in the form of web application. One other drawback of Sefaira was that it only presented a limited list of building typologies (for both the plug-in and web application), which did not include gymnasium or recreational building type. And, school was the closest option to choose for the purpose of energy consumption simulation. This was one of the major drawbacks of Sefaira analysis tool since building typology has a significant impact on energy consumption data due to various scheduling, occupancy, lighting, and equipment requirements.

BEM tools create their analysis models based on *Rooms* assigned in 3D BIM model. They create an analysis model comprising of spaces and surfaces, which eventually affect building area calculations. In this research, even though the exact same BIM model was used to create BEM analysis models in GBS and Sefaira, they both read it differently. This different BIM model treating impacted the calculation of building areas in BEM programs. For instance, in Sefaira, areas with less than 43 ft^2 were ignored since they could crash EnergyPlus analysis if included in the BEM model.

In Table 7, simulated monthly and annual energy (electricity and gas) consumption in GBS and Sefaira web applications are shown against the actual consumption data. GBS's monthly and annual electricity consumption was close to the actual electricity usage data. Its gas consumption was higher than the actual steam usage. In contrast to GBS, Sefaira monthly and annual energy (electricity and gas) consumption was much lower than the actual data. Therefore, the calculated EUI was very low. However, GBS EUI was almost double of the actual EUI, which was due to gas vs. steam comparison, as well as different building area calculations.

Table 7. Energy simulation results (Sefaira and GBS) vs. actual energy usage in the case study building.

	Monthly Electricity Usage (MBtu)			Monthly Gas/Steam Usage (MBtu)		
	Actual	GBS	Sef.	Actual	GBS	Sef.
Jan	360	420	164	967	2311	335
Feb	334	285	150	663	1444	284
Mar	335	294	174	821	1015	227
Apr	364	314	159	465	577	108
May	510	432	198	386	249	24
Jun	389	497	236	236	192	2
Jul	450	586	260	163	166	0.3
Aug	493	591	248	160	163	0.8
Sep	562	480	198	333	174	12
Oct	425	326	183	430	384	48
Nov	332	281	168	502	751	149
Dec	344	314	148	869	1505	247
	Annual Usage (MBtu)					
	4900	**4820**	**2286**	**6000**	**8932**	**1438**

In Table 8, total annual energy consumption, building areas and types, EUI, and percentage differences are shown. Since the case study building was an existing building, its energy consumption data was used as a benchmark for the percentage differences calculations.

Table 8. Baseline (actual) and simulations data comparison.

	Baseline	GBS (Web Application)	Sefaira (Web-Application)
Annual Energy Usage (MBtu)	10900	13752	3724
Percentage Difference	0%	**26%**	**-66%**
Building Typology	Gymnasium	Gymnasium	School
Building Area (10^3 ft^2)	160	99	108
Percentage Difference	0%	**-38%**	**-32%**
EUI (kBtu/ft^2/yr)	68	139	34
Percentage Difference	0%	**104%**	**-50%**

Discussion and Conclusion

Considering each BEM tool simulation procedure, and inability to properly define analysis models, it was concluded that neither of the investigated BEM tools was able to completely streamline design and analysis. They both were analysis tools within BIM Revit, which made their application easier, but not really integrated with this BIM application. Although GBS provided results that were closer to the actual data, it did not provide as detailed/precise BEM inputs as needed. For instance, district steam-based heating HVAC system was not an available input option for the analysis run. Comparison of GBS built-in results with that of web application did not indicate any gbXML data exchange/interoperability shortages since web results were closer to the actual energy performance. However, the BIM model was relatively a non-complicated 3D model. Research on more complicated models needs to be done to capture and investigate gbXML interoperability capabilities between GBS and Revit. In addition, another important step toward more integrated and accurate energy analysis is that BEM tools provide users with the ability to assign multiple spaces within the same building. In this research, building typology of the case study was gymnasium, but it had several other room/space applications such as offices, restrooms, and even unconditioned spaces. Different space applications result in various energy consumptions in the same building, which eventually affects the overall energy consumption. Sefaira provided the option to assign multiple spaces, including conditioned and unconditioned for the simulation. However, the ending results were not accurate since building typology could not be assigned as it really was in reality. It indicated that building occupancy type had a more significant impact on energy performance aspects comparing to assigning multiple space applications. Therefore, selection of BEM tools depends on a variety of variables such as interoperability capabilities, accuracy of results, workflows and the ability to integrate with BIM. BIM-BEM integration main objective is to incorporate energy performance analysis in the early steps of architectural design. However, it is not yet possible for investigated BEM tools to seamlessly work well with BIM. It is necessary to manually manipulate energy models created from BIM, assign and override input data, and properly define design parameters.

Further research is needed to investigate various BEM applications and evaluate their integration capabilities with BIM to improve the current state of knowledge about the BIM-BEM process. Results and findings of that research will provide a deeper understating of various tools, which can be used by a software developer company to develop a new tool that can improve interoperability, modeling capabilities and selection of inputs, as well as accuracy of results.

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Automated Comprehensiveness: Sectional Practices and the Misuse of Revit

Jessica Garcia Fritz
South Dakota State University

Abstract

All architectural drawings leave gaps in information. Drawing sets leave the impression that a combination of drawing types is comprehensive, that more information is better, but gaps always exist. In generating architecture, these gaps serve as opportunities for ambiguity, speculation, and exploration. The introduction of BIM in the late twentieth century and its more ubiquitous application in Autodesk's 2004 release of Revit, challenged these previous notions of orthographic comprehensiveness as many images could be output from a single digital model. As representational types, plans, sections, elevations, and details did not disappear. Yet, the historic and conceptual practice for generating architecture through them started to. In Revit, the particular disappearance of sectional practices has been impacted by the automation of the section cut. What is lost when section cuts are automated through a digital tool like Revit and how can the tool be used to support sectional practices once again? The studio work presented in this paper focuses on the ontological transition from orthography to BIM, the impacts of automated processes, and the role of implementing sectional practices in a post-orthographic setting by critically examining specific tools and commands used in Revit. Ultimately, the work exemplifies a pedagogical approach that stems from the "misuse" of Revit as an archaeological and generative sectional tool for exploring gaps in information.

Keywords: Pedagogy, Computational Design + Analysis, Structures, Materials + Construction Techniques

Orthography and BIM

Orthography is dead in architecture. Perhaps, this is too strong of a statement (and too soon) for those of us educated and practiced in orthography. It may be better to say orthography now belongs to the historical realm of mechanical processes that shaped the discipline and profession for hundreds of years. While Building Information Modeling (BIM) attempts to mimic familiar representational types in the forms of plans, sections, and elevations, as a tool it is fundamentally different in shaping space. This difference underlines the conceptual backing of the pedagogical approaches implemented in this work. In his essay, *Everything is Already an Image,* John May states "the notion that ideas exist apart from their technical formation (in the brain or "the mind") is one of the most pervasive fallacies of modern life".[1] May further positions architecture in a post-orthographic world by describing the ontological shifts from orthographic thinking to BIM thinking. Ultimately, May says, BIM makes us understand architecture and the world differently than orthography.

At the core of orthography lies mechanical gestures for arranging marks into geometrically based lines and texts.[2] For the orthographer, geometry is the organizational scheme for seeing, understanding, and structuring the world through conventions that have now been standardized through the discipline and profession. To practice architecture, one had to be able to make and read through these conventions. Additionally, the speed for recording gestures occurred at a rate in which decisions unfolded with the speed of making marks. Once complete, the drawing worked as a solidified representation of the orthographer's thought. The emergence of BIM disrupted this method of working as well as the decision-making rate for making space through commands. In BIM platforms, the rate of transformation is much quicker than orthographic methods leading to the processing of multiple options within the same timeframe.

Although the concept of BIM emerged in the late twentieth century, its ubiquitous implementation in architecture did not arrive until the early twenty-first century. Before its emergence, Nicholas Negroponte posited that "digital technologies first mimic the processes that they are designed to replace, then extend them, and eventually disrupt them completely".[3] This prediction from 1970 prophesized the emergence of Computer Aided Design (CAD) tools that provided a digital platform for orthographic projection. This initial technological wave then extended to digital platforms outside of architecture in the form of NURBS-based modeling tools used primarily in the manufacturing realm. From this second wave, a third wave of digital technologies were made possible in the form of BIM tools. They have completely disrupted the methods for making architecture through parametric processing.

The focus here lies primarily in one BIM platform, Revit, since the platform provides the specific tools under examination in this studio work. Revit's emergence in 1997 and its subsequent acquisition by Autodesk in 2004 coincides with the rise of BIM software in the architectural profession. The platform introduced an unfamiliar process for making architecture by presenting multiple possible outcomes through a single revisable digital model. The output of images through plan, section, and elevation views, however, remained familiar. As a representational type, plans, sections, and elevations did not disappear. Yet, the historic and conceptual practice for generating architecture through them started to.

Because BIM platforms are based in telegraphy, the processes for making and outputting images are largely unseen. Behind the simple rotation of a model or the multiple commands used to alter it are a series of calculations processed through electrical signalization. The differences between these quick electrical signals and the slower mechanical gestures that accommodate drawing lie in the speed and reflection built into both processes. In orthography, the slower speed for constructing a drawn line allowed for the point of decision-making to be made before the line was drawn, then to be reflected upon before the next line was placed on paper. Electrical signalization, on the other hand, lends itself to automation meaning questions pertaining to points of intentional decision-making as well as reflection remain open.

Automated Sections

Automation refers to the replacement of a human task with mechanical or telemetric labor. Though it is widely discussed alongside autonomous processes, those processes which have agency to act independently beyond the control of the individual operating the process, it is important to establish a difference between the two and to stress a focus on automation here.[4] In Revit (and BIM software), two levels of automation are at work in the production of a digital model. The first refers to the previously discussed telemetric processes that calculate the various possible outcomes of the digital model. Unlike mechanical processes, which are made visible through the movement of working parts like gears or hand-scaled gestures, telemetric processes conceal these calculations at a physical scale made non-visible to humans.[5] This is something inherent in BIM as well as other digital tools. The second level of automation relates to the specific commands or the default interface given in a platform. Sequencing commands within a digital space take place under radically different conditions than constructing lines on paper. In orthography, to draw a series of repetitive objects, for example, meant the lines for each object had to be drawn and the exact operations had to repeated again and again for each subsequent object. To digitally model a series of repetitive objects, on the other hand, means the initial object must be modeled and a copy or array command applied to quickly multiply the object. The outcomes may be the same, however, the operations for making the repetition are different. While certain efficiencies develop from commands that automate, it is questionable when this activity begins to automate thought and mental labor. It is this second level of automation that the studio work addresses by attempting to develop a more conscious approach through the misuse of sectional tools.

In Revit, sections are cut by placing a view in a model that is initially constructed from a plan view or they are revealed in three-dimensions through a section box. The accumulation of views cut from a model compose the final output of a project while carrying the notion that a combination of drawing types builds a complete and comprehensive drawing set. Unlike orthographic drawings, these cuts are not constructed through a collection of lines that represent the elements and spaces composing them. Instead, cuts are modeled in plan and automated in section, which points to a form of automation that replaces the mental labor of slowly constructing a section through lines. The work here, does not stem from a nostalgic call for a return to orthographic hand drawings. Instead, it examines how sectional practices can unfold through tools that no longer promote orthography.

Sectional Practices

Throughout history, the changing role of the section cut reveals sectional practices that have affected the way form and space were made during any given era. In architecture, a section is “a representational technique as well as a series of architectural practices pertaining to the vertical organization of buildings and related architectural and urbanistic conditions”.[6] Though it has become a standard drawing type in any set, a section was not one of the original drawing types that established the profession. In *the Ten Books on Architecture*, Vitruvius states that an architectural arrangement’s forms for expression are, “the ground plan (orthographia), elevation (ichnographia), and perspective (scaenographia).”[7] Each of these drawing types refer to the program of the building, the façade or main face of the building, as well as the experience of the building, respectively. The vertical organization of a building visualized through a section cut(s) is not mentioned. In fact, sectional drawings did not emerge through the architectural discipline, but instead as an archaeological act for discovering what already exists.

Archaeology of Sectional Practices

“Archaeology, as a discipline is devoted to silent monuments, inert traces, objects without context, and things left by the past, aspired to the condition of history, and attained meaning only through the restitution of historical discourse”.[8] Foucault’s definition of archaeology moves beyond the simple observance of objects by upholding discourse as a descriptive effort in identifying transformational ruptures in history. Here, archaeology extends to the rules and standards that emerged from the transformation of sectional practices during various eras. Alone, the origin of section does not entirely describe the shifts in architectural thinking that resulted from sectional practices. Rather, the transformational ruptures in sectional practices that stemmed from the cultural, social, and political conditions that defined these shifts led to codified architectural thinking that now impacts approaches to making section cuts in BIM.

As previously mentioned, the origin of section did not emerge through the architectural discipline, but as a reflective act in describing anatomy and architectural ruins. The description of the human body as well as the practice of recording the surviving decayed monuments from antiquity gave birth to the section as a conscious projection of architectural intentionality.[9] The crumbled remains of an architectural ruin already exhibited sectional features in the exposed material thickness of the remaining roofs or walls that served as mediators between exterior and interior spaces. The origin of the section cut, therefore, was a way to reveal what might otherwise be hidden.

The fifteenth-century, marks a transformational rupture in the standardization of the section cut in the architectural profession. Observers of the Pantheon documented the classical structure similar to other ruins, however, the Pantheon was not a ruined structure. In its completeness, observers sketched sections that speculated the relationships between interior and exterior spaces. In these early Renaissance drawings, dimensional accuracy was traded for the illusion of a perspectival scene. Section perspectives, therefore emerged as a tool for understanding space conceived and experienced volumetrically. In the sixteenth century, section further developed into a measurable drawing that combined the section cut with interior elevations in order to allow for geometric and dimensional accuracy. Additionally, the cut was made parallel to the picture plane. These Orthographic sections led to initial standards for making sectional drawings by further aligning the section with plans and elevations as a primary architectural drawing and tool.

What chronologically ensued were transitions that layered rules and standards onto the section cut and drawings. During the eighteenth-century Enlightenment era, sectional practices proliferated in architecture as interior volumes were drawn in relation to the exterior context of the site. In the nineteenth century Modernist era, sectional drawings delineated the interdependency of space and form through emerging industrial material relationships. Organization of these materials through a vertical cut demonstrated how building assemblies resisted and carried loads. In contemporary practice, the section cut has been subjected to a unique set of conditions that have ruptured traditional standards. Digital technologies like CAD and BIM have polarized the section as efficiencies have pushed toward volumetric repetition and sectional practices are automated rather than constructed. The pedagogical approach in this studio work anchors these historical layers as chronicled sectional practices that contribute to archaeological acts in generating new sections. The additional study of an existing building mimics the origin of section as a method for observing and recording ruins. In this way, established building assemblies are made present in the Revit interface.

The studio is a first-year, pre-comprehensive, graduate studio. Though most students enter the course with some exposure to Revit, they have less exposure to building assemblies. To model the existing building, students must learn the tool, identify the existing volumetric relationships inherent in the building through section, and develop a basic understanding of the present material connections and relationships. In the most recent version of the studio, students studied a former 1918 Stock Judging Pavilion, a pavilion for judging cattle, pigs, and sheep. The building was added to in 1926 to include the University’s Meat Lab, where previous generations of students learned how to slaughter and prepare meat. Today, the building serves as the University’s Agricultural Heritage Museum, a building program in desperate need of more space. The building assembly ties brick bearing wall construction to steel framed trusses (Fig. 1). The riveted gusset plates that hold the trusses together are remnants of the massive bridge building practices performed in the area during the early twentieth century. The building, in addition to early drawing sets, which include modernist section drawings, served as a basis for generating sectional practices through the misuse of Revit.

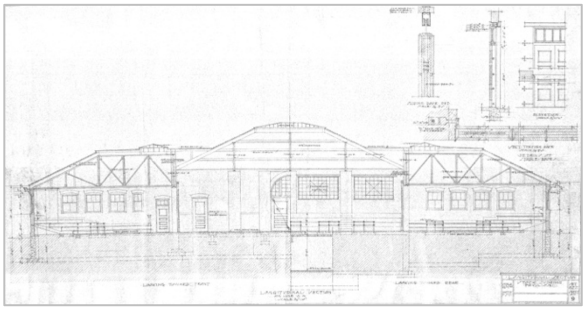

Fig. 1. Section Cut through the existing building.

Generation of Sectional Practices

The methodology established in the studio addresses the automation of sectional practices by identifying and misusing the commands or "tools" that cut sections in Revit. It is the second level of automation, the use of a specific command or a default interface, that this work seeks to confront. By layering the outcomes of two sectional tools and processes, the section work plane and the section box, section cuts are not only constructed, but examined through gaps in information.

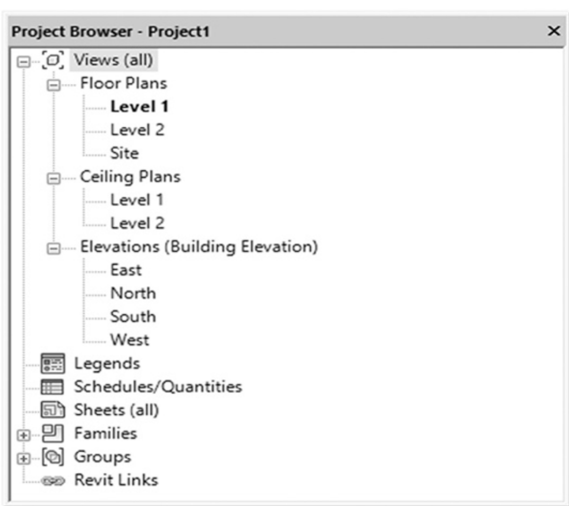

Fig. 2. No section view appears in the default project browser.

In Revit, a work plane is a virtual two-dimensional surface used primarily for the origin of a view.[10] Work planes are used for the attachment of sketched elements such as model lines and detail lines, for enabling other tools in particular views, and for placing work-plane based components. Automation of work planes lie in platform's default state. Upon opening Revit, a single work plane exists in the plan view or level one (Fig. 2). This points to the initial generation of digital models in plan, since elements must attach to an established work plane. The subsequent generation of a section cut or view is made by placing a section header in a plan or elevation view. Therefore, the first misuse of the tool, is the establishment of a default work plane in the vertical orientation for sectional elements to attach to.

The second misuse of the tool addresses the methods for constructing a section cut upon the newly established work plane. Rather than attaching system, loadable, or in-place families to the work plane, section cuts are "drawn" upon the work plane using model lines and details lines. Technically, these lines are modeled not "drawn" since they exist in three dimensions. By modeling each line, the process for constructing the cut is slowed in order to build an understanding of the tool as well as the elements and spaces resulting from the cut. Though this is not a form of orthography, since automated telemetric processes are present, other automated processes are surpassed as the section cut is constructed rather than taken from another view. In some ways, the method mimics CAD processes more than BIM. However, this method needs another sectional method as basis for comparison.

The section box (Fig. 3), serves as a tool in creating sectional relationships in Revit. It is applied to a three-dimensional view in order to limit the geometry shown in the view.[11] For the purposes of this studio, elements that lie beyond the plane of the section cut are modeled as elements rather than lines. They are categorized as modeled or cut elements. This descriptive effort is put forth to better define the role of these elements in the output image. A Modeled Element, for example, is a three-dimensional object placed behind the "drawn" section cut. It is automatically categorized by Revit according to its role in the building assembly. A Cut Element is a three-dimensional object that is cut through or it is hidden by the section box. Though the element is not deleted from the model and the data for the element is still present, the element is not visually present. Ultimately, the modeled lines constructed upon the vertical work plane in a two-dimensional section view and the modeled and cut elements created by a three-dimensional section box result in two methods for making section cuts in Revit.

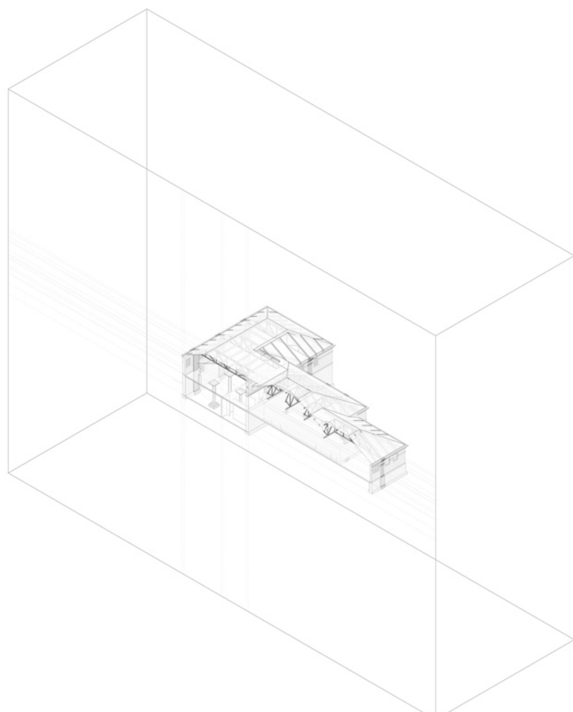

Fig. 3. The Section Box.

The third and final misuse of the tool involves the layering of both sectional methods into a final stitched view. In Revit, a Stitched View combines multiple views, plans, sections, elevations, and 3D views onto a layered sheet or image. It is as much a construction as the building and project itself. The overlap of both sectional methods introduces visual inconsistencies in the gap between both types. As one student pointed out in their completed project, these inconsistencies and gaps in information serve as opportunities for exploring imprecisions inherent in the platform. The initial focus of this student's project centered on the existing building working as a constructed building system rather than an assembly. The student observed how window openings were driven by units of brick rather than a pre-fabricated window component. Most brick units remained fully intact throughout the existing building. When modeling these observations, the student used measurements to calculate the amount of bricks used in a section cut. To advance the project through an addition to the museum, the student continued the language of the building assembly by implementing a series of Gaussian vaults. Using the work plane in the section view, the student first used model lines to model each brick and arranged them accordingly. Stitching this view with the modeled and cut elements that comprise the section box view revealed a gap between both types of section. In spite of perceived comprehensive notions laid upon the digital model, the gap exhibited how pertinent information, like the precise module of a brick, can be left behind (Fig. 4). The imprecision this student found countered another student's examination of demolition processes in BIM. This student found the tool to be too precise in demolishing masonry components to the point that demolition worked more like disassembly. The sectional practices employed by both students not only generated a final addition to the existing museum, but also critically examined moments of precision and imprecision in the platform. Another student challenged the presentational platform of Revit. Post-orthography is rooted in presentation or the ability to present all possible outcomes at once. Orbiting a model or zooming in and out infinitely supports this notion. The student discovered that the constructed section, which is based in orthographic representational practices, resisted detail in three-dimensional space (Fig. 5). Matching the precise moment in which the section cut through the clay tile roof, did not match the modelled elements behind the cut. These observations were not criticized for their limits, but were supported by explorations in the misuse the tool.

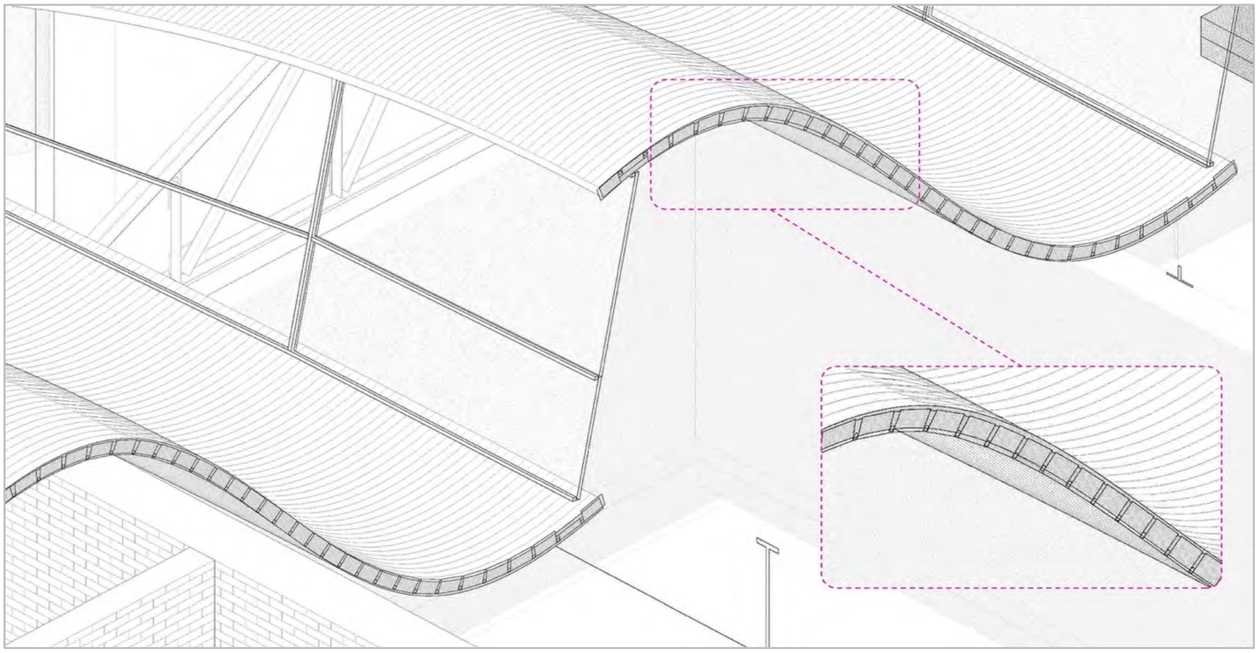

Fig. 4. When overlapped, the different methods for making section cuts in Revit present gaps in information.

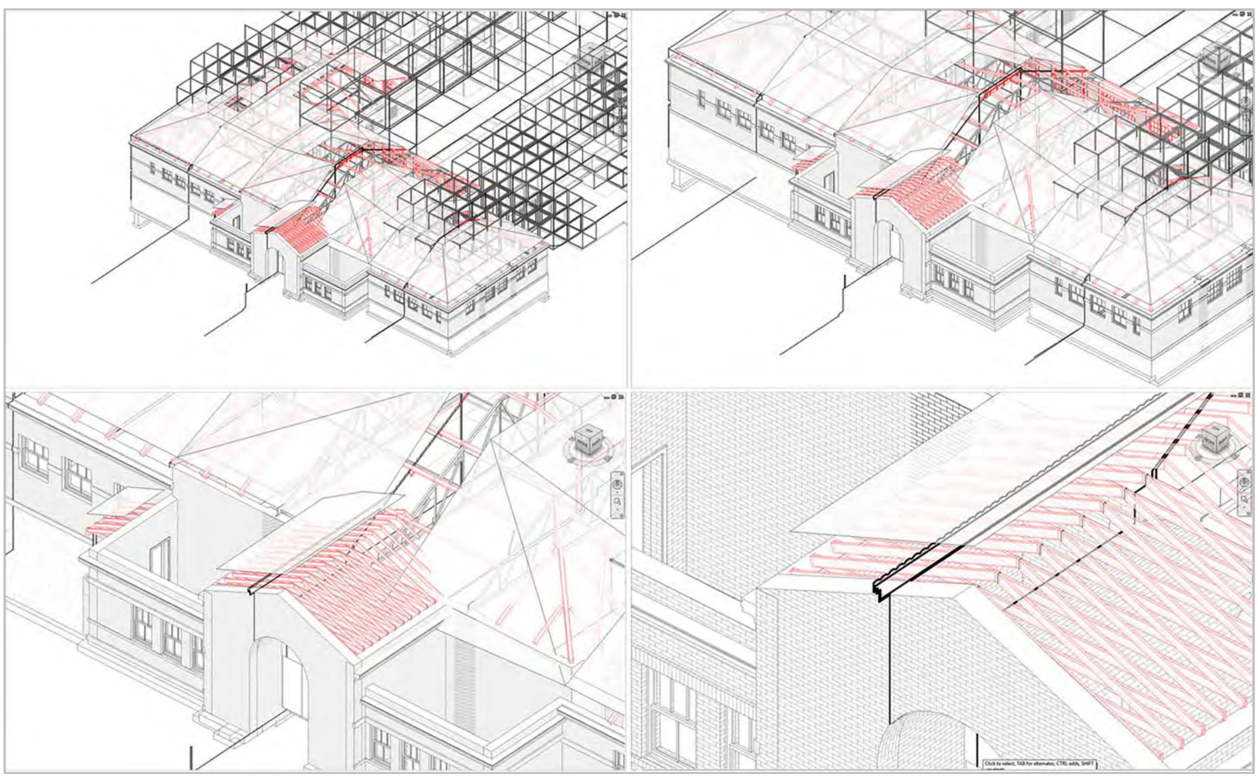

Fig. 5. Zooming presents no scalable or finite detail between the "drawn" section and the modelled elements.

Conclusions

The focused examination of the commands, tools, and interfaces used in BIM platforms like Revit not only point to a shift from mechanical processes like drawing to telemetric processes like digital modeling, but also point to an ontological shift in thinking. The development of ideas and their execution is directly tied to the tools and technical process that manifest them. The detailed history of the origin of section and its associated rules and standards are further tied to this notion. From Renaissance to Contemporary section cuts, the emergence of tools and methods impacted the spatial outcomes in each of these eras. In Revit, the automation of sectional practices disrupted the orthographic standards that developed over the course of centuries. In no way does this study negatively judge this disruption. Instead it places orthography in history and attempts to make sense of sectional practices through post-orthographic methods. Working against the default work plane, modeling with lines, and layering different methods for making sections together in Revit are attempts to slow the process for cutting sections in order to understand the resulting spaces as well as imprecisions or hyper precisions in the tool. Ultimately, the work exemplifies a pedagogical approach that stems from the "misuse" of Revit as an archaeological and generative sectional tool for exploring gaps in information.

Beyond Conclusions

Because the work presented here forms the pedagogical foundation for a studio, the ubiquitous question students receive during reviews, "what would you do next", seems applicable here too. Though the methods implemented in the studio are post-orthographic, in examining the individual outcomes of the projects, the output of images align with more familiar orthographic representations. Therefore, future versions of the studio must consider methods for reviewing the work. How should a post-orthographic review unfold? Work must be presented rather than represented meaning perhaps the live or animated model should be reviewed or performed rather than representing the project through plans, sections, and elevations that are output from the model. Though section cuts provide the impetus for a project, they do not necessarily need to constitute the output.

Notes:

1 John May, "Everything is Already an Image," *Log 40*, (New York: Anyone Corporation, 2017), p 9.

2 John May, "Everything is Already an Image," *Log 40*, (New York: Anyone Corporation, 2017), p 14.

3 Phillip G. Bernstein, "Parameter Value" in *The Politics of Parametricism: Digital Technologies in Architecture,* ed. Matthew Poole and Manuel Shvartzberg (New York: Bloomsbury Academic, 2015), p 205.

4 Skylar Tibbits, "From Automated to Autonomous Assembly," *Architectural Design* 87, no. 4 (2017): p 13.

5 John May, "Life, Autocompleted," *Harvard Design Magazine: No Sweat* 46, (2018): p 14-15.

6 Paul Lewis, Marc Tsurumaki, and David J. Lewis, *Manual of Section* (New York: Princeton Architectural Press, 2016), p 6.

7 Marcus Vitruvius, *The Ten Books on Architecture*, trans. Morris Hicky (New York: Dover Publications, 1914), p 13.

8 Michel Foucault, *The Archaeology of Knowledge and the Discourse on Language*, trans. A.M. Sheridan Smith (New York: Vintage Books, 1972), p 7.

9 Jacques Guillerme and Hélène Vérin, "The Archaeology of Section," *Perspecta 25*, (1989): p 226-227.

10 "Work Planes," *Autodesk Knowledge Network: Revit Products,* last modified January 15, 2019, https://autode.sk/2PmCm06.

11 "Change the Extents of a 3D View," *Autodesk Knowledge Network: Revit Products,* last modified April 09, 2019, https://autode.sk/2UJkDpn.

Note: Unless otherwise indicated, all images were created by the author.

Synchronic and Diachronic Labor:
Deconstructing Eladio Dieste's Ruled Surfaces

Federico Garcia Lammers
South Dakota State University

Abstract

Eladio Dieste was a Uruguayan engineer whose practice prioritized the choreography of on-site labor during the second half of the twentieth century. Dieste's structural innovations in reinforced masonry are admired for their geometric audacity, material economy, and experiential effects. This paper discusses the work and pedagogy from an ongoing architecture class, which focuses on the deconstruction and construction of one of Dieste's innovations, ruled surface brick walls – double curvature surfaces defined by a series of vertical lines (Fig. 1). One of the most underexamined aspects of Dieste's oeuvre is its link to labor. This scholarly blind spot is the foundation of the labor-based pedagogy defined in *Synchronic and Diachronic Labor*.

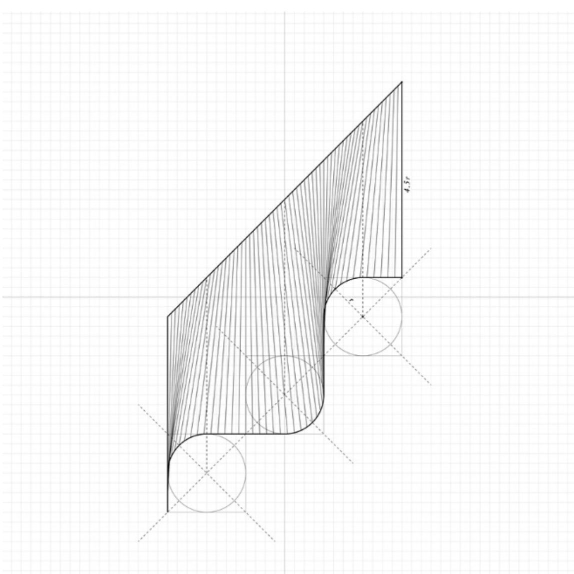

Fig. 1. Ruled Surface Drawing

Introduction

Labor is central to the discipline and profession of architecture, and has been the subject of philosophical, economic, and societal concerns for centuries. In this paper, labor is the organization of human force that enables the time-based material production of a building or structure. Additionally, labor is referred to as forms of production that leave no visible trace of their effects, such as, mental labor and other forms of immaterial production. In all of its forms, labor is a time-based condition. In order to consider notions of *time*, it is important to distinguish between *synchronic* and *diachronic* labor. Synchronic forms of labor connect people working in the same moment towards a shared goal, often resulting in a single object. Diachronic forms of labor connect efforts across time, forming relationships between distant objects in different places.[1] Labor of this kind is evident in the material legacy of construction techniques that emerge across time and cultures. Diachronic labor is part of an ongoing technological project. The fluid interaction between people, tools, and place is at the center of this form of labor. This paper is interested in the pedagogical effects of studying the role of labor in Eladio Dieste's practice through an architecture class called *Dieste Building Shop*. The paper is organized by a set of intersecting pairs: *Labor and Work, Technics and Technology, Machines and Translation*. The relationship between these pairs and the work of Eladio Dieste form the pedagogical core of *Dieste Building Shop*. The time-based implications of *synchronic* and *diachronic* labor reinforce this core.

For three consecutive years, thirty-five students ranging from second-year undergraduates to second-year graduate students have collaborated on the construction of three single-wythe walls made with the same bricks. Every semester, students start with the deconstruction and material cataloguing of the wall built by the previous group of students. After choreographing and graphically documenting the deconstruction of the wall, students design formwork systems that define the double curvature geometry of the "new" wall. Scaled representations – drawings or models – do not precede the construction of the walls. The precise placement of strings, vertically tensioned at different angles inside a wooden framework dictate the construction of each new structure. The assembly of strings and wood is the formwork or *encofrado*. Each adjustable *encofrado* enables the construction of several ruled surface walls.

> *"The resistant virtues of the structures that we are searching for depend on their form. It is because of their form that they are stable, not because of an awkward accumulation of matter. From an intellectual perspective, there is nothing more noble and elegant than resistance through form. When this is achieved, there will be nothing else that imposes aesthetic responsibility."* [2]

Material economy is integral to this process and it is emphasized by resisting gravity through form. Before, during, and after construction, students read Dieste's writings about the relationship between architecture, construction, and people. Through reading discussions, journal documentation, and collaborative construction, students engage the intellectual and physical dimensions of labor. *Synchronic* labor defines each fifteen-week semester. The ongoing scholarly project is *diachronic*, physically linking student labor across three years, and conceptually connecting it to historic structures on a different continent.

Historical Labor and Work

Philosophers and thinkers who are particularly interested in tying humanity to the production of things and thoughts have examined the distinction between work and labor. Most notably, in *The Human Condition* (1958), Hannah Arendt marks the difference between *work* and *labor* as the result of visible or invisible traces of production. For Arendt, *work* is the production of things that last; their material presence is felt in the world. Unlike *work*, *labor* leaves no material trace, the efforts of *labor* are invisible – labor is the unending cycle of biological reproduction. The distinction between *work* and *labor* is reinforced by her introduction of two hominization categories: *homo faber* and *animal laborans.*[3] The former is tied to notions of *work* and material-based construction, while the latter is linked to *labor*. With these two categories, Arendt repositions previous distinctions made about mental and concrete labor, and the potential to intellectualize the production of things and thoughts. These are not semantic differences, but rather deep-rooted constructs that shape the western teaching and production of architecture. From Plato to Marx, the conflict between physical and mental exertion shows the historical schism between *design work* and *construction labor*. Plato's political philosophy placed value upon physical labor, but always considered mental contemplation superior to physical activity. Following Plato, Aristotle viewed *labor* as a commodity that had value, but could not give value. Work was the activity and privilege of free people, while labor was synonymous with physical enslavement.[4] The intellectual superiority ascribed to contemplative work was integral to the advancement of slavery and its ties to forced acts of construction throughout the western world. Even before the Renaissance, and Leon Battista Alberti's authorial paradigm, on-site physical construction was considered an inferior, unintellectual activity.[5] *Animal laborans* exerts the indispensable efforts for living, without ever becoming essential for living a thoughtful life, while *homo faber* produces value through reflexive mental practices.

The tension in this philosophical legacy was fuel for Marx's assertions about the role of the *proletariat* – industrial class of *Animal Laborans* – in the reconfiguration of political thought and material production. Contemporary architectural education and practice reflects the chronic separation between these material and immaterial worlds.

"In architecture, a building, a project, a model, a drawing, a text, or a book is usually referred to as *a work*, as in *the work of the architect*." [6] Pier Vittorio Aureli affirms the architectural implications of Arendt's seminal distinction by stating that *work* invokes the authorial context of architecture, while *labor* exceeds traditional outcomes – drawings, models, books – used to establish architecture as a representational discipline and profession. It is possible that a rigid distinction between *work* and *labor* is an over simplification of the complex systems that define contemporary capitalist production. What is important is not the direct application of these definitions, but rather their educational impact in the twenty-first century. If architectural labor, as Aureli points out, exceeds the traditional outcomes used to measure work, then how do we teach that "behind the production of something there is a much larger and wider agency than what is acknowledged in the public presentation of architectural work." [7] Labor transcends the manifestation of the poetics of craft, or *techne*, typically attributed only to *homo faber*.

One approach is to expand the repertoire of historical precedents and include practices that focus on the role of *labor*, or rather that do not make hierarchical distinctions between *homo faber* and *animal laborans*. Historically, such practices have a tendency to prioritize socio-technological issues above individual authorship. The preference for the intellectual merits of collaborative technical work is an essential factor in understanding the pedagogical implications of *labor*.

Eladio Dieste and the Job Captains

Dieste and Montañez S.A. was started in 1945 by Eladio Dieste and Eugenio Montañez. Both Dieste and Montañez were engineers who graduated from the Faculty of Engineering in Montevideo, Uruguay. Throughout their forty-year partnership – the firm continues today under different leadership – they developed four structural innovations in *cerámica armada* (structural ceramics) using steel-reinforced brick masonry. Working as a design engineering and construction firm, they built nearly one and a half million square meters of structural ceramics, in the form of gaussian vaults, self-supporting vaults, and ruled surfaces.[8] Images of the audacious spans and phenomenal curvature of these structures have been recently published with increased frequency. In spite of a recent surge in interest, Dieste and Montañez's work remains rather unknown in the context of modernist scholarship, even in the regionalist setting of Latin America. There could be several reasons for this anonymity; small size of Uruguay, historical political turmoil, lack of self-promotion, etc. Without diminishing the inventiveness of Dieste's well-documented structural intuitions, the methodology of *Dieste Building Shop* claims that Dieste and Montañez's practice is overlooked because of its inextricable link to physical labor.

For almost four decades, Vittorio Vergalito, Edio Vito Pacheco, and Alberto Hernandez worked as job captains with Dieste and Montañez. [9] Their role as job captains should not be underestimated. Each one of them was responsible for recruiting and coordinating the teams of local workers that labored on the construction of notable projects, such as, *La Iglesia del Cristo Obrero* (Church of Christ the Worker) in Atlántida, Uruguay. Vergalito's work in Atlántida was instrumental. He figured out how to translate the double curvature geometry of the walls into measurable, mechanical construction systems that were communicated to a team of on-site masons.

Eladio Dieste was explicit about his views on architecture and construction, “the builder is indispensable. In fact, the project for a building is not really complete if it does not consider how it will be built, and the ways in which a building can be built have a notable power of inspiration…all viable new structures are intimately related to construction methods, and these methods are visible in the finished building.” [10] This statement may seem like an anachronistic view of labor or the ubiquitous call for architecture projects – especially academic work – to be more “real”. It is neither of those things. In *Art, People, and Technocracy*, Dieste implies a reconfiguration of *animal laborans* by paying close attention to construction systems and the people that engage with them. Without fetishizing representation, or the intellectual work of inventing unprecedented structural innovations, Dieste proposed a vision of architecture that was inseparable from its construction force. In his estimation, imagining that force – the synchronic efforts of workers – was indistinguishable from seeing the structures come to life.

Dieste Building Shop is a combination of history/theory seminar and building technology class. The combination puts students in close proximity to the theoretical underpinnings of Dieste’s practice and his attitude towards labor. The work of reading is an essential part of this course. Reading Dieste’s writings about the role of workers is a precondition to understanding the labor-centric aspects of Dieste’s thinking and it is a way to link intellectual work with subsequent forms of physical labor. Reading discussions and questions are recorded in individual student journals (Fig. 2). The journals are formally and informally reviewed on a biweekly basis. During formal reviews, students submit their journals to the instructor, while informal reviews consist of students exchanging journals with each other. Both types of reviews are ways of prompting discussions around issues that affect the trajectory of the course. The journals become a way to visibly trace physical labor and reflect on its implications. Each journal is an individual reflexive document and a collective record of the semester’s work.

Fig. 2. Dieste Building Shop - Student Journals

Time of Technics and Technology

The introduction of the paper describes the difference between *synchronic* and *diachronic* forms of labor. Ideas of *time* connect this precursory distinction with the historical difference between *work* and *labor* outlined in the first section of the paper. *Synchronic* and *diachronic*, *work* and *labor*, these two pairs intersect to generate another pair, *technics* and *technology*.

A lot has been written about the history of technology in the context of architectural pedagogy. It is self-evident that "technical life is inseparable from processes of hominization – inseparable, that is from the very processes by which a group of animals learned to think of themselves as human subjects." [11] Simply put, this anthropological view asserts that life is lived through an external set of technical objects, whose relationship to humans establish *technics* as a conceptual category that is different than *technology*. [12] This categorization is reinforced, but certainly precedes Heidegger's efforts to describe the poetics or essence of technology as a form of *techne*. [13] While this distinction adds layers of specificity to the pedagogical implications of labor, its most significant contribution is associated with conceptions of *time*. In this case, *time* is a formulation of *technics*.

There are two primary ways of thinking about the pedagogical relationship between *time* and *technics*:

1. *Engagement with medium(s);* the external objects or tools that define the internal conceptual space of *technics*.

2. *Transfer of knowledge*; the ontological effects of external objects or tools that define *technics* as an evolutionary condition, not a fixed category.

Both categories can operate *synchronically* and *diachronically*. However, it is important to consider how each category tacitly supports traditional views of *work* and *labor*. Students labor synchronically – in the same moment towards a common goal – through forms of media all the time. Media-based *diachronic work* that stretches across time, producing a range of distinct, yet intellectually connected objects is much more unusual. This type of *diachronic work* is usually limited to studios or representational courses that stretch across an entire semester. Without disregarding the obvious *synchronic* sharing of ideas, it is evident that *diachronic work* is typically associated with the *transfer of knowledge*. In architectural education, it is common that this type of work is considered instrumental or simply used to achieve predictable outcomes. Working diachronically is analogous to working through *technics*. To become enmeshed in diverse, potentially conflicting histories, which can manifest their contemporaneity through specific mediums is the challenge of *diachronic labor*. The difficulties of this challenge are evident when *technics* is understood as a system that "usually has embodied in it characteristics suiting it for survival in a particular time and place." [14]

How does student work stretch across multiple semesters and years to form deep connections through the study of *technics*? The assumption that all contemporary curricula are based on *diachronic transfers of knowledge* is naïve. There are, of course, internal and external forces that affect curricula and displace concerns about the modes of transfer that affect the relationship between *technics* and *technology*. In *Dieste Building Shop*, this relationship is designed to highlight methods of *diachronic transfers of knowledge*.

Deconstruction with Many Hands

“Western culture has built a cultural system where works of the intellect, regardless of their material complexity, are expected to be ideated by an individual author and the expression of just one mind.” [15] This implies that all objects must be designed prior to being made – design work precedes, in both value and time, the labor of construction. The tension between this historical separation and contemporary collaborative media is marked by what Mario Carpo refers to as “the style of many hands”. [16] If Carpo’s term implies the *synchronic* bias of contemporary tools, and their ability to dissolve perceptions of singular authorship, then how can acts of deconstruction become *diachronic*?

The same set of six-hundred bricks has been used to build and deconstruct three ruled surface walls in as many years. While reading about Dieste’s practice, student teams design the deconstruction of the wall built by students in the previous version of *Dieste Building Shop* (Fig. 3). The deconstruction of the wall is performed synchronically during class time. Through the measured choreography of bodies, tools, and material cataloguing, each student implicates themselves in the efforts of previous semesters.

Physically and conceptually linking student hands across multiple semesters is *diachronic*. As part of this process, students record the existing wall through a series of point-based vertical sections that produce an error-filled impression of the wall as it is being deconstructed (Fig. 3). Students make images of the labor of deconstruction. This is a way of using media to affect the *transfer of knowledge* based on designing *diachronic labor*. The two methods for laboring diachronically are self-evident, but worth reinforcing:

1. Students work with objects (walls) built across time by other students. Multiple students, multiple walls, multiple semesters, same bricks.

2. Students build one of Eladio Dieste’s structural innovations, a ruled surface (double curvature) wall, connecting students to buildings in another context, built in the past.

The notion of ideas existing apart from their technical formation is a precondition of the traditional dominance of *work* over *labor*. “The kind of people that are captivated by a machine-driven society of the future and theorize about it are usually not people that do things…someone has to design the prototypes and processes.” [17]

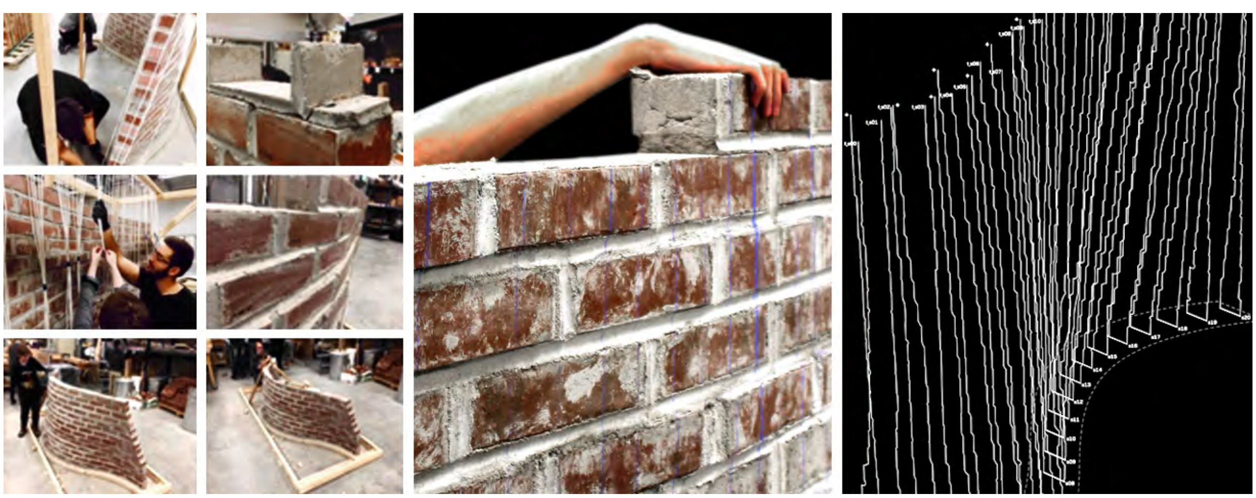

Fig. 3. Dieste Building Shop - Wall Deconstruction

Machines and Translations at Work

Machines have always made their presence felt in architectural history and theory discourse. Without invoking the contemporary implications of electronic machines, it is possible to consider that "a machine can be defined as a human-made, artificial construction, which essentially functions by virtue of mechanical operations." [18] Machine participation on the production of work and the labor of construction has been widely acknowledged in contemporary education and practice. Their participatory nature is central to Nicholas Negroponte's argument about authorship; "as soon as a designer furnishes a machine for finding methods of solutions, the authorship of the results becomes ambiguous." [19]

Contemporary interest in autonomous, robotic labor and the architectural ramifications of artificial intelligence are important to this authorial ambiguity. If contemporary labor concerns are about relocating physical labor over to machines, what are the historical alternatives that combine machine and human labor? Architects claim that the reconfiguration of physical labor is about concerns for the people performing dangerous, dirty, and dull labor.

This altruism is contradicted by a lack of interest in teaching students about people performing physical labor and their historical presence on construction sites. Acknowledging the role of workers reveals an issue that is essential in Negroponte's work – the translation from human to machine language.

Machines foreground two primary systems of translations, *direct* and *transfer*. These two systems are analogous to the two ways of thinking about *time* and *technics* outlined in the previous section of the paper. *Direct* translation systems generate a translation directly from an original language to another language with no intermediary form of representation. *Transfer* systems are typically more complex than direct translation because they integrate forms of syntactic analysis, which expand the content of the original language, avoiding direct one-to-one translations. [20] These two approaches to translation are not mutually exclusive. When overlaid onto Alberti's authorial paradigm, the instrumentality of orthographic representation becomes a *direct* system of translation, while Negroponte's *thinking machines* become types of *transfer systems*. This is an acknowledgement of the differences between each system; it is not a value-judgment.

Fig. 4. Dieste Building Shop - Ruled Surface Wall Construction

The role of machines in Eladio Dieste's work exists somewhere in the spectrum from *direct* to *transfer* systems of translation. It is important to point out that Dieste and Montañez's buildings were designed and constructed before the advent of computational tools. Every structure built from 1943 to 1996 was imagined and described using hand-mechanical orthographic drafting and analog numerical calculations. The double curvature geometries of ruled surfaces and gaussian vaults were constructed through the combination of formwork machines called *encofrados*. Encofrados were the intermediary transfer systems between numerical calculations and material construction. Knowledge of the machine's operating language was inseparable from the ideation of the buildings. Through the use of *encofrados*, traditional notions of unintellectual *labor* drifted into the realm of *work*, articulating the wider agency of architectural labor postulated by Pier Vittorio Aureli.

In *Dieste Building Shop*, the intermediary translation systems are a series of wood and string machines that describe the double curvature geometry of the ruled surfaces (Fig. 4). Instead of making representations of potential versions of the wall, students worked on the construction of *encofrados*. Each *encofrado* can produce multiple, non-identical versions of the wall. Non-identicality is a product of mortar inconsistencies, hand error, number of bricks, placement, etc. The implications of designing the machines and laying the bricks is central to the *diachronic* condition of student labor. Through this process, formal complexity becomes independent from material precision. As long as the geometry of the wall is not undermined, the system of construction can absorb inconsistencies, which in most cases would read as construction errors. In Eladio Dieste's practice, these errors were absorbed and mitigated by the sophistication of the *encofrados* and the knowledge of the people working with these machines. If we recognize this type of knowledge as the *technics* of architectural *work*, then pedagogical models centered on the intellectual dimensions of *labor* may emerge.

Conclusion

There are many outcomes documented in three years of student work and discussed while reflecting on the pedagogical impacts of *Dieste Building Shop*. The three points outlined below are synthesized from observations made in student journals.

1. Authorship of processes over object ownership
2. Disassociate precision from complexity
3. Make it economical, not cheap

A seemingly innocuous question reoccurs in students' writings and connects these three points into an enduring polemic about labor: "What if every time we had to build something, we had to deconstruct something else first?" This question hinges on students' concern over the contemporary idea that the act of building is independent from any type of deconstruction. This independence is not liberating, nor is it true. Architecture usually follows some act of physical deconstruction. Academic evasion of this self-evident fact reinforces the intellectual distance between architecture and physical labor. The effects of this distance are discussed in this paper and unfolded through the distinction between synchronic and diachronic conceptions of time. Eladio Dieste's physical work lives in the space defined by this historical schism.

Labor-based pedagogies can establish diverse socio-cultural networks that are intrinsic to the advancement of technical knowledge. The three points outlined above, reassert that technology is the study of skill, not simply the product of skill. This pedagogical approach is not based on reviving anachronistic forms of construction or proposing a return of the *Master Builder*. *Dieste Building Shop* is a call to expand architectural history and theory discourse by studying the role of physical labor before we rush to erase it from our future.

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Scaling Up Passive Energy to Suburban Developer Housing

Craig Griffen
Thomas Jefferson University

Abstract

Recent reports paint a dire picture of the potential worldwide affects climate change. Since our buildings' energy consumption plays a significant role in the production of greenhouse gases, many more energy-efficient buildings could affect a major reduction in carbon production. Single-family developer housing represents a high percentage of US construction at a million starts per year. Yet, the typical subdivision is designed with little to no regard for orientation to sun, wind and thermal envelope efficiency. Since single-family homes consume around 80% of residential energy use, a million *passive energy* house starts per year could have profound effects on our energy use but most architects appear uninterested in suburban housing design. This segment of the market is prime opportunity for applying passive energy strategies on a massive scale. So with the looming specter of climate change, why do most architects and builders seem apathetic to the suburbs and continue to disregard this opportunity despite the potentially catastrophic results?

This research/design project questioned: if passive solar houses have been around for decades, why are there few passive single-family housing communities, and why haven't they made the leap in scale? The research component investigates the historical reasons for the disconnect between architects, large housing developments and passive energy. Based on the findings, the design component proposes a variety of model house types, based on the Charleston House typology, and subdivision designs, both in the suburbs and as urban infill, as potential present-day strategies for extending the strategy to the massive scale. The research produced two governing questions that informed the design solutions: 1. How do we apply passive energy strategies to the pre-manufactured developer house? And, 2. How do we make passive houses marketable in a well-established industry?

Keywords: Energy, Passive, Solar, Systems, Suburban, Developer, Housing

Introduction

Most scientists agree, if not already too late, that to slow the effects of climate change will require enormous changes to the way we produce and use clean energy. In our built environment, to achieve measurable success in integrating sustainable energy systems into buildings will likewise require application on a sizeable scale. However, wind and solar sources supply only a small percentage of power for building energy systems that still rely heavily on fossil fuels. In terms of construction volume, single-family developer housing starts account for a huge percentage of construction each year. (US Census Bureau reports levels of over one million starts per year for the past several years)[1] And more recently, suburban style developments have been constructed on large tracks of vacant land in large cities. With the vast majority of new house construction produced by these large housing development companies, this segment of the market is prime for applying passive strategies on a scale great enough to have a significant impact on energy use. Yet developers typically build entire subdivisions with little to no regard to orientation to sun and wind (Figure 1) and most architects appear uninterested in becoming involved with suburban housing design. The increase in quantity of passive house construction is laudable, but at the current small volume it will not have a measurable effect on our environment. However, a million *passive* house starts a year could have profound effects on our ecosystems. With the looming specter of climate change and the potentially catastrophic impact, can architects ethically continue to ignore the problem as it grows into a major environmental concern? This design/research paper investigates the reasons for this disconnect between architects, large housing developments and sustainable energy, and then identifies potential design strategies for improvement.

Figure 1: Houses Face Street Regardless of Sun Direction

The Lack of Demand for Sustainable Suburban House Construction

> *Rethinking suburban design is an enormous challenge because many suburban neighborhoods have been designed, developed and managed precisely to avoid change and limit uncertainty. …the issues remain just as relevant, except the houses have gotten bigger and more wasteful and the environmental imperatives more urgent* [2]

Why have developers stayed out of the passive energy housing market and what would it take to convince them of the feasibility of sustainable single-family housing? At the same time, while there is a high demand for single-family homes, why is there is not a strong demand among buyers for sustainable suburban housing? Two major fears among both developers and clients are resistant to change and cost. The construction industry (at least in the US) is notorious for using the same construction techniques again and again with little desire for innovation. This is especially true in the suburban house market. "Is there anything made in America that's less innovative than the single-family home? While we obsess over the new in terms of what we keep in our houses...we're incredibly undemanding of the houses themselves."[3] Change is a financial risk to developers because new techniques have not proven themselves through repetition and are more vulnerable to unseen cost fluctuations. Lightweight wood-frame designs are replicated across the country, regardless of location and climate, because they are cheaper and efficient to build. Builders have little incentive to take risks, and so follow the adage, "If the buyer wants it, give it to him".[4]

Proponents of energy efficient housing agree that initial costs of showcase "green" houses are more expensive but argue that the savings in energy bills over time will more than pay for the additional first costs. But speculative builders who sell their houses immediately upon completion are not the future owners/occupants, and therefore are less concerned with future operational costs. Unfortunately, seeking the bottom-line and suspicion of new techniques make reducing initial costs and maximizing profit the main goal. "Initial cost will always be important and many of the showcase projects have a short-term flaw in that it has generally been perceived by the wider construction industry that there must be a monetary penalty when demonstration developments are transferred, in a somewhat diluted form, into the more affordable mass market".[5] So the wariness is understandable.

A harder question to answer is why don't more home buyers demand higher energy efficient houses? In a recent on-line article titled *Ask The Agent: What Home Features Are Most In Demand When Buying Or Selling*?[6], many real estate agents across the country gave a predictable reply that the focus was on location and luxury amenities: "I noticed that buyers really love when properties are move-in ready with the decked out kitchens, bathrooms and hardwoods floors." However, several agents did mention that in addition to those desires, there is a newer demand for energy efficiency: “Buyers and sellers are starting to demand amenities that are energy-efficient, low emission and cost-effective like tankless water heaters, solar panels, Nest-type thermostats, low-water toilets and the like.” So the demand for energy efficiency may be increasing among home buyers, albeit slowly.

In addition to developers and buyers, our legal environmental energy codes in this country are not very demanding. With a few exceptions, most municipalities follow the far-from-stringent ASHRAE 90.1 or similar minimum level of energy efficiency. So if “...neither building codes nor buyers demand that homes be energy efficient. And given the lack of incentives to go green, most builders prefer to do what they know, rather than master new — and more demanding — building techniques and materials.”[7] Until the public demands it or the government requires it, builders will have little incentive to change.

Some architects argue that single-family homes are not a sustainable use of land and resources; preferring multi-unit housing as a better approach. But single-family homes consume around 80% of residential energy use.[8] To affect change on a massive scale requires a willingness to confront the big issue. Although unpleasant to many architects, the continual demand for detached single-family suburban housing is an issue that needs greater attention to investigate how to make this enormous number of homes energy sustainable. To continue to ignore the issue is an ethically questionable decision.

The Solar Suburban House and Subdivision – A (Very) Brief History

> *During and right after the war, hundreds of solar houses were built across the United States, most using passive radiation to reduce heating load. Typically these designs featured a narrow plan and an all-glass façade, in order to allow solar rays to penetrate deep into the house in the winter, and also a carefully designed overhang, in order to deflect the summer heat.*[9]

Although rare, the passive solar suburban house is not a recent development. While there was much experimentation in the 1960’s and 70’s, the origins are earlier. After World War 2, oil was in short supply so there was a search for new forms of energy including solar. However, these solar houses were not very effective and required continual maintenance which, when combined with newly discovered oil, doomed this first generation of solar houses.[10] So while passive solar houses have been around for decades, more extensively in Europe, they exist only as individual cases or in small groups. Few large passive single-family housing communities exist, and none close to the scale of a suburban development containing hundreds of houses. The Village Homes community built in Davis, California in the early 1970’s is one of the truly rare examples of a passive solar oriented subdivision but very few followed their lead, and none on a similar scale. This paper explores why passive energy systems are not part of US suburban developer housing and which issues might be preventing the leap in scale. These ideas were then tested through potential design solutions on the scale of both an individual prototype Passive Suburban Developer House (PSDH) model and a community master plan. Out of the research grew two major questions. First, how do we apply passive energy strategies to the pre-manufactured suburban house, and second, how do we make passive houses marketable in a well-established industry?

The Challenge of Making Developer Houses Passive

> *Not so long ago homes were designed to make the most of their surrounding climate and terrain. Vernacular forms like the shotgun, in places like New Orleans, served a purpose that went far beyond aesthetics — they encouraged natural cooling by improving cross-ventilation. ... Houses were sited and windows placed to maximize or minimize sun exposure as needed* [11]

With the advent of central heating, air-conditioning and electric lighting, houses could ignore the sun and wind conditions of a site and depend on solely mechanical means for thermal comfort. Current developer housing is designed and sited with little to no relation to the direct solar gain, wind movement or daylight. Streets of a typical subdivision are often laid out in a pattern of gently curving drives and dead-end cul-du-sacs with the houses oriented towards the street regardless of which cardinal direction they face. A prime challenge is how to adapt and site these non-directional houses to maximize natural passive environmental benefits. To also take advantage of the sun and wind requires orienting the house in a specific direction.

Orientation Towards Sun and Wind

The first step to make a house energy efficient is to use *Passive House* thermal performance principles of continuous well-insulated walls, an airtight envelope, and high-performance windows. Recent improvements in technology and affordability in performance standards mean these principles can be applied to most styles of houses including developer housing. This also means that the passive solar heating components of the energy supply systems can be reduced, resulting in less glazing that can lose heat and less reliance on thermal mass. Developer houses typically use small double-hung windows of relatively the same size on all elevations that do not adjust for the varying solar demands on the four faces. While this reduced glass area is good for minimizing heat loss (same for the Passive House) it also limits direct sunlight, restricts views and separates interior and exterior space. The PSDH is a *solar hybrid* model that exists between the Passive House with fewer windows and the passive solar home with excdssive glazing that can lose heat easily. This middle ground presents a design opportunity to spatially connect the interior rooms with the exterior spaces on the south without great risk of over or under-heating. It also reduces the amount of required thermal mass which is harder to achieve with typical wood frame construction common to developer homes.

Figure 2: Charleston House Type

A basic principle of all passive solar-oriented houses is to elongate the floor plan in an east-west direction to expose most occupied rooms to the southern sun. But a substantially glazed facade facing the street or close to neighbors would also reduce privacy. And to correct privacy issues with the daytime use of curtains would negate the solar gain. Therefore, an open south façade works better *if* it can face a private yard space. One solution is to exchange the large front and back yards of a standard subdivision house for one big side yard, a house type similar to the Charleston House of a long, side-yard facing building with a gallery along the south wall. (Figure 2) While the Charleston house type was mainly created to provide ventilation cooling, (a similar goal of the PSDH) it also works well to promote passive solar heating while maintaining privacy. In the PSDH, the main living spaces are located along the south side overlooking the side yard with service spaces located on the north with few windows. Since all houses are oriented the same general direction, the heavily glazed south walls look across a landscaped yard at the predominantly solid north wall of the neighbor, to preserve privacy. A gallery and the deep roof eaves extend out from the wall to provide for shade in the summer while allowing low-angled winter sun to penetrate. The public street-side entries are best located on the narrow east or west elevations that require smaller windows for sun and also provide privacy from the street. (Figure 3) Renee Chow has already written about how the urban fabric pattern of the Charleston typology can be a sustainable solution for increasing density and reducing suburban sprawl.[12] This same strategy becomes more attractive with the incorporation of passive energy strategies.

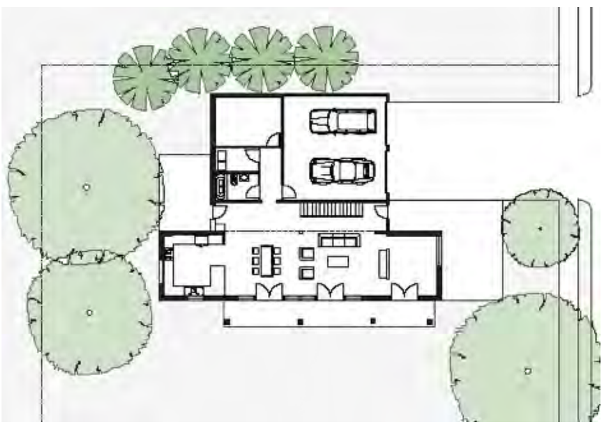

Figure 3: Basic PSDH home plan

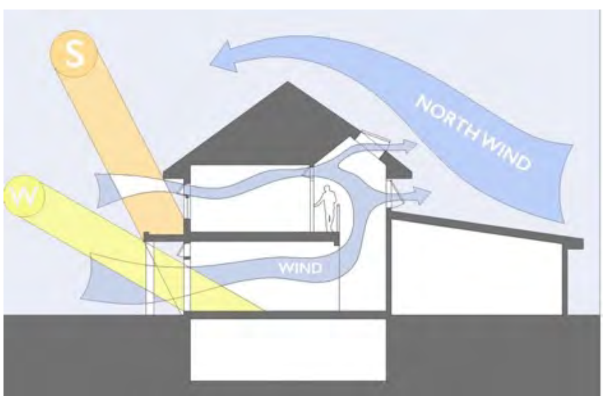

Figure 4: PSDH Section - Passive Energy Diagram

To minimize the need for air conditioning and artificial lighting, the PSDH should make use of other passive energy strategies such as natural ventilation and daylight for their energy-saving, health and psychological benefits. The deep-plan developer house with its closed plan and small windows does not allow for efficient cross ventilation and restricts daylight to only spaces along the perimeter. The linear, open-plan form of the PSDH, allows for an efficient cross breeze by bringing in cooler air low on the south side and ventsing warm air out high through the northern clerestory window in the two-story atrium stairway. This clerestory which runs the length of the atrium brings abundant soft northern daylight into the usually dark core of the house to compliment the light already provided by the extensive southern glazing. By stacking two stories on the south and placing one-story service functions on the north, the house forms a wedge shape that deflects cold north winter winds over the house and creates a sheltered, sunny outdoor space on the south. (Figure 4)

The Challenge of Making Passive Houses Developable

Passive Suburban Houses can't have an effect on the environment if they don't sell in great numbers so they need to be attractive to a broad spectrum of buyers. The typical developer house presents a nostalgic image of the traditional house as a symbol of *home*. Developers aren't pushing one style over the other. They say they will build whatever style sells; that they are only giving the client what they want. So, any design for passive suburban developments must be financially feasible and aesthetically marketable to a massive audience.

Conveying the Image of 'Home'

A Passive House whose only goal is to maximize energy efficiency is at risk of becoming a data-driven machine that, while efficient, will have less appeal to the public as a cherished family home. The image of house as *home* is deeply imbedded in the public psyche as evidenced by the long-time popularity of the historical pseudo-colonial style house. The challenge is how to retain this *feeling* of home without resorting to outdated historical pastiche; something architects understandably detest. But the modern house that appeals to designers is not as appreciated by the developer house-buying public. Looking at the traditional styles of developer homes that are purchased today, it becomes evident there are certain common defining characteristics that are desired by buyers. While the counterfeit historic language of false gables, pasted on brick, and screwed-on plastic shutters are less appropriate, incorporating structural sloped roofs and sustainable building materials make it possible to convey the image of home in a more authentic way.

Making It Cost Effective

> *Many of these radical homes can be characterized as showcase developments, which employ all manner of state-of-the-art techniques, as well as sound, basic passive solar principles, to produce often expensive, prestige homes designed to demonstrate what is possible. The theory is that money will be saved over the lifecycle of the building.*[13]

The increased amount of higher-performing building materials needed to create passive house envelopes also drives up their initial cost. Since developers shy away from increased initial expenses, passive house construction needs to be cost effective to be adopted and marketable. There are many examples of high-end architect-designed custom sustainable houses that are very efficient in terms of energy use, but not in terms of construction cost. Their one-off design makes them too expensive for the developer market. As Allison Arieff asks,

> *Devoting this much R&D and software development to so few homes feels akin to installing a $250,000 solar array on a garden shed. Why not devote that energy to transforming cookie-cutter developer homes?*[14]

The developer housing industry has developed successful methods for pre-packaging building elements to reduce labor and material costs. This strategy can be extended to passive houses. To be economically feasible, these houses should not be site-built, but ought to utilize Modular and Prefabricated Construction techniques to be competitive. One current solution is the use of heavily-insulated, prefabricated panelized building envelope components, such as those manufactured in the US by the Ecocor company, that are shipped to the site and erected by cranes to shorten construction time and save material and labor costs.[15] Another firm, GO Logic, has developed reproducible designs for prefabricated passive homes they call GO Homes that are in styles similar to what suburban buyers want.[16] (Figure 5) While not expensive one-off designs, these homes are still built one at a time and located on large rural sites. The challenge is to scale up this idea to the level of the developer subdivision to improve affordability.

Figure 5: Passive GO Home Model, GoLogic

GO Homes also uses the *panelization* process to factory assemble complete wall panels up to 30 feet long to make Passive House construction more affordable. (Figure 6) Below is a chart of GO Home estimated sales pricing in Maine where they are based:

Plan	$/SqFt	Total
600 sq ft	$298	$179,000
1000 sq ft, plan A	$275	$275,000
1000 sq ft, plan B	$276	$276,000
1100 sq ft	$268	$289,200
1400 sq ft	$244	$341,600
1500 sq ft	$243	$365,000
1600 sq ft	$241	$385,400
1700 sq ft	$241	$409,000
2300 sq ft	$229	$548,400
2500 sq ft	$227	$567,000

At Toll Brothers, a major home builder in the US, their average single-family home is about 3,500 square feet and sells for around $800,000, or $228 per square foot, similar to GO Home per square foot prices[17] While home construction costs in Maine are generally less than other parts of the country, the price per GO Home is still relatively expensive because of the increased amount of construction materials and each house is constructed as an individual home. However, the efficiency of scale that developers like Toll Brothers can provide through mass production and factory prefabrication could improve cost efficiency to make pricing more affordable.

Figure 6: GoHome Panelization House Assembly Process

Planning Passive Neighborhoods

> *"In general, the planning profession is not concerned with or particularly well trained in the physical performance of buildings, yet decisions made at this stage can radically affect the performance of passive solar designs".[18]*

Like all solar-oriented houses, the PSDH needs to be oriented mainly to the south with streets running mostly north-south. Therefore, there is a risk of creating repetitive, monotonous neighborhoods through unrelieved orthogonal street grids. Although the rectilinear grid is a successful urban strategy, it is less desired in suburbs where relentless rectangular grids can create look-alike neighborhoods that lack a sense of identity and place. Therefore, initial planning is critical. Likewise, there is a need to avoid repetitive house styles. Developer housing subdivisions are often created using only a small handful of house designs and a limited palette of materials.

Passive Houses have become so thermally efficient they will still effectively capture enough solar gain if oriented to within 20 degrees to either side of true south.[19] This 40 degree swing creates greater flexibility in house orientation than the stricter direct north-south orientation recommended for passive solar houses. Without the requirement of only straight, north-south oriented streets, roads can be gently curved and angled, which when combined with pocket parks and green spaces, relieves a relentless grid. (Figure 7) PSDH's energy efficiencies don't make sense without sustainable land use as well. Typical suburban sprawl master plans often use large half-acre lots; more land than usually needed by the owners. The Charleston House model, with its large side yard, allows for smaller 1/6 to ¼ acre lots. The increase in density can nearly double the number of houses in a subdivision (from 45 to 86 in the site plan shown) while maintaining the same overall amount of public green space and creating walkable, livable neighborhoods. With more houses to sell per acre the developer could potentially offset increased capital costs with an increase in total home sales.

Figure 7: Subdivision design with PSDH homes

To avoid repetition of house styles, several house models should be designed to accommodate diverse family structures and sizes, as well as models for the small amount of houses that whose public façade faced north or south. These models could use the same basic plan but vary in scale, color, materials and features; making them excellent candidates for mass customization. A large number of combinations would help provide initial variety, and owner modifications over the ensuing years would provide additional character and neighborhood identity. Richard Pendranti Architects, an architecture firm that works with Ecocor, has already created a portfolio of basic passive house models that can be adapted to each individual client.[20] Models vary in size, number of stories, roof shape, exterior material finishes to allow for a wide variety of combinations. (Figure 8) Like with the prefabricated GO Home, the next step would be to scale this idea up to the level of the suburban development which is already well versed in the process of mass customization.

Figure 8: Passive Home Model Option, Pendranti Architects

Conclusion and Next Steps

Passive houses already exist that are attractive, affordable and non-repetitive so the next challenge is how to make the jump in scale to large suburban housing developments to increase the positive effect of energy savings through sheer volume. But are we at the point yet where we can make that jump? To test the feasibility of this idea I needed the feedback from someone in the industry who knows the market well. Therefore, I presented my house and subdivision designs to Tim Gehman, an architectural executive for a national Fortune 500 homebuilder, for review and comment. While he was personally supportive of the idea, he felt there would still be many hurdles in changing the very imbedded status quo of suburban home buyers. First is the legal problem of in increasing density. Many zoning boards are reluctant to change codes to allow additional lots per acre as it could overburden roads, schools, infrastructure, traffic, etc. But the biggest challenge may be that suburban home buyers still don't demand energy efficient housing. As he states:

> *Real-estate is valued by location, square footage and bedroom/bath count. Attractiveness matters as an opener, but doesn't drive a yes or no, and annual maintenance and energy usage are an afterthought at best for most buyers. That's a systemic long-term behavior, how do you change it?*

Unfortunately, for the majority of today's buyers, bottom-line cost and lot location still far outweigh issues of requests for energy efficiency, and until they do, builders will have no incentive to change. There are a growing number of buyers who are concerned with the sustainability of our environment and would prefer an energy efficient house, but they are mostly younger first-time buyers who can not afford the price of a GO Home for their first purchase. But the increasingly palpable effects of climate change are causing a corresponding increase in the public's acceptance and concern. Sixty-two percent of the public now understands that global warming is caused mostly by human activities, an increase of 10 points since 2015.[21] As climate change worsens and affects more people, we may see an increasing demand for more efficient homes as well.

In the meantime, I have refocused attention inward to the cities where there is greater potential for a clientele that highly values sustainability and is comfortable with smaller, denser housing. The post-war exodus from cities to the suburbs left abandoned houses that became abandoned lots and blocks. A 2001 study of 70 US cities found an average of 15% of urban land was vacant.[22] Since this land comes with an existing infrastructure of utilities, streets, and public services, it provides prime opportunity for housing development. Government housing authorities in cities like Philadelphia have taken advantage of this vacant land to construct multi-block neighborhoods, but the houses designed there look nothing like the row homes they replaced. Instead, pseudo-suburban style homes set back from the street incorporate gable roofs, driveways, lawns and other suburban elements that feel out of place in the city fabric. It appears the American Dream of the gabled suburban house is as powerful in the city as outside it. But the grid form of urban streets is a favorable geometry for transferring passive subdivisions strategies to the city. If a city's grid is oriented within 20° of south (11° off in Philadelphia) it can serve as a prime planning layout for passive solar houses. The Charleston House Type, being an urban form itself that fronts on the street, works well here. When arranged in a staggered pattern, it can provide secure side yards and off-street parking while maintaining a density level more in tune with an urban environment than the current homes on the site. Redeveloping vacant urban neighborhoods to their former density may never be economically feasible, or even desirable, but filling these sites with passive houses rather than inefficient suburban style houses could attract a wider audience back into the city while conserving energy.

If we could apply passive energy strategies to the scale of the vast developer housing market, whether in the suburbs or the city, over time the magnitude of the effects at the macro scale could have significant environmental impacts. Architects alone cannot have a major effect on the environment by designing passive houses one at a time, but the massive scale of developer housing presents a prime opportunity to have a demonstrable effect on the larger ecosystem. The potentially devastating effects of climate change make it even more important that developers and architects find a way to create passive developments on a scale large enough to produce profound results.

Notes:

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3 *Shifting the Suburban Paradigm*, Allison Arieff, NY Times, October 2, 2011
4 *Fulton Homes Sells Houses Like Trousers, To Great Effect,* Teresa Burney, Builder Online, September 6, 2011
5 *Passive solar design of mass housing: Ensuring environmental improvements at the planning stage for suburban housing*, Jonathan Scott, Martin Edge, Richard Laing, Journal of Building Appraisal; September 2006
6 *Ask The Agent: What Home Features Are Most In Demand When Buying Or Selling?*, Grant Simmons, Homes.Com, February 8, 2016
7 *Can expensive, ultra-green homes sell in a gritty suburban Maryland town?,* Washington Post, May 18, 2017
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18 Scott, Edge, Laing
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20 Richard Pedranti Architect website, http://www.richardpedranti.com
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CRM Manufacturers in Architecture

Dana K. Gulling
North Carolina State University

Abstract

Computer-aided manufacturing (CAM) has revolutionized architecture. Proponents argue that CAM's computer numeric controlled (CNC) machines make individual architecture components that are not prohibitively expensive, reconnects designers directly to making, and transforms architectural form.[1] Despite these accolades, there is a distinction between CNC equipment directly and indirectly fabricating architecture components. Directly, CNC equipment punched the holes in the copper screen for Herzog and deMeuron's DeYoung Museum and the steel skin and structure for SHoP's Barclay Center. Indirectly, makers use CNC equipment to fabricate tooling (e.g. molds, patterns, and dies) to repetitively manufacture components that have been customized on a per-project basis. Examples include the pressed ceramic tiles on Machado Silvetti's Center for Asian Art at the Ringling Museum and the precast concrete panels for COOKFOX Architects' 260 Kent Street in Brooklyn.[2] The term 'customized repetitive manufacturing' or CRM refers to this process.

Through research, we have collected over 200 examples of CRM in architecture. Our CRM examples are located around the world and demonstrate a global application of CRM in architecture. *See figure 1.* A wide range of architecture practices use CRM in their building design; this includes high profile firms such as Foster and Partners, Herzog and deMeuron, and REX; as well as local and experimental practices such as LMN Architects, 5468796 architecture, and Assemble. Some firms, such as Kengo Kuma and Associates and Neutelings Riedijk Architects, are 'repeat offenders' and have many projects on our list of examples (four and six, respectively). Some firms, such as Gramazio Kohler Architects and Herzog & deMeuron are well-known for experimenting with CNC technology but have used CRM for several of their award-wining projects.

In architecture, CRM's production runs are smaller and manufacturing more flexible than those typically associated with repetitively manufactured, mass-produced components. CRM manufacturers need to respond to orders as they are placed, tooling changes must be quick, and machine set-up times short. There are specific types of manufacturers and manufacturing facilities that can take on CRM work. This paper defines manufacturing terms and provides broad overviews of manufacturers, while focusing on those elements that relate to CRM in architecture. We concentrate on manufacturers that are able to take on custom work via contracts, while demonstrating that the types of manufacturers for CRM in architecture is broad. Using

[1] Kolarevic, Branko and Kevin Klinger. *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. Routledge, 2013

[2] Machado Silvetti. Center for Asian Art at the Ringling Museum of Art. 2016, Sarasota, FL plaster molds were fabricated with a CNC mill. COOKFOX. 260 Kent. In-progress, Brooklyn NY used large-scale, 3D printed molds that were CNC milled to their final shape and finish.

the case studies, this paper explores, categorizes and qualitatively identifies different types of CRM manufacturers of architecture components.

Defining Manufacturing Methods

We define **'manufacturing' as to make from raw or unformed materials by hand or by machinery, especially when done systematically.**

Figure 1 | World Map of CRM in Architecture – locations of built case studies

With this definition, manufacturing refers to the forming of raw or unformed materials into a component's final form. The term 'manufacturing' can include the rotary cutting of a log to make wood veneers, the laminating of those veneers into plywood sheets, or the hydraulic pressing of thin, flat plywood sheets in a mold to make a bent plywood component. For the last example, manufacturing includes the deformation of the unformed plywood into its bent, final form. This is analogous to stamping a metal blank or extruding an aluminum billet. The cut mental sheet (i.e. blank) or cylindrical aluminum billets are not complete on their own; instead those merely formed for the manufacturing ease of the subsequent processes of stamping or extruding, respectively.[3] The definition of manufacturing does not necessitate a production quantity or size limitation. Manufacturing can include the making of

[3] In context beyond this paper, manufacturing can include the making of non-discrete items such as chemicals, textiles, foodstuff, or energy. It can also refer to postproduction processes—such as cutting, joining, and finishing, or product assembly.

a single, or bespoke, item, such as a man's suit or custom nameplates; the making of large products, including manufactured buildings or the making of ships; or the assembly of other standardized pre-manufactured components, such as the making of custom floating docks from standard aluminum extrusions.[4]

Like the making of a bespoke suit, manufacturing does not necessarily favor mechanized or industrialized processes and can include hand-crafted and labor-intensive processes. Generally, manufacturing by hand is viable where labor costs are low and where financial capital, necessary to purchase large equipment, is difficult to acquire. CRM examples of these labor-intensive manufacturing processes include the wood-molded, blown-glass spheres manufactured by craftsmen in Guadalajara, Mexico, for the Hesiodo in Mexico City by Hierve Diseneria and new concrete masonry units (CMU) manufactured on a concrete block hand press for MR 299 also in Mexico City by HGR Architects with Ariel Rojo.

Repetitive manufacturing makes repeated use of tooling (e.g. jigs, patterns, molds, or dies) for the production of similar units. Production runs for repetitive manufacturing can be varied, ranging from small-batch productions to production runs over one million units. The production run lengths primarily depend on tooling costs, because the tool's costs are amortized over the number of units produced. If a tool is inexpensive, then few units need to be produced to cover the tool's cost; whereas large production runs are necessary to offset high tool costs. If a mold costs $50,000, but produces 100,000 units, the added cost of a custom mold would be just 50 cents per unit. Different tools, and thus tooling costs, can be used in the same manufacturing processes. For example, metal casting can use wood patterns and sand molds for low-volume productions, or hardened tool steel molds for high-volume productions.

Figure 2 | SHoP Architects. 290 Mulberry Street. 2010 New York City. joevare. Flickr. October 4, 2008.

In repetitive manufacturing a particular tool is used for a particular shape; however, the manufacturing processes can be customized or adjusted to introduce differences in the produced components. For example, tools may be partitioned so that portions of the tool form different shapes. An architectural example is the CNC-milled master molds for SHoP Architect's 290 Mulberry Street that were partitioned into smaller shapes to cast multiple, differently-shaped rubber molds for the building's precast, brick and concrete panels. Additional manufacturing adjustments can be made through manufacturing speeds, conditions, or changes in media. This allows for some variation while still making repeated use of the tooling. An example is the dimpled surface of Herzog and deMeuron's DeYoung Museum in which a CNC-controlled, metal stamper used a steel-hardened, static-shaped, custom tool to strike the

[4] Wahoo Docks is a dock manufacturer in Georgia that manufacturers docks from components made at from a local an aluminum extruder. Gulling, Dana K. "Manufacturing Architecture: Case Studies of Collaborations between Designers and Makers" *Made: Design Education & the Art of Making Proceedings of the 26th National Conference on the Beginning Design Student, Charlotte, NC, 18-21 March 2010*. Ed. Jeffery Balmer and Chris Beokrem. Charlotte, NC: University of North Carolina Charlotte, 2010. 45-52.

copper skin at different forces, causing the dimples to appear irregularly shaped.

Manufacturers operate with either 'push' or 'pull' models of production. A push model of production is when a manufacturer starts producing units before orders are placed, essentially pushing the manufactured units onto consumers. A pull model of production is when manufacturer waits for orders before manufacturing units, essentially allowing the demand of the customer to pull units from production. Generally, push models require more capital than pull models as manufacturing costs are spent before the manufactured items are purchased, requiring a financial risk. Pull models of production have less financial risk than push models, but the manufactured items are not immediately available and require time to be produced after orders are placed. Manufacturers operate within both a push and pull model, depending on available capital, capacity, storage space, and predictability of sales.

Customized repetitive manufacturing (CRM) is repetitive manufacturing processes that have been customized on a per-project basis. In recent years, CNC technology has reduced tooling costs for repetitive manufacturing. Today, many repetitive manufacturers use tools fabricated by CNC equipment. Contact fiberglass molders and plastic thermoformers use CNC-milled, high-density foam for their molds. CNC routers, CNC millers, and EDM wire and spark machines fabricate hardened-steel molds for transfer moldings and dies for extrusion. New developments in rapid tooling (RT) have been using this equipment to make tools. For example, sand-casters can use FDM and SLA printed patterns for small production runs, researchers are investigating using metal laser sintering to make injection molds for plastic[5], and precast concrete manufacturers are using large-scale, carbon-fiber, 3D-printed mold plugs for casting precast concrete. Since tooling costs are amortized over the number of units a tool produces, reduced tooling costs reduces the production run necessary to offset those costs. This means that CNC technology has enabled smaller production runs for repetitive manufacturing and therefore has increased opportunities for customizing.

CRM is not specific to architecture; however, architecture easily employs the benefits of CRM for the manufacturing of building components. Like the manufacturing of ships or airplanes, buildings are made from several highly repetitive, discrete elements.[6] These elements may include extruded, aluminum mullions; extruded, stiff-mud bricks; spun, metal hardware; and cast metal fixtures. It is these repetitively-manufactured elements that hold the opportunity for customization. In addition, buildings have the potential to be bigger than ships or airplanes; therefore, the production runs of building components can be large with plentiful opportunities for potential customization. Additionally, the project scope of a building's construction is defined, containing the customization of the repetitively manufactured component within a project's building or a collection of buildings.[7]

[5] Lan, Hongbo. "Web-based Rapid Prototyping and Manufacturing Systems: A Review". *Computers in Industry*. June 2009. Combrink, J. et al. "Limited Run Production Using Alumide Tooling for the Plastic Injection Moulding Processes" *South African Journal of Industrial Engineering*. Online.

[6] Both Le Corbusier in *Towards an Architecture* and Stephen Kiernan and James Timberlake in *Refabricating Architecture* have made the analogy of ships and airplanes to buildings.

[7] There are some CRM components that were custom manufactured for a particular building or project that after that product was completed, the components were then available commercially. This includes the custom brick Peter Zumthor's Kolumba Museum now available through Petersen <https://en.petersen-tegl.dk/kolumba/> Accessed 18 February 2019; and custom blow-molded polli-brick Miniwiz's EcoARK. These are included because they were commercially available after they were first customized their corresponding projects.

Defining Manufacturers

Defining manufacturer terms can be ambiguous, as the terms often change depending on manufacturing sectors. In this section, we define the different types of manufacturers that produce discrete components that would be most often associated with architecture.

Original Equipment Manufacturers (OEM) are the final manufacturers of a product before it is purchased. Examples include pre-hung doors, light fixtures, airplanes, and cars. For simple products like drinking glasses—where only one manufacturing process (i.e. pressing glass) is used—the component manufacturer is the same as the OEM. For complex products like a car, the OEM assembles the final product and often subcontracts some of the car's component manufacturing to other manufacturers. This is typically done for the making of small components that may require specialized manufacturing skills—such as the extruding of polymers for tubes and belts—or when manufacturing of components an be done elsewhere at a lower cost.

There is ambiguity in the term 'OEM', as there is not consistency as to what define an OEM manufacturer. Some OEMs can manufacture some of the product's components, sub-contract other parts, and assemble all the parts together. Some OEMs only assemble components that have all been manufactured by other subcontract manufacturers. Generally, OEM products are available for commercial purchase; however, they can be sold under another company's name (i.e. Foxconn, a Taiwanese electronics company produces the products for Apple). Some OEMs can also be an end-product producer while other OEMs produce parts that end up in another product. Examples of this include Goodyear tires that come with a new car, or a Trane air-handling unit that comes with a Butler manufactured building. Both products are part of the final OEM, as well as being commercially-available for retail purchase as products themselves from another OEM (i.e. Goodyear and Trane). The term OEM is then further complicated as it can also refer to the manufacturer of aftermarket parts, such as using a Carrier HVAC unit to replace the Trane HVAC unit that came with the Butler building. In architecture, the term 'OEM' is analogous to the construction of the building, regardless of the building's components.[8]

Product manufacturers are manufacturers that produce only their own products. In architecture, this could include Valli&Valli door hardware and clay brick by General Shale. Generally, product manufacturers are not able to fulfill custom orders, as they are designed and optimized to efficiently manufacture their own products. General Shale offers a pre-described list of 'custom' shapes—such as bell coping, bullnose stretchers, and concave radial—which are prescribed special shapes and not actually custom designed.[9] Product manufacturers may operate on a push model of production, particularly if their product market is predictable.

Contract manufacturers (CM) do not produce any of their own products and instead manufacture items to

[8] Kieran, Stephen and James Timberlake. *Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction*. McGraw-Hill Education, 2003.

[9] On the company's website, the shapes are listed as 'custom' under a specific tab but then are full specified and dimension in a downloadable brochure titled "Special Shapes". General Shale. "Products/ Custom Brick Shapes". General Shale, Inc. 2015. https://generalshale.com/products/custom-brick-shapes/ Accessed 18 February 2019. General Shale. "Special Shapes". General Shale, Inc. 2018. https://generalshale.com/resources/file/612aecc0-01b4-4736-99b5-cf19eedd2061.pdf Accessed 18 February 2019

the specifications of the contract. CMs manufacture components or products as orders are placed. They operate on the pull model of production, waiting to produce after the order is placed. Examples of contract manufacturing is casting of architectural precast panels and injection molding, plastic car bumpers. Other terms for contract manufacturers might be 'job shops' or 'work shops', in which the facility does the manufacturing as per the job or work requires. Contract manufacturers may have contracts to manufacture a single production of units in a limited among of time or they may have a contract to produce a certain number of units, for each given cycle, over a long period of time. This second option allows the CM to continually supply the product manufacturer or OEM. For example, each month, a plastic, injection molding CM sends 100 bumpers to an OEM to install on their new cars.

The benefits of a using a CM for manufacturing is flexibility and increased specialty. CMs can handle the uneven demands for units and small production runs by balancing its workload through multiple contracts. In contrast, a product manufacturer not using a CM would need to sell enough product run to operate its facility year-around. Unlike OEMs that make complex products assembled from different parts, CMs focus on a limited number of manufacturing processes such as Penn Compression Molding that does compression, transfer, and injection molding with thermoset, reinforced plastics.

Figure 3 | Large press for compression molding thermoset plastics. Penn Compression Molding is a CM and focused on manufacturing with thermoset plastics.

Drawbacks of manufacturing with a CM may include capacity limits, scheduling, and oversight. CM manufacturers fulfill multiple contracts and therefore may not have the capacity to schedule jobs that will dominate their facilities. CMs schedule their productions to keep their workforce and machinery busy, and incoming jobs may not be able to be started until after a preceding contract has completed. CM have their own methods of operations that may be different than the contracting company. This may include employee hiring practices, shift hours, and safety measures. Unless the contracting company specifies how the CM should operate, the CM's operation may conflict with the goals of the contracting company. This is particularly a concern when the CM is located far from and in a different culture than the contracting company. Recently, this has been particularly problematic for clothing and shoe manufacturers, when it comes to issues of worker safety and child labor.

Some manufacturers are not easily categorized as solely product manufacturers or contract manufacturers. Some manufacturers will produce their own product lines, while simultaneously fulfilling manufacturing contracts for other companies. An example is Penguin LLC in Sturgis, Michigan that does plastic injection and blow molding contract manufacturing. In the same manufacturing facility is the OEM for their proprietary line of folding office tables.[10] Both the contract and OEM manufacturers are in the same space with dedicated blow-molding and pipe-bending stations, and powder-coating lines for their office products. Manufacturers may choose to do both product and contract manufacturing if their products are seasonal or are sensitive to economic downcycles. Generally, for these manufacturers particular manufacturing lines or stations are dedicated to fulfilling contracts, while others are pushing out products.

Figure 4 | Large plastic blow molding machine that make tabletops for Penguin LLC own line of folding tables.

The ability for a product manufacturer to customize depends on the manufacturer's size and flexibility. Generally, large companies that have high production runs of their standard building products, are not able to easily customize. Manufacturers such as General Shale have invested a lot of capital to optimize their assembly lines and equipment. This allows them to produce their standard products quickly; however, this investment may mean that their lines and equipment are not flexible enough to accommodate custom shapes. Contrasted with General Shale is Taylor Clay Products, Inc. located in Salisbury, North Carolina. Taylor Clay survived the economic downturn in 2010-2015 by taking their assembly line robots off-line and increasing their ability to manufacture custom brick shapes.[11]

Shops and Studios: Alternative Contract Manufacturers

Figure 3 | Jeff Goodman Studio website. 2019 <http://www.jeffgoodmanstudio.com/> Accessed 19 February 2019.

[10] Iceberg Enterprises is Penguin LLC's sister company with its own web presences and distribution systems. Although separate companies, manufacturing for both takes place in the same facility.

[11] In contrast to General Shale, Taylor Clay Products' website list their custom brick shapes under "Special Shapes" but states clearly "Charles Taylor does not recognize the work 'no' when it comes to ceramic brick." 2014 Taylor Clay Products, Inc. http://taylorclaybrick.com/wp/special-shapes/ Accessed 18 February 2019.

The term ‘contract manufacturer’ is an umbrella term that refers to the relationship between the manufacturer and the contracting company. **A subset of ‘contract manufacturer’ includes small manufacturing facilities such as fabrication or machine shops, craft production, or artisan workshop or studio.** These shop facilities are smaller than typical contract manufacturers, have fewer employees, and are not automated. Generally, fabrication shops, and machine shops are dedicated to custom work. They are set up to produce one-offs and prototype, but may be able to manufacture small, batch productions. Craft production and artisan workshops or studios often produce some of their own products for sale but can usually accommodate small-to-medium-sized production runs.

Since these alternative manufacturing shops and studios produce short production runs, their scheduling is more flexible, offering shorter lead times than traditional contract manufacturers. Workers are highly skilled and can produce high-quality items. Generally, shops and studios may experiment outside of a CM’s production parameters to produce unique units. In addition, shops and studios are more adept at collaboration between designers and makers. An example is Jeff Goodman Studio’s collaboration with Hariri Pontarini Architects for their kiln-cast, custom glass panels used for the Baha’I Temple of South America (2016) in Santiago, Chile. Jeff Goodman Studio is a Toronto-based glass studio that does primarily glass blowing, with some glass casting and slumping. Goodman Studio produces their own commercial and fine-arts work, and collaborates with architects, interior designers, and others for commissioned, custom-designed projects. The Temple’s glass panels resulted from a four-year research project between the Studio and the architects, in which 200 samples were made to achieve the desired design.[12]

There are disadvantages for selecting shops or studios as the contract manufacturer. Because of their small size and less-automated equipment, lead times may be longer than traditional contract manufacturers. Shops and studios may have limited manufacturing equipment, restricting their capacity to manufacture to certain specifications. Because they are less automated, costs for manufacturing in shops and studios is often higher than manufacturing with traditional contract manufacturers. Although quality of production is high, depending on the process and the materials, consistency between the manufactured units may be difficult. For certain architectural projects, consistency between units may not be a desired trait. Examples of this include the hand-thrown, black quartz grains for the cast stone panels for Duvall Decker Architect’s Mississippi Library Commission Headquarters (2010); the artist-applied glaze for the slumped clay tiles of Cloud 9’s Villa Nurbs (2009); and the glass panels for Hariri Pontarini’s Baha’I Temple.

Manufacturer Selection

Generally, manufacturing processes and manufacturer types are local or regionally-based. A manufacturer’s location is based on the availability of and access to raw materials, human resources, available transportation, and proximately to markets. This may mean understanding a region’s history to know of it manufacturing capabilities. First, in North Carolina, because of the state’s nature clay deposits, has ten brick and tile manufacturers in the state. Second, because of North Carolina’s history with boat-building, the state has a high number of contact-molders that work with

[12] Justin Ford. Hariri Pontarini Architects. Personal Interview. 2 November 2015.

fiberglass reinforced plastics (FRP). These include Piedmont Fiberglass that does spray-on FRP; Windsor Fiberglass that does hand-layup, specialty items; and a small two-person workshop, called Custom Fiberglass International that does highly specialized work and boat repair. Third, western North Carolina has many artists and craftspeople, educated at Black Mountain College or Penland School of Craft, that settled in the Blue Ridge Mountains, near Asheville. There, we find many artist studios that make blown-glass and are able to do custom productions.

When considering a CRM manufacturer, architects should look toward contract manufacturers and may be able to approach small-scaled, more unknown product manufacturers. Small product manufacturers are less well-known than high-volume product manufacturers and may be flexible enough to accommodate custom productions. In North Carolina, Taylor Clay is more adept at producing custom shapes for brick than General Shale, although both manufacture their own brick lines.

To search for manufacturers in the United States, Thomasnet.com is the leading to find manufacturers, and can restrict searches to geographic areas. Thomasnet is not exhaustive and is best for traditional contract manufacturers and product manufacturers that meet certification specifications (e.g. ISO). We have had some ability to find some small, one-person fabrication shops listed on Thomasnet; however, we have yet to find a sourcing platform that can be used for consistently identifying workshops or studios.[13]. Currently, we rely on simple web-based searches.

As an architect new to understanding manufacturing processes that can be customized, one should consider selecting a manufacturer who can collaborate during early design phases. This may restrict you to smaller workshops and studios, as many contract manufacturers competitively bid prospective projects without accounting for collaboration costs, unless specified in the bid. Some CMs will work with designers during design development with the hope that they may be awarded the bid contract. This involves financial risk that many conservative CMs are unwilling to do. An alternative to this is to include a manufacturing design consultant for a small fee.

Conclusion

CNC technology has made the fabrication of custom molds cost effective for small-volume productions that have been customized on a per-project basis. We have collected over 200 examples of CRM in architecture that are located around the world and have been designed by a wide range of architecture firms. For architectural application, the production runs for customized repetitive manufacturing are smaller than those typically associated with commercially-available components. CRM manufacturers must be flexible; respond to orders as they are placed, with quick tooling changes and short machine set-up times short. Generally, CRM manufacturers are contract manufactures with all or part of the facility work on a pull model of production. The definition for contract manufacturing is broad, with small workshops or artisan studios also able to do CRM.

13 This included Bill Ganz & Company, a one-man fabrication shop in Midvale, Utah, which makes spun metal components for light fixture and aerospace companies.

Blown Away: a Case Study in Modulating Airflow through Digital Modeling and Fabrication

Liane Hancock, Thomas Cline, Adam Feld, Yonas Niguse
University of Louisiana Lafayette

Abstract

This paper describes an interdisciplinary project: the design and fabrication of a HVAC diffuser for the University of Louisiana Lafayette School of Architecture and Design. The project acts as case study on data collection, research, and design for environmental factors. Students learned how to frame a research question, follow an organized practice of data collection and analysis, relate that data to industry-established standards, hypothesize about solutions through prototyping, test those solutions through digital analysis, and then verify hypotheses through empirical collection of data once their design was installed. This methodology allowed students to relate benchmarks established by ASHRAE's standards for comfort to the qualitative experience of their own design. Additionally, this project serves as an example of cross-disciplinary research, and provides a model for college initiated grant development, specifically tailored to STEM research.

Introduction

In a data driven world, energy and systems courses' digital modeling and analysis evaluate thermal comfort, but the experience of that comfort remains difficult to understand. Students can only imagine the experiential outcome of their projects. Holistically and pedagogically, it seems the best practice would be correlate empirical study with digital analysis. At University of Louisiana Lafayette, we devised a project that provided the opportunity for digital analysis, empirical study, and, perhaps most importantly, a project which gave students the chance to improve their own community, teaching students to value the consideration and design of thermal comfort.

The site for the project was both convenient and optimal. Fletcher Hall, home to our college, was constructed in 1976 and underwent a first phase of renovations five years ago. A second phase of construction anticipates renovation of the HVAC system. Eight air-conditioning diffusers distribute ventilation across the first floor's open plan. Traveling at high velocity, the air conditioning has a history of blowing directly on students' desks, creating extremely cold adverse working conditions. Here existed a design opportunity that the students know all too intimately, and which drove home the importance of properly controlling environmental systems. The project: design an attachment to the current diffusers that dispersed the ventilation evenly across the studio.

"My first semester was spent in the midst of a frozen whirlwind. I dreaded coming back to my desk just to find models scattered around the studio like artifacts in an adventure movie. After retrieving them, spelunking in the depths between the desks, I returned to sit in front of a glacial phenomenon." – Stephen Corcoran

Cross Disciplinary Experience

Within the school, industrial design, interior design, and architecture students share no interdisciplinary coursework beyond first year; our professional curricula are too straightjacketed by accreditation requirements. Yet a project like this served all three disciplines: it mediated the environment but also was a designable product. To capitalize upon the collaborative nature of the work, this project occurred outside of the curriculum on weekday evenings as a voluntary effort. Students were excited to do research that would have a direct impact on their studio space, which was associated with a grant, and had the possibility of publication. Additionally, three students received honors credit for their studio work. Industrial design, architecture, and mechanical engineering faculty led the meetings collaboratively.

We were surprised by the level of student interest. Sixteen students initially came forward, and twelve participated through completion. The group included: three industrial design upperclassmen; one mechanical engineering upperclassmen; and twelve second year architecture students.

To manage this large group we adopted a distributed way of working. To accommodate variation in schedule, we established two meeting times: Monday | Wednesday; or Tuesday | Thursday. This led loosely to two groups working on the project. We also established early on that students could plug in and plug out based on availability, and without judgement. This format worked well for data collection, but became more difficult as students attempted to build upon each other's ideas during conceptualization. Once the group selected a design, the faculty broke the construction work into two-hour sessions, leading again to relative ease in management between the two schedules. The relative shortness of the working sessions reduced student burnout, and we believe led to greater student participation. To manage schedule, we used Groupme to communicate and schedule meetings. Groupme also allowed our mechanical engineering student, who was largely working off-site, and our visual arts student videographer to come and go with perfect timing.

The project presented a distributed network of both students and faculty with regard to visual and verbal communication and in design and research interest, from data collection and analysis, to design thinking, to working with materials and constructing, to digital modeling and analysis skills. We made no attempt to break down perceived silos to create baseline equality. Instead, we built an infrastructure of communication and respect across these silos to give agency to those with individual knowledge while building confidence in those who had less expertise in a particular method or area or ability.

As one might expect, we found the representational language of industrial design and architecture differ. Industrial designers use a process of ideation, which heavily emphasizes drawing, especially in perspective, in the early stages of design. By contrast, the architecture students tended to focus upon model making and their sketches remained less synthesized, instead utilizing either plan or section. The industrial designers clearly emphasized the development of an object or product, whereas the architects exhibited more interest in the behavior and control of the wind, and conceptual opportunities of conditioning the entire space.

The introduction of the subject matter of environmental factors to second year architecture students provided both opportunities and difficulties. Lacking previous experience, we found the students approached the subject matter with outside of the box thinking in lieu of typical solutions. At the same time, during the design phase, the students spent a long time considering the behavior of wind abstractly, and it took some concerted effort by the faculty to get the students to produce initial designs. By contrast, the upper class industrial designers had a firmer grip on functionality: they were far more willing to jump in and start designing, but this resulted in more expected and traditional solutions. For all of the architecture and design students, the introduction of the mechanical engineering student was magic: employing his acumen allowed them to visualize the function of their designs within the computational fluid dynamics environment, introducing an entirely new tool to ten out of the twelve students.

With regard to modeling and fabrication, our second year architecture students also had no previous experience with the digital fabrication equipment. By contrast, the industrial design students understood the patterning, fastening, and fabricating within the digital environment. While, the upperclassmen industrial designers were familiar with digital modeling software, most of the architecture students were receiving instruction in rhino in a support class simultaneously with the commencement of the project.

Project Process

"The vent blows very cold, forceful air that can be felt from as far as ten feet away. In my first semester of freshman year, I sat in the direction of the air flow and I often found myself unproductive and unencouraged to work."

– Kristen Lyon

To distribute the ventilation properly, we, as faculty, were agnostic about the students' selection of form, materiality, and production of the detachable diffusers. To prompt the students, we asked "What if the designs are not rigid, but instead take form when operating? Could kite technology be a precedent?" We felt it was important to throw the possibilities open wide. Additionally, because the diffusers were envisioned as a temporary installation, with a life expectancy of 2 to 3 years, we asked the students to consider issues of permanence versus impermanence – including durability, weight, and options for connection.

The faculty members felt it was important to introduce standard research methods. The project taught students how to frame a research question, collect and analyze the data, relate that data to industry-established standards, hypothesize about solutions through prototyping, test those solutions through computation fluid dynamics analysis, and then verify their hypothesis through empirical collection of data once the design was installed and tested. At the same time, the process allowed for fun, creativity, and real time problem solving.

Because this project was not within the curriculum, we emphasized understanding rather than ability in for each learning outcome. This introductory, project-based, interdisciplinary approach kept the project from becoming stymied when the students were unfamiliar with the particularities of a certain computer program. Eschewing minutiae while being proactively involved, the faculty leveraged the students' knowledge to focus on big takeaways while always moving the process forward.

Data Collection

To begin the design process, we charged the students to record data measuring the air velocity around the diffusers using an anemometer. To locate station points for measurement in the studio, the students made use of an existing ceiling grid to develop the x and y dimensions, and then clipped standardized lengths of yarn to the intersections. (Fig 1) Our plan was to take measurements with an anemometer, recording the data for the digital model. It is with this first step that the students learned how our expected model of research and reality could diverge. This project was conceived in early fall when the air conditioner operated at full force. By the time we received approval, the entire building had become still. We contacted the Facilities Office to turn on the air handler for our data collection. The response was unexpected – we were told the air handler was on, and that it was forty-year-old equipment in dire need of emergency repair. When we relayed that it did not seem to be working at all, the facilities manager inspected the unit, and instructed his workmen to replace what were termed as "very old filters and slipping belts." The handler had been spinning in place – causing no air to distribute through the building.

Fig. 1. Yarn segments showing wind velocity.

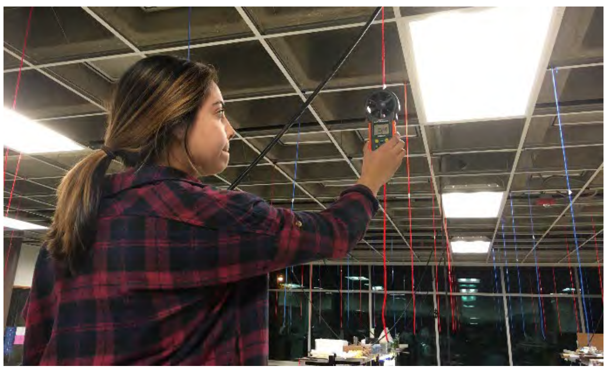

Fig. 2. Measuring wind speed with the anemometer.

Fig. 3. Student mapping the ASHRAE thermal sensation.

Fig. 4. Full-scale test of a student's design.

Much to our surprise the deferred maintenance of changing filters and belts resulted in the system distributing the air more evenly. In our attempt to turn on the air handler – had we actually solved the worst of the ventilation issue through a simple maintenance call? While velocity diminished, the airflow from the diffuser remained particularly concentrated and uncomfortable over several desks near the diffuser, while desks at the far ends of studio now received no ventilation. As of publication, we do not yet know if the original speeds will return once the chiller engages this summer.

Acquainting the students with the ASHRAE thermal sensation scale they were able to rate their desk locations within the studio on a range from Hot (+3), Warm (+2), Slightly Warm (+1), Neutral (0), Slightly Cool (-1), Cool (-2), Cold (-3) that directly correlated with the wind speed coming from the ductwork.

Measurements from our anemometer produced readings between .2 m/s and 1.72 m/s in the area down the center of the studio. (Fig 2) The studio periphery measured at 0. According to the IAQ Guide, distributed by ASHRAE "Air distribution systems should be designed to achieve an appropriate air velocity near the occupants (sometimes referred to as terminal velocity), which is often about 50 fpm (.25 m/s)."[1]

Utilizing the CBE Thermal Comfort Tool[2] based on ASHRAE Standard 55-2017, at a measured temperature of 72% and humidity of 50%, and assuming working at ones desk in typical interior appropriate clothing (trousers, short-sleeved shirt), the student found their collected data did not comply with the ASHRAE standard. The data did align with the student's ratings of their desks on the thermal sensation scale. (Fig 3) In addition to collecting the numerical data, the student observed the movement of the lengths of yarn in response to the airflow. This movement traced to trajectory of the air, identifying both where the velocity was strongest and showing movement felt on the skin but which was below the threshold of the anemometer's sensitivity.

Design

Once the students could visualize the movement of the air, they began brainstorming and hypothesizing on how best to control the air. The segments of yarn aided in visualizing the fluid character of the airflow. Several designs provided variations on ductwork typology, featuring perforations or shaping flanges to distribute the air. The duct-like solutions sought to concentrate and enhance airspeed – propelling the air forward while allowing a portion of the air to filter through perforations or slots. By contrast, three designs employed rudders or fins and waterfall-like shelf structures to create spouts, conceiving of the air as a fluid, similar to water. (Fig 4 & 5) Both of these designs did not attempt to close the upper portion of the duct. Fins or rudders widened the airflow in the horizontal direction. Base plates for these two designs acted as a shelf for the air to flow over – allowing the velocity to gently slow and fall. The students' re-envisioning of ductwork typology would have been perfect to propel the air to the far reaches of the studio if that had been the task; but the task was to spread and slow the air and the waterfall like solutions seemed destined to be most successful.

After initial design and digital modeling in Rhinoceres by the students and faculty, our mechanical engineering student ran computational fluid dynamics on the six designs. (Fig 5) The results showed what we had hypothesized. The ductwork based solutions did an excellent job of propelling the air, whereas the more shelf like versions resulted in a distributed free-flowing result. Additionally, the size of the circular solution resulted in the most even slowing and distribution of airflow. This was a first introduction to computational fluid dynamics, and the students were excited to see how their hypotheses played out in these models.

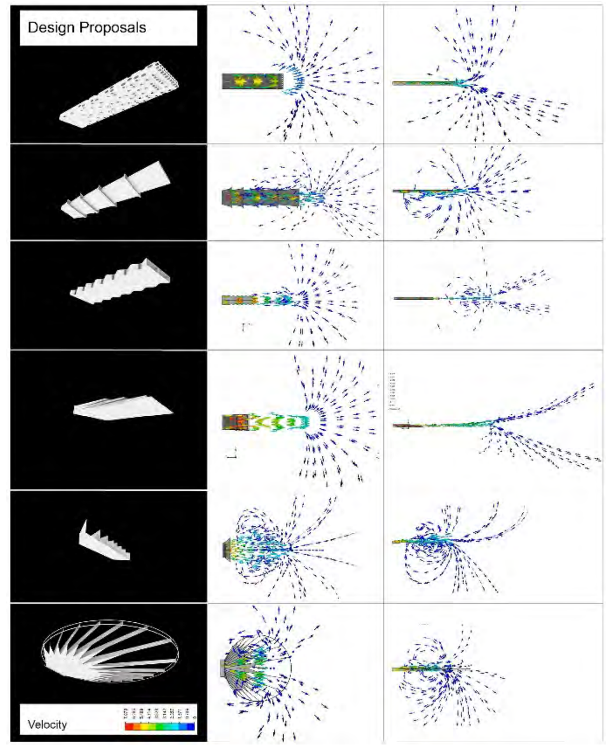

Fig. 5. The six design options and their CDF analyses.

The next step: choose a design. Partially because of the CFD results, partially because it would be the biggest design statement, and partially due to ease of constructability, we selected the circular shaped design.

The design we chose was large – eighteen feet in diameter. (Fig 6) Typically, ventilation systems act as an infrastructural system in support of architectural design. In this case, the diffuser design became the focus of the space, removing one's gaze from the detritus of ceiling grid, grid hangers, electrical conduit, sprinkler pipes, and discolored waffle slab. It not only served to condition the space but it also acted as a design intervention, a focal point that created a sense of identity within the studio environment.

Fabrication

"The creative energy that we students should be applying to our project is instead going to jerry-rigging contraptions that redirect the air." – Jacob DeJean

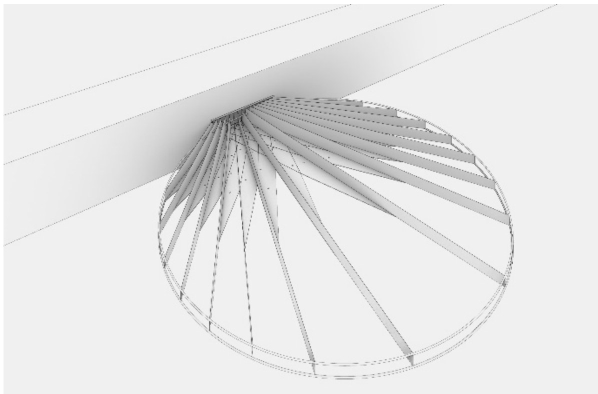

Fig. 6. Digital model of selected diffuser.

Fig. 7. Diffuser installed.

Because of the short duration of the project, it was impossible to provide time for material testing and selection. Instead, the faculty suggested a shortlist of possible materials that preserved the character of the Rhinoceres model. The faculty proposed ¾" PVC pipe to maintain rigidity of the frame, to offer the correct amount of visual weight to the project, and to provide ease of workability. For the bottom surface, initially the group considered canvas, but there was concern that it would not maintain rigidity under pressure from the HVAC. Instead, the faculty suggested 4 millimeter corrugated plastic, which provided strength and stability but also had little weight. Initially, the faculty recommended sheet metal for the fins, but the students voiced a concern that they might generate noise. As a group, we discussed canvas, but this choice seemed too heavy and not sleek enough for the project. Finally, the faculty decided upon a greenhouse grade mylar, with little weight. White on one side and reflective on the other, it gave the project presence within the studio. Additionally the mylar reflected light, an attribute seen as attractive when the group initially considered sheet metal.

To start we took measurements from the Rhinoceros model for the PVC frame. The students and faculty made the cuts, and cleaned the PVC, and then the students assembled the framework, developing a method of assembly that kept pieces perpendicular while affixing them with the PVC glue. Next came the fabrication of the fins. Because the fins had a geometric warp, and were very big, it would have taken a prohibitively long time to construct drawings of them on the mylar. Instead, printing templates from the Rhinoceros model was fast and easy. Armed with paper patterns the students were able to cut out all the fins in about four hours. Testing the behavior of the fins, we discovered that they cupped and rolled along the span. Instead of strengthening the top and bottom of the fins, one of the students solved the problem by adding vertical dowels every two feet, disguising them with white duct tape on the white side of the mylar. We then used the Rhinoceres templates to cut the pieces for the corrugated bottom plate. Discussion centered upon laying out of the bottom pieces to ensure book matching of pattern, while white duct tape was once again used to join the pieces.

With all individual parts assembled, full installation occurred during a final eight-hour marathon. (Fig 7) All of the fins were attached to the vertical struts of the frame with white duct tape, keeping the fins rolled until final installation. The students identified anchors for the ceiling tile grid and used them to hang the frame. Next, the team attached a Plexiglas grill, which had been laser cut, to the original diffuser using commander strips. The students then unfurled and affixed each fin to the grill.

The final challenge was attaching the corrugated plastic baseplate. The faculty developed a detail of 3D printed fasteners for threading with paracord. While the fasteners did a good job of supporting the board, it was impossible for the students to tie them as the faculty initially envisioned – the students could not work blind and beyond arms reach. Flipping the way the fasteners worked, the students located the knots on the underside of the panels – providing what became an additional finishing detail.

During installation, we also discovered that it was impossible to keep the bottom base plate flat without adding fasteners. Instead, the students decided that the endpoints should be brought up taut, allowing the base plate to curve gently. The entire group agreed that this change, attuned to the pliant character of the material, provided a much more elegant solution – creating a curving surface as a counterpoint to the slight warp of the fins.

All agreed that the new diffuser decreased the velocity of the air substantially and distributed it more evenly across studio. Once the chiller engages, the students are eager to take new measurements to confirm the comfort level now falls within the ASHRAE standard.

"I'm interested in designing a solution to the problem because it would boost the morale of the community in Fletcher Hall, and prevent the airflow from inhibiting our workflow." – Kristen Lyon

Funding the Project: Leveraging a Single Project to Serve the Broader Goals of the University

This project exists as a case study within the larger trend across design academia to engage in STEM practice based research. It also serves as a model by which individual universities can develop methods of financial support. Anticipating the increased inclusion of research into design education, our university developed a competitive grant within the college that annually awards money to faculty who collaborate on projects that incorporate digital resources and STEM based learning methods to produce creative works. The grant program gives special emphasis to interdisciplinary projects. With our college providing grants of up to $4000, this initiative provides significant support for practice based research.

Two paid-admission public events underwrite these projects with an annual revenue of $40,000, with one of the events featuring TEDX style presentations by the faculty. In addition to materials, we are able to purchase equipment and to fund a videographer to record the process of the project. The university will use the video for recruiting. Finally, this project will serve as a case study for our new research institute for Industrial Design as it cultivates work with the community.

Conclusion

“To me, solving small problems makes the most significant impact. Right now, I think about those vents constantly. But what if we solved the problem and everything normalized? That uncomfortable reminder would be replaced by complacency in everyone's mind and that interests me.” – Stephen Corcoran

As a case study, this project provided students with an introductory level understanding of applied research. It taught students how to frame a research question, follow an organized practice of data collection and analysis, relate that data to industry-established standards, hypothesize about solutions through rapid prototyping, test those solutions through digital analysis, and then verify their hypotheses through empirical collection of data once the design was installed and tested. This methodology allows students to relate benchmarks established by ASHRAE’s standards to qualitative experience. Additionally, it challenged students’ tendency to view the outcomes of digital analysis as sacrosanct. By having the students relate the digital model to the final installation, the students could reach conclusions about the strengths of digital modeling, and the opportunities of full-scale fabrication.

Most importantly, this project taught each student, as a citizen of the school, that designing environmental control can make their community a better place to be.

Notes:

1 American Society of Heating, Refrigerating and Air-Conditioning Engineers, et Al. *Indoor Air Quality Guide, Best Practices for Design, Construction and Commissioning* (Atlanta Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2009): p 585.

2 Hoyt Tyler, Schiavon Stefano, Piccioli Alberto, Cheung Toby, Moon Dustin, and Steinfeld Kyle, 2017, CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley, http://comfort.cbe.berkeley.edu/ (accessed February 1, 2019)

Design-Build for Discovery: Applied Research on the Construction Site

Mary C. Hardin
The University of Arizona

Abstract

The University of Arizona's architectural education program utilizes the dual learning vehicles of design-build pedagogy and affordable housing projects to investigate the cost effectiveness of regional vernacular construction methods paired with contemporary energy and water conservation strategies to control initial construction costs and long-term operational costs of single-family dwellings.

Earth, clay and stone, indigenous building materials with long histories in the arid deserts of the southwestern U.S., have diminished in use as labor prices have risen in the construction industry. Over the course of six design-build projects, Building Technology faculty and students experimented with and improved wall forming systems for rammed earth and pumice-crete, in order to reduce labor costs and bring these vernacular materials into use for affordable housing. The focus of the applied field research was the design of the wall forms and the sequence of building multiple walls with bond beams. Students built full scale wall mock-ups, created budget and energy models, tackled critical path construction scheduling, and interacted with subcontractors, inspectors, and building permit officials during design and construction of the housing units.

Our methods of earthen wall construction were refined over three main iterations and six projects, resulting in streamlined procedures, reduced construction time, and costs that were much lower than similar commercially built systems. The value of the design-build and research processes for students goes beyond exposure to the entire spectrum of housing design; the iterative investigations of wall forming systems across multiple projects teaches the value of Building Technology research and discovery through architectural practice.

Keywords: Design/Build, Pedagogy, Materials + Construction Techniques

Pedagogy

Twin goals of providing affordable housing with low long-term energy and maintenance costs to the low-income population in Arizona, and offering hands-on design-build learning experiences for architecture students at the University of Arizona led to a series of prototypical dwellings designed and constructed by faculty and students between 2000 and 2017.

Design objectives included the identification of low-cost building assemblies for maintaining thermal comfort in hot-arid climates. In order to build with locally available (earthen) materials, some experimentation with construction methods was necessary in order to contain costs.

Pedagogical objectives included involving students in all aspects of architectural practice; from site analysis, site selection and procurement, through schematic design, design development, and construction documents to the creation of budget and energy models, critical path construction scheduling, and interaction with subcontractors, inspectors, and building permit officials during design and construction in order to support their integration of the many aspects of the undergraduate architectural curriculum.

Figure 1. Projects 1-6; from left to right, Rincon Vista Classroom Facility, Gila River Reservation Residence, Tucson Rammed Earth Residences, and Scoria Residence.

Research: Methods of Affordable Earthen Wall Construction

Vernacular building materials and methods of construction were once the only choices for building dwellings in the arid southwestern region of the United States. Before the advent of the railroads in Arizona in the late 1800's, most homes were built of earthen materials and the limited small timbers available. Some indigenous peoples in the Sonoran Desert excavated "pit houses" that were roofed with small branches and trunks of mesquite trees and cactus ribs, then daubed with clay-rich soil. Because the living space was recessed 3 or 4 feet into the earth, the interior temperatures gained some stability from the earth itself.[1] Other indigenous peoples built of rammed earth and adobe bricks, constructing thick walls that served as thermal masses to regulate interior temperatures. Once the railroads began to deliver other types of building materials, the palette for residential construction gradually became homogenous with that for the rest of the nation. In the contemporary U.S. building economy, the use of earthen wall materials has been priced out of the mass production housing market due to the high amount of labor involved. Adobe blocks are still made mostly by hand, and the unit costs reflect that fact. Rammed earth contractors use heavy machinery to move wall forms and compact the earth within the forms in order to save on labor, still driving the prices skyward.

While using earthen materials to build thermal mass walls may still make sense today for environmental reasons, do-it-yourself labor is about the only way to bring costs down. Faculty and students at the University of Arizona began to experiment with lightweight, movable forms as a cost-saving measure, with the goal of building affordable housing that would also be energy-conserving due to the thermal mass of the wall assemblies. A series of full-scale built works allowed for experimentation with wall forming systems and gradual refinement of the methods that proved manageable by small groups of people without heavy equipment. Beginning with the leads in David Easton's book, "The Rammed Earth House"[2], faculty and students worked through three general iterations of form methods in six design-build studio projects.

Iteration One: Project 1

Project 1 was a classroom building for the University of Arizona's Department of Athletics and Recreation, sited in a large practice field and park near the main campus. The Rincon Vista Classroom Facility was meant to be energy-efficient, low-maintenance, and able to maintain indoor comfort even when the HVAC system was not in use. Rammed earth was selected by the design-build students and faculty members for the wall construction due to its ability to stabilize interior temperatures via thermal mass. The first iteration employed moveable, reusable plywood forms clamped to "volume displacement boxes" (VDBs) built of plywood and anchored to the foundation in order to create the rammed earth walls. After the walls were constructed in increments with the reusable forms, one-use forms that encircled all of the earthen walls simultaneously were constructed to pour a continuous concrete bond beam at the top of the walls. After completion of the earthen walls and bond beam, the VDBs were removed and the voids were filled in with windows and doors. This method depended upon having lots of regularly spaced window openings – a practice that worked well for a classroom building with one central space and many apertures. Using the VDBs to establish the heights for form boards and as attachment points for other materials allowed careful calibration of the lines left on the surface of the walls by the form boards, as well as the ability to line up the dirt lifts and the resulting "cold joint" lines between the lifts.

Figure 2: First rammed earth project in construction, showing VDBs and movable forms.

Figure 3: Second rammed earth project in construction, showing end boards and movable forms.

Iteration Two: Projects 2 & 3

The use of many regularly spaced and same-sized openings doesn't fit a residential design as well as an institutional building, due to the various uses of different rooms and therefore varying window and door openings. The second iteration of formwork, therefore, dispensed with the VDBs, and supported movable forms on concrete stem walls and temporary end supports anchored or braced to the floor slab. The second project, a dwelling for a Native American family on the Gila River Reservation, still employed the construction of separate, continuous forms around the tops of the completed earthen walls in order to pour a continuous concrete bond beam. This last step was difficult to support and level, and took three or four weeks of studio time to complete, which created a serious bottleneck in the construction schedule. With the end boards removed, there was no structure for attaching the forms except for the pressure of clamps. As the forms were leveled and clamped, they often slipped separated, and finalizing their alignment was a long process. Roof framing and interior partition wall framing had to be delayed until the entire bond beam was in place, as it served as the main lateral bracing for the structure.

One tangential innovation was made during the Gila River project construction. The homeowners, currently living in a traditional wattle and daub dwelling on the same parcel of land, requested the embedment of cactus ribs near the surface of the rammed earth walls, in order to achieve as aesthetic similar to their original dwelling (which was actually supported by the cactus rib framing). Students built full scale mock-ups of several possible ways to embed materials in rammed earth, until they found a way to anchor cactus ribs against the forms during high pressure tamping while allowing the surface dirt to fall away with gentle scouring once the wall forms were removed. They struggled with the notion of embedding what would essentially be a decorative material in a structural wall of a different type, but found a way to accomplish this while making it clear that the cactus ribs had no structural role in the rammed earth walls (by not bringing the saguaro ribs near the edges or corners of the wall panels).

Figure 4: Gila River dwelling with saguaro ribs embedded in entry wall.

An improvement was made in the process during the construction of the third project, a dwelling for a low-income family in Tucson, AZ. Since the holes left in the rammed earth walls by the removal of pipe clamps (that were later filled with earth) were always at the same heights all the way around the walls, the pipe clamps could be reinserted into the holes at the same height all the way around the structure and used as a scaffold for setting up and leveling the continuous bond beam forms. This minor adjustment shaved considerable time off of the construction period for the bond beam, but all other phases of the construction were still dependent on completion of the bond beam pour.

Figure 5: Third rammed earth project in construction; with pipe clamps supporting the continuous formwork for a bond beam.

Iteration Three: Projects 4, 5 & 6

The third iteration challenged the notion of pouring a continuous bond beam, and experimented with incremental bond beam pours in the tops of the forms already set up for the earthen walls – with continuous reinforcing steel that created the lateral stability and tensile strength of the bond beam. Full scale mock-ups were built to test the difficulty of extending the reinforcing steel through the end boards to create the required overlaps and negotiating corners with rebar bends. Faculty and students met with local building officials to confirm that the method would be approved by inspectors in the field.

Project 4 was built as a dwelling for another low-income family in Tucson. In this construction process, the tops of the wall forms were used as the bond beam formwork, too, with the rammed earth stopping at the level of 7'-4" and the bond beam steel and concrete occupying the top 8' of the forms. The rebar was extended through ½" holes in the end boards in order to create splices for the next wall segment. Rather than having 20" of rebar sticking out into the air, impeding work in the next wall segment, small end boards were created 20" back from the end boards of each wall segment, and the subsequent concrete pour allowed the flow of concrete back into the top of the previous form segment. These small end boards took some tinkering, to ensure that they would not become trapped by the pressure of the poured concrete, etc., but saved a great deal of time overall because framing could begin in other areas of the dwelling (where bond beams had already been poured) while the rammed earth walls were still being constructed in other areas.

Figure 6: Incremental bond beam construction in Project 4.

Figure 7: Rammed earth wall of Project 5; this wall constructed with industrial forms.

Project 5, also a residence for a low-income family, was another version of this method of pouring within the wall forms – except the design broke the rammed earth walls up into several parallel walls instead of a continuous rectangle. The rammed earth work went relatively quickly because the design-build program owned enough formwork to form one long wall without having to move the forms around. In this instance, a set of industrial concrete forms was also loaned to the project by a rammed earth contractor, to allow students to compare the methods of building with standard forms and equipment. Because the industrial forms are much heavier, the struggle was in lifting them and leveling them without a fork lift (equipment our school does not own). But, the results of the varying wall surfaces due to the different form sizes and the use of snap ties versus pipe clamps, was interesting for students to see.

Project 6 is the most recent project, which investigated the process of forming raked walls of scoria with incremental forms and incremental bond beam pours. Scoria is the local name for pumice-crete, a mixture of crushed pumice stone from local quarries with cement and water. It is poured into forms in a damp state, but is not tamped or consolidated under pressure the way rammed earth is.

This project, a residence for a low-income Tucson family, was engineered as an earthen structure rather than low-strength concrete (which is another possibility because the cement content is higher than in rammed earth). Low strength concrete construction does not require a bond beam, but does requires cylinder compression tests, and the mock-ups and test cylinders done by students ahead of the actual construction achieved the required compressive strength for low-strength concrete only half of the time. All of the results were well over the compressive strength required for earthen walls, so in this first prototype, the faculty leader chose the conservative route of using a bond beam. Designing the process of pouring incremental bond beam segments with continuous reinforcing steel at an angle turned out to be very difficult and time consuming. The incremental bond beam method devised for rake walls in earlier projects proved difficult to control because the forms hide the earthen walls, and the string lines that mark wall heights and rake angles were constantly disrupted as forms were moved. Originally meant to be exposed to view, the bond beam was later covered with roof flashing and ceiling trim in order to disguise the lapses in alignment. This challenge is one that remains for future iterations of the construction methodology.

Figure 8: Scoria walls with incremental bond beam.

Students were indispensable to these many iterations and refinements, brainstorming about methods and building mock-ups to test ideas and convince code officials of the efficacy of new methods. Each iteration was accomplished by two to three different studio classes, and therefore the students and faculty had to learn from their predecessors and extend the body of knowledge with each new project. In this way, students were not only learning about known building methods, but also experiencing the challenges and satisfactions of original field research. Bringing students into the process of inquiry during a construction process makes them partners in discovery, and encourages creative thinking even during the most performance-critical stage of building delivery.

Project Costs

At the time of the first design-build studio involving rammed earth wall construction in 1998, the cost per square foot of wall face charged by building contractors in Tucson, AZ was $24. (The cost of the materials per square foot of wall face was $4.80). Contractors cited the cost of labor and equipment as the reason for this high price, but it was also due to the fact that there were only two contractors who built with rammed earth and the demand was high once several projects by local architect Rick Joy received national design awards and were published widely. Using the movable forms and student labor calculated at minimum wage, the studio project was built for $10.80 per square foot of wall. The difference in costs between contractor-built and school- built earthen walls has grown wider over the years, as rammed earth construction becomes even more expensive ($75 a square foot of wall face in 2019) due to shortages of contractors working with the material and difficulty in finding skilled laborers. The cost of the most recent design-build dwelling built of rammed earth, in 2013, was $20.30 per square foot of wall face, including student labor hours valued at $10/hour. In today's dollars, that would be $22.15 per square foot of wall face.[3] These comparisons illustrate the cost saving that can be had with movable forms and without the necessity of heavy equipment, suggesting that a DIY construction may be the most affordable option for homebuilders with a small group of laborers and rudimentary construction skills.

Pedagogical Results

Students participate in the design of these experiments and learn through the iterations of past trials and results. In this way, they are brought into the long-term research agenda of the faculty and are partners in discovery. Their involvement in a trajectory of research that spans decades may be as significant as their short-term learning about the materials and methods of construction, coordination with other trades, budget considerations, interactions with building officials and client groups, and the resolution of details with design intentions in the field - but the short-term experience is where they report the most satisfaction.

The following excerpts from testimonial letters, student course evaluations, or required field work journals are typical of the feedback we receive about their learning experiences:

"(The) design build studio which I was involved in over the course of two semesters in 2016 was without a doubt the most rewarding and greatest experience in my college education. As students, we were able to lead the entire process of designing and building a home for a low-income family in Tucson. (Our) professor guided us through every step of the way from finding and purchasing a suitable plot of land into conceptual design and design development through construction documents managing a real-world budget and through every phase of construction and ending the process with selling the home to a deserving family. This experience was formative in my evolution as a designer and as a human being. I know that the experience is something that every student who was lucky enough to be involved is proud of and will cherish for life."[4]

"From 2007-2008, I was part of Professor Hardin's and Folan's studios – designing and building a 3 bedroom - 2 bath house that we built for an out of pocket expense of just over $100,000[5], allowing it to be affordable to working class population in the barrio in which it was built. As a student in the Design Build studio, we were tasked with not only the labor to construct the house but to manage the construction process. Our class inherited the project as a foundation, rough framing, and an undeveloped set of Construction Documents. As a studio, we designed the details and were tasked with their execution. This process solidified an understanding of construction details, process, and the challenges design decisions can cause or solve. I was on the team in charge of overall budget management, which was critical for a home that was going to be sold to low-income families via a HUD-approved first-time homeownership program. We were also tasked with the coordination of materials and subcontractor labor. Learning the process and execution of construction in a hands-on environment lent itself to a deeper understanding of other elements of my education. Of course, this prepared me more thoroughly for the real world of construction. "[6]

Conclusions

While the design-build program at the University provides for hands-on educational opportunities and community outreach experiences for the students in the School of Architecture, it also serves as a field-testing vehicle for design hypotheses of many kinds. Some of the hypotheses involve explorations of methods of construction in relation to costs, and others investigate the efficacy of wall assemblies with regard to energy use. This kind of applied research differs from laboratory testing, where the small-scale wall panels are isolated from any other factors such as human use and flaws in workmanship. The conditions of construction and inhabitation of the design-build dwellings are similar to what happens all over the region in the production and inhabitation of standard housing stock and so allow for comparison to the most common circumstances.

Students who participate in the design-build research and building projects generally come away with a strong sense of purpose, a realization of the significance of their contributions to the community, better understanding of materials and methods of construction, and some knowledge of the long-term research trajectory particular to building technology in the arid southwest climate.

[1] Easton, Robert and Peter Nabakov. *Native American Architecture.* Oxford University Press, 1989.

[2] Easton, David. *The Rammed Earth House*. Chelsea Greene Publishing Company, White River Junction, Vermont, 2007.

[3] 2019 minimum wage in Arizona is $11.00, however, and the total is not adjusted for that.

[4] Andrew Marriott, UA SoA Class of 2017

[5] This included land and soft costs

[6] Maggie Kane, UA SoA Class of 2009

In Spite of Pragmatics: The Pursuit of Both/And for Integrated Architectural Solutions

Hans C. Herrmann, AIA, NCARB, LEED Green Assoc.
Mississippi State University, School of Architecture

Jacob A. Gines, AAIA
Mississippi State University, School of Architecture

Abstract

Architectural design studios that are tasked with the responsibility of addressing and demonstrating NAAB criteria for Integrated Architectural Solutions (IAS, formerly Comprehensive Design) can, by their very nature, become venues for promoting strict pragmatism. By its very definition pragmatism is primarily concerned with *relating to matters of fact or practical affairs often to the exclusion of intellectual or artistic endeavors* - thus setting up a preferential condition by which project proposals may be evaluated. Pursuits to such an end, although perhaps expressing a certain level of competency and technocratic ability, more often than not fall short of higher architectural aims. The challenge being that good/great design is difficult to define through a set of predetermined instructions, formalized processes, or applied systems. For example, utilizing a highly-sophisticated filtration and distribution system for capturing rainwater to be used in gray-water systems throughout a project does not automatically define the project as exceptional. On the contrary, the pursuit of the exceptional is one that is extremely difficult to define because it is often unspoken. For the Indian architect Balkrishna Doshi the architectural endeavor is:

> *a search for the unknown which (is) not known, neither do I know how it will manifest. It begins somewhere, it ends somewhere, and in that process, I grow and the work grows. And we both grow together.*[1]

Because of its elusiveness, the true value of a proposal is often only revealed at a much later time and in unexpected ways.

Thesis

This paper aims to address the topic of achieving the condition of *Both/And* (technocrat/visionary) within a design studio attempting to meet the expectation of NAAB's Integrated Architectural Solutions. As a point of special focus, the paradox of achieving an Integrated Design (i.e. achieving *Both/And*) through a prescribed systematic reconciliation of contingent parameters will be interrogated. Our findings suggest that the realization of a truly integrated design is actually not through the accounting of every parameter of full integration but rather the ability for students to maintain the *And* component of any great work of design through a method of acknowledgement and accounting. In essence the architecture emerges/endures in spite of a perceived limiting host of contingencies. We argue an Integrated Design is fully manifest only when all contingencies are addressed and none require direct accounting for when the design is presented and critiqued. This position, while perhaps clear to practiced architects and educators may prove difficult to convey to the novice student. Peter Zumthor touched on this issue when he suggests:

> *First of all, we* [in speaking with students] *must explain that the person standing in front of them is not someone who asks questions whose answers he already knows. Practicing architecture is asking oneself questions, finding one's own answers with the help of the teacher, whittling down, find solutions. Over and over again. The strength of a good design lies in ourselves and in our ability to perceive the world with both emotion and reason.*[2]

As such, the challenge of this work is to outline how one may mentor/coach/instruct/guide in order to ensure that the result of an integrative process/project is not a reckoning but rather an autodidactic undertaking that results in the acknowledgement of parts contingent to the whole and valuable to only that self-defined situational context. (Fig. 1)

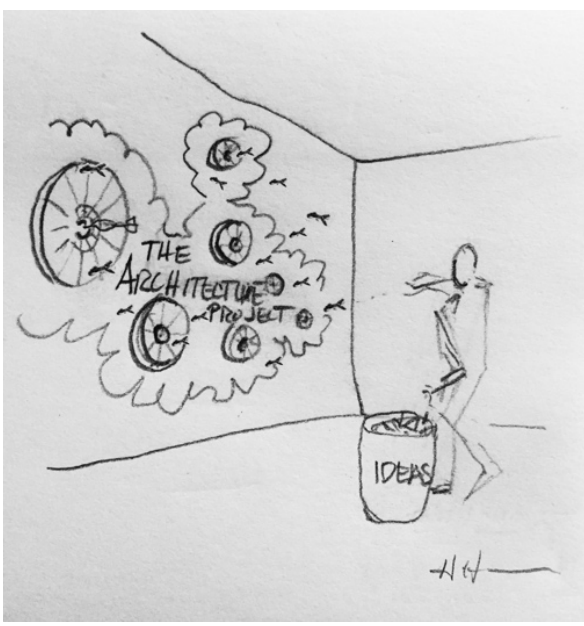

Figure 1: Types: Program(s), Setting(s), Material(s)

Integration is fundamentally an act of incorporation to the extent that individual elements no longer may be isolated as discrete, self-deterministic components within the larger whole. As the architect designs she or he must account for, and integrate environmental systems and materials as their work, not as a part of their work. The buildings we strive to have students develop are made of these practical elements and not in spite of them. They are the ingredients used to witness and appreciate light, shadow, air, weight, tension, or escape. (Figs. 2,3,4) It is our contention that the atmosphere, experience, and memory of a work of architecture is manifest through neither technocrat or visionary means alone, it is the meaningful blend that forms a lasting work.

Figure 2: *Models in plaster that talk back*, by Ria Bennet

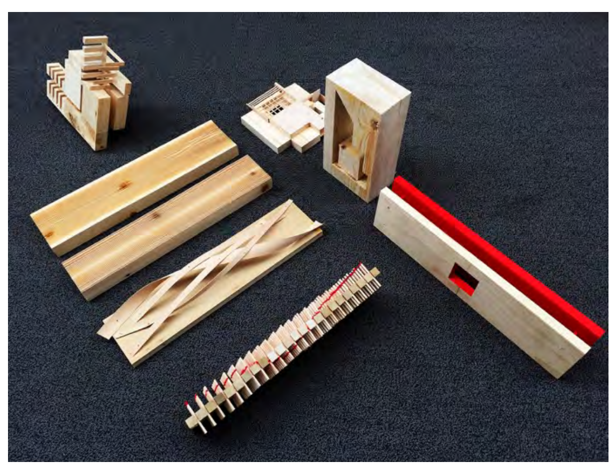

Figure 3: *Models of wood that talk back,* by various 4^{th} year IAS studio students

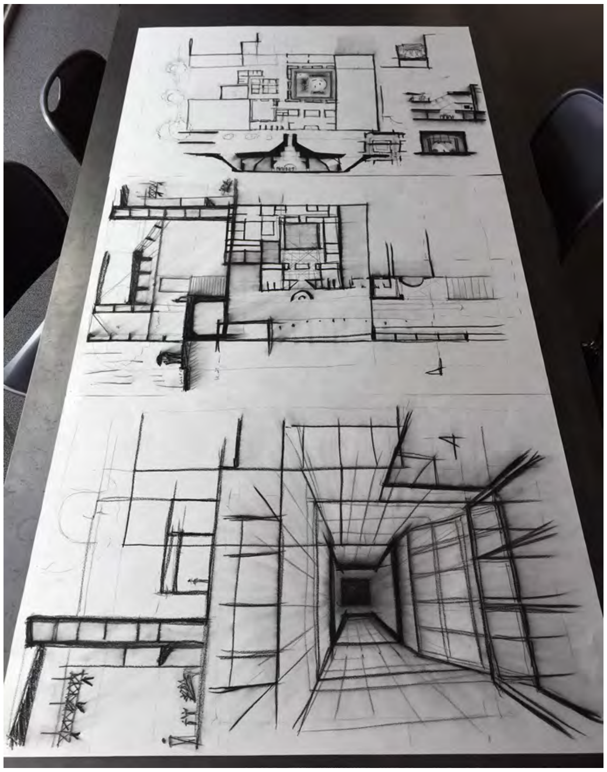

Figure 4: *Drawings that talk back,* by Robert Warlick

In our teaching, the *types* of topics and parameters we require students to consider are used to develop an appreciation of the value of integrated design thinking and not necessarily design specification. To initiate the novice student to integrated thinking one must consider carefully the potential result a program and project type may yield. Framing the context of the project, and critically defining the boundaries and limits, is essential to the student's probability of finishing the work with a level of completion and sophistication that is formative, productive, and above all, self-satisfying. We believe for the NAAB IAS to be a meaningful metric; the student must internalize the process to the extent that they value the result enough to willingly and independently repeat the process. To reference Peter Zumthor once more in his consideration of *Teaching Architecture, Learning Architecture,* we also insist that students design with materials at the forefront. As Zumthor suggests:

> *All design work starts from the premise of this physical, objective, sensuousness of architecture, of its materials. To experience architecture in a concrete way means to touch, see, hear, and smell it. To discover and consciously work with these qualities-.*[3]

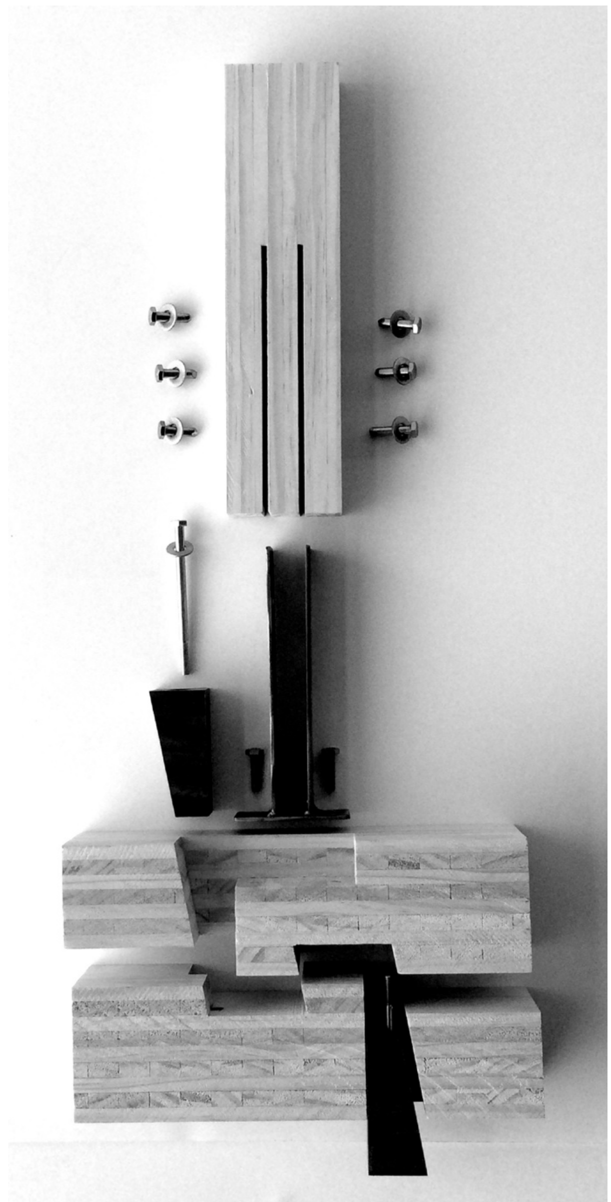

Figure 5: CLT column and floor assembly detail model, by Kirby Lockard

As a means of forcing the beginning, seemingly a necessity in the education of many students, a material type is determined by the faculty at the offset. In some instances, concrete, sometimes brick, steel or as we are currently requiring, cross-laminated timber (CLT) serves as a jumping off point for students to begin learning the potential of a material. With that, a dialogue may be opened about the value, intent, appropriateness of that materials in the project. As the work progresses exception may be made but only if documentation is put forth as to why a material is insufficient. In this way students (and the School) acknowledge and account for one topic area within the cloud of topics that form the IAS learning outcome. (Fig. 5)

Loose Lines & Hard Lines

With the understanding that students come to decisions based on pragmatic and visionary logics, often with a bias toward one or the other, pedagogical preparations are made to ensure that neither position be allowed to form the sole focus of the student's work. Over the past several years, students in our studio have been asked to respond to various questions about the building from both a practical and visionary point of view. Additionally, each project was required to be develop through a system of what we termed *catalyst inquiries*. Moving week to week, a critical issue would form the weeks' focus, i.e. Building Foundation, Site Response, Envelope, Active Systems, etc. Students were prompted to explore the theoretical implications of the issue and how that issue might be made manifest in physical terms. For instance, how might the building be a landscape? In this question, we explore what that might mean, why one may desire such an aesthetic, performative potential, spatial experience and so forth. The inquiries were fueled by required acts of analogue-based making - models, drawings, sketches, paintings, drafted works, sculpture, casts, etc. All of which had their place while contributing to the ultimate goal of the work and the students continued exposure to various procedural means. By requiring an artifact of the students thinking/consideration of the issue, the issue became known. As is clear, knowing something may be done through many means but knowing a thing by making the thing, or trying to make the thing, allows for a feedback loop to form. (Fig. 6)

Figure 6: *Models of wood that talk back,* by Robert Warlick

This method of knowledge generation is not unlike that of numerous architects including Allied Works Architecture. In a 2016 interview for Co.Design regarding the exhibition titled "Case Work", which explored the design methodology of Allied Works Architecture, firm principal Brad Cloepfil explained the value of this form of design production/thinking as such:

> *What I like and what I believe about those sketches and models is that they're distillations of ideas,"*

> *“They could become art installations, or they could become buildings. They’re sort of hybrid pieces in the world of visual ideas before they become buildings—tools to understand the possibility of architecture, but things in and of themselves.*[4]

In our studio, the process was repeated again and again as a way of testing what each of the topics the faculty selected as *central to achieving an integrated project*, meant to the student’s way of understanding their complete project, or what Ove N. Arup might have referred to as the *Total Architecture*. Arup, a legend in the field of concrete design and structural engineering, defines a *Total Architecture* as - the comprehensive integration of all processes associated with the completion of a building project. While Arup was focused on engineering, his ideas about design thinking resonate across multiple fields, particularly as we see an increased degree of collaborative design and Integrated Project Delivery in professional practice. Arup shared his beliefs about the importance of inclusive design widely, most clearly articulating his concept in 1970 in what is now referred to as his *Key Speech*.

> *In our work as, structural engineers we... have to satisfy the criteria for a sound, lasting and economical structure. We add to that the claim that it should be pleasing aesthetically, for without that quality it doesn’t really give satisfaction to us or to others... We are led to seek overall quality, fitness for purpose, as well as satisfying or significant forms and economy of construction... We are then led to the ideal of ‘Total Architecture.’ ...This means expanding our field of activity into adjoining fields - architecture, planning, ground engineering, environmental engineering, computer programming, etc. ...The term ‘Total Architecture’ implies that all relevant design decisions have been considered together and have been integrated into a whole by a well-organized team empowered to fix priorities.”* [5]

Through this lens, the students were guided toward an understanding that while they cannot singularly know all there is to be known, they know enough to understand the potential value of each topic they were directed to consider. While some *catalyst inquires* became central in the students’ project others became faded but were nonetheless present and accounted for in the final project. (Fig. 7)

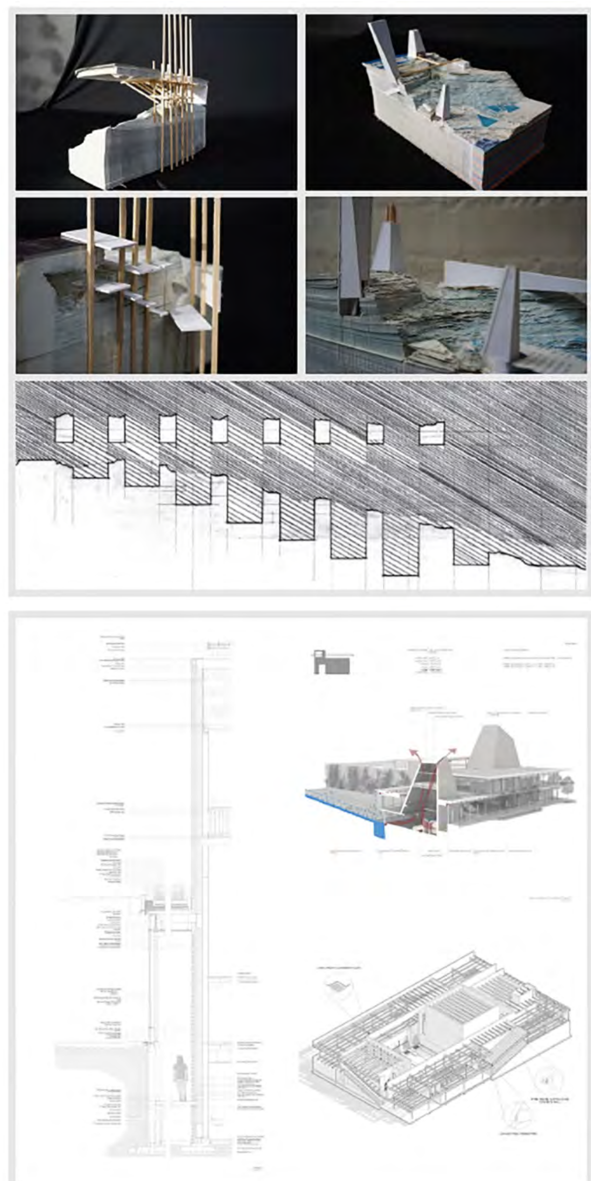

Figure 7: *VISIONARY* – Sample of Creative Process (abstraction, model making, speculation) *TECHNOCRAT* – Sample of Technical Documentation (envelope, materials, systems, structure) in a 4th year Integrated Design

Solutions Studio. By West Pierce and Ashton Aime

This emergent hierarchy rendered an understanding about the various topics that made it possible to discuss those topics as Both/And. While some leaned more to one side or the other they all presented as having both visionary and pragmatic potentials. The deliberate casting of either or both potentials became the point of critique as opposed to a literal accounting of the topic's inclusion regardless of the depth of consideration and integration.

Finding Focus

The goal of this pedagogical exercise was not to drive focus but rather to find focus within the field of latent topics any work of design will inevitable intersect. By placing topics before the students and asking them to consider each from two points of view the question of who's priorities are we addressing becomes a little less predictable. As educators we have the advantage of experience. We also have the knowledge that experience is not something easily conveyed. The importance of trying for the sake of deciding is the purpose of this work. With the trying underway students inherently gravitated toward various topics as places of comfort and delight. By creating a field of opportunity, we hoped to see students congregate and embrace certain topics moving them from hurdles to be bounded to productive self-imposed obstructions that serve as guides to be sought after in the definition of their *Total Architecture* project. The variety of potential points of view became a powerful force in motivating the students. As is typical, the desire to be different drives many of the exceptional students. The pedagogy of the studio appreciates and celebrates the differences of student approaches and priorities when selecting from a field of options that all fall within the realm of "necessary issues" in a comprehensive project. Rather than far flung theoretical constructs or issues of material, planning, social engineering that often collect the wandering students' eye, the topics remained central to the task of developing a holistic architectural project.

Elephant for Breakfast, Lunch and Dinner: Notes on delivering the project

We all know the reply to the question; *How do you eat and Elephant*? Or so we think we do, the value and necessity of pacing the novice student should not be underestimated in the pursuit of an integrated architectural solutions focused studio. Through experience we have come to understand how critical our task is as educators to guide, and when necessary require, students to address multiple issues in an effort to drive forward the total project. We posit the claim that a significant risk exists in the under-directed first attempt at an integrated project. The risk is one of a *drifting course* being adopted by the student wherein the work requires a level of self-direction that they are unprepared/unable to manage. In such a scenario, the student becomes lost and often gravitates toward "busy work" which is easily defined and discrete in nature. This scenario presents the risk of student work resulting in the antithesis of what we strive to achieve, a project in which topics of comprehensive design are plugged into, attached, overlaid and shoehorned into a schematic building form. We cannot claim this risk to be universally apparent however we do note a consistent emergence of this outcome when the pedagogy allows for too much uncoached time.

The key difference in our approach over the years has been to move away from assignments that result in a particular aesthetic language, material exploration, spatial development, etc. Instead we now work to facilitate a variety of considerations be made in an effort to be inclusive and thoughtful. The requirement to bring catalyst inquiries to a legible degree of completion seems to drive the students' appreciation of depth in design development. Without the paced delivery we find students are likely to wait and eventually fall back to a position of shallow and superficial topical application. Waiting to start and restarting does little to develop depth thus we prefer complete missteps over incomplete ideas. ‘Talk is cheap’ and ‘the work is the work’ hold true in this approach. Both visionary and pragmatic topics of a project require rigorous development. Until an artifact is realized, it does not exist.

Presenting the Architecture, NOT the building:
Critical Reflection Aided by Documentation

> *When architects talk about their buildings, what they say is often at odds with the statements of the buildings themselves. This is probably connected with the fact that they tend to talk a good deal about the rational, thought-out aspects of their work and less about the secret passion that inspires it. The design process* is *based on a constant interplay of feeling and reason.*[6]
>
> Peter Zumthor

The intent behind presentation and documentation is of no small importance and so we seek to outline our approach to this facet of the IAS focused studio very carefully. Over many years, the issue of formatted verses unformatted presentation artifacts has churned over and over but never been resolved. In our approach we ask that students deliver their work within a square panel format of 10”x10” up to 40”x40” increasing in 10” intervals as necessary per the student’s discretion. (Fig. 8)

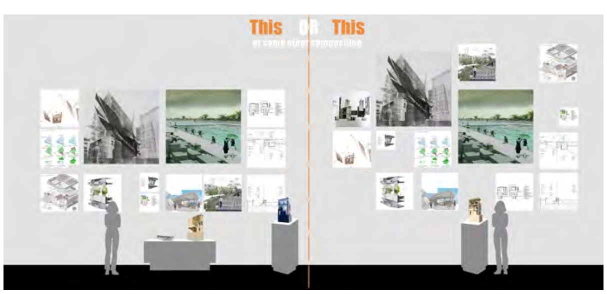

Figure 8: Panel layout strategies

The intent is for each student to assign a logic to each artifact that relates to that artifact’s overall importance to the project and that student’s idiosyncratic design thinking. Small panels typically link to discrete issues of a practical sort which are easily understood and resolved in the greater project. However, this is not always the case and students are asked to make decisions for themselves about what size panel the various topic of inquiry might deserve. In so doing a visual hierarchy of importance emerges from the student’s production. This approach helps also for students to see where they may be neglecting topics or focusing too much in one facet of the total project. The format is not about a limit it is about definition and delivery. It forces the question and reply about how much time was spent and how critical certain topics are in the over architectural inquiry. In a way, this exercise is an autodidactic exhibition of the students process and logic. The critique formed by this presentation parameter informs both the maker and reader providing feedback and definition.

Conclusion:

As Integrated Design Solutions becomes a better understood student learning criterion, it may also become less infamously known for its potential to limit a student and more famously known as a means of motivating one. We have been seeking a way of replicating the experience of full-scope project delivery within a context and timeframe that will likely never allow this to happen. As a result, however, through the collective sharing of knowledge among students, faculty, institutions, we are gaining an awareness and capacity to better foster student learning and architectural creation that is not limited to a Technocratic or Visionary attitude. The *And* in our *Both/And* approach may only be achieved through the successful acknowledgement, attempt, merging, and management of both Technocratic and Visionary design thinking methodologies in service of a larger conception of the *Total Architectural Project*. We believe beginning with only one or the other often leads to finishing with only one or the other, so why not begin with the *And* rather than the *Both*.

Notes:

1 Ramachandran, Premhit. *Doshi*. 2010; Hinterland Films, 2010. Vimeo.

2 Zumthor, Peter. "Teaching Architecture, Learning Architecture" " in *Thinking Architecture, Second Expanded Edition* Birkhäuser; Basel, Boston, Berlin. 2006. p 65-66.

3 Ibid., p 66.

4 Cloepfil, Brad. "How Allied Works is rebelling in the age of Vapid Architecture" Interview by Budds, Diana www.fastcompany.com/Co-Design 02.01.2006

5 Arup, Ove Nyquist. *Philosophy of Design* – Essays (1942-1981) Prestel; Munich, London, New York. 2012. P 161.

6 Zumthor, Peter. "Away of Looking at Things" " in *Thinking Architecture, Second Expanded Edition* Birkhäuser: Basel, Boston, Berlin. 2006. p 21.

The geographical dimensions of patent innovation: history, precedents, praxis, and pedagogy, in an expanded field of landscape technology.

Richard L. Hindle
Landscape Architecture and Environmental Planning, UC Berkeley

Abstract

Innovation has geographical dimensions, ranging from site and building technology, to infrastructure and environmental systems. As the allied professions of environmental design expand disciplinary scope beyond aesthetics into questions of territory, landscape infrastructure, performance-based design, and issues related to climate adaptation and the Anthropocene, an expanded concept of technology and innovation becomes essential to address new pedagogical adjectives and praxis. One of the most effective ways to track technological change in a specific sector of technology is through patent innovation. The global patent archive is the world's largest technological dossier. An estimated 90 million patents have been granted globally, and the United States Patent and Trademark Office (USPTO) alone has issued more than 10 million patents since 1790. A unique subset of these inventions relate to site and building technology as well as large-scale environmental systems such as rivers, coasts, and cities. Since patent innovation is an ongoing process, patent documents provide insights into the ever-evolving sectors of technology, which may be understood as an expanded field of landscape technologies that define site, cities, and regions. This paper explores the histories of patent innovation related to the physical built environment and argues for an expanded definition of "Landscape Technology". The paper also includes examples of New pedagogical approaches that integrate patent innovation studies into environmental design curriculum, and a discussion of strategies for implementing novel technologies and patent innovation studies into professional design projects.

Introduction - Geographical Dimensions of Patent Innovation

The geographical dimensions of patent innovation span six-centuries, and counting, with scales that range from discrete site technologies and building systems to urban and territorial infrastructure. An estimated 90 million patents have been granted globally, and the United States Patent and Trademark Office (USPTO) alone has issued more than 10 million patents since 1790. Individually each patent document describes the unique function and configuration of a specific technology, yet in aggregate the geographical dimensions of patent innovation portray a complex narrative of human ingenuity and invention environmental design dating back to early Venice. In 15th century Venice, patent rights were conceived as a legal tool to incentivize innovation manufacturing and industry, but also as a sociotechnical mechanism to advance the physical infrastructure essential to urbanize the lagoon and facilitate territorial development.

The coevolution of city-building and inventors rights suggest that a distinct urban innovation model was created, and later emulated, as patent rights spread from Venice to Europe and the United States to solve environmental "problems" through technological innovation.[i] Today numerous case studies exist, explicating the geographical dimensions of patent innovation, ranging from the development of Mississippi River's levee and jetty systems, to the advent of complex coastal armoring systems (Fig.1). The parallel evolution of technology and the built environment not only substantiates the unique role of innovation in physical environment but also suggest a unique form of design agency relevant to design practice and pedagogy today as the allied professions of environmental design focus disciplinary agendas on issues related to performance, infrastructure, adaptation to climate change, and issues related to the Anthropocene – all of which suggest a shift towards an expanded field of technology.

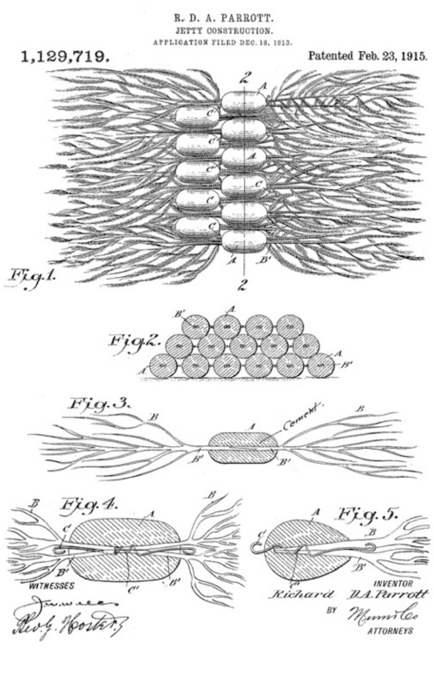

Fig. 1 A 'biomimetic' jetty patent from 1915 US129719. The patent describes the creation of pill shaped concrete blocks that anchor massive woven structures that mimic seaweeds or tree roots, with the intention of accreting sediments to stabilize the jetty and catalyze growth

Distinction between form and aesthetics has a clear legacy related to patents. The United States Patent and Trademark Office (USPTO) distinguishes between two major classifications of patents: design and utility. A design patent is issued for "a new, original, and ornamental design embodied in or applied to an article of manufacture, whereas a utility patent is issued by the USPTO for "the invention of a new and useful process, machine, manufacture, or composition of matter, or a new and useful improvement thereof." Simply put, design patents protect the form and appearance of everyday objects, while utility patents define innovative processes, materials, modules, systems, and infrastructures. A disciplinary shift towards instrumentality may make this distinction especially relevant to contemporary discourse.

Recent research in the field of architecture and technology has clearly identified the manifold ways in which intellectual property interacts with building systems, ranging from architectural components and systems, to copyright.[ii] Yet, when viewed through the lens of landscape and environment, a distinct subset of patents gain geographical dimension and situate technology with environmental contingencies. As we expand the disciplinary boundaries of environmental 'design' beyond aesthetics and appearance, and into broader discussions of instrumentality and agency in the Anthropocene, our conceptions of technology must coevolve. This makes patent innovation particularly relevant to contemporary discourse in the wider field of environmental design, including Landscape Architecture, where geographical scales and the dynamics of large-scale environmental systems are a primary consideration.

Venice and Patent Law – A geographical perspective

The first modern, or "true", patent is often attributed in the history of law to Filippo Brunelleschi, the eminent Florentine architect, in 1421 for a floating vessel to transport materials for his Duomo di Firenze.[iii] Although prescient, Brunelleschi's patent was an anomaly in Florence, where patent law failed to develop until later in Italian history. Brunelleschi's patent is significant as is contains all the components of the modern "patent bargain" between inventors and the state, and clearly indicates the intimate mirroring that often occurs between invention and the built environment. It is striking to consider that the patent was so intricately intertwined with the realization of the Duomo of Florence, that the structure might not exist without the protections granted to Brunelleschi for his invention.

Brunelleschi's nascent foray into intellectual property was an anomaly, as Venice is widely considered the birth city of patent law.[iv] Precedents for inventor's rights and early patent law are documented in Venice since the early 14th and 15th century, primarily in the form of privileges and monopolies granted to inventors and manufacturers, but also for the development of public works such as the digging of canals and dredging exiting waterways. These rights and privileges later served as important precedents for patent law in the city. In this manner, innovation and urbanization became intimately intertwined in Venice prior to the formal codification of patent law in 1474, and continued as the city developed over the next few centuries.

Environmental and Urban innovation was essential to the survival of Venice. The city was founded in the estuarine landscape of the Leguna Venata on March 25th, 421 AD. Venice's watery refuge was defensible from invasion, but presented a challenge to conventional land-based forms of urbanism. Prospects of building a thriving metropolis in a dynamic lagoon environment required technological and social innovation to remain competitive in global trade and manufacturing, but also to reconcile the inherent conflict between city building and the environmental contingencies of sedimentation, fluctuating water levels, and miry soils. It was in this environmental and urban context that patent law was conceived. Inventor's rights, or privileges, granted in association with public works may seem antithetical today, yet many have forgotten the public and inherently sociotechnical and urban aspects of patents as they were first conceived. Contrary to contemporary notions of patents relating to items of manufacturing and trade, the early patents often had no immediate commodity associated with them and were conceived in terms of their public and geographical scope. Mario Biagioli, a leading scholar in law, science, and technology summarizes the issue as follows:

"It is striking how specific and local the early notion of utility was when compared to the increasingly generic definition we find in today's patent law. In the age of global economies utility seems to have no identifiable beneficiary beyond a generic 'public' situated in an equally unspecified future. By contrast, some of the earliest patents - like those related to the making and dredging of canals in Venice or the drying of swamps in the Netherlands - concerned public works, not privately-owned technological products to be sold on a generic market. Though not many patents were so site-specific, a distinctly local and immediate notion of utility informed all early privileges, especially those issued before 1700" [v]

Records of these early patents are striking for their distance from contemporary notions of a patent, but also for their emphasis on public and urban works. For Example, the Maggior Consiglio (The Major Council) issued an "award" to the inventors Leonardo Albizio and Franceso "dalle barche" in 1334 and 1346 respectively for their invention of time saving dredge vehicles, and allowed them to operate the machines in the city. And, similarly in 1371 Hendrigeto Maringon was hired for the clearing of canals using an excavator of his own invention, essentially granting him a monopoly for the machine he created and the geographical scope of work.[vi] Agreements, such as these, between inventors and city mangers served as important precedents for patent law in Venice, but also established a trajectory of experimentation and testing in urban infrastructure. The lagoon city literally and metaphorically created a fertile ground for innovation. The Venetian Patent Statute of 1474 was conceived as a public/private partnership designed to promote individual innovation and the advance the state. Sociotechnical, public, and urban aspects of the law cannot be understated. The act reads:

"WE HAVE among us men of great genius, apt to invent and discover ingenious devices; and in view of the grandeur and virtue of our City, more such men come to us every day from diverse parts. Now, if provision were made for the works and devices discovered by such persons, so that others who may see them could not build them and take the inventor's honor away, more men would then apply their genius, would discover, and would build devices of great utility and benefit to our commonwealth."

Evolution of patent rights in Venice is intimately tied to geography. Venetians realized that building a thriving metropolis in a lagoon required legal, social, and technical ingenuity in both industry and infrastructure. It is therefore unsurprising that many archetypal patents have distinct geographical dimensions that site and situate innovation in Venice, both to attract inventors to Venice and deter foreign competition. For example, the rights issued to Ser Franciscus Petri on February 20th, 1416 for the manufacture of wool involved the use of a previously known type of Byzantine fulling device for the cleansing of wool. This agreement precluded use of the method by others within a 10-mile radius of Rialto (Venice) for a period of fifty years.[vii] Ser Franciscus Petri's patent was essentially a form of monopoly that prohibited production of similar products within a geographical radius of the city, but did not necessitate that an invention be new - only requiring that it be new to Venice and be operated within its territory. This not only applied to industry, but also to city building.

From the Canals of Venice to the Department of Interior

Patent law spread through Europe, to England, France, Germany, and the Netherlands after the Venetian Patent Statute on 1474. The historian Bruce Bugbee has even claimed "the international patent experience of nearly 500 years has merely brought amendments or improvements upon the solid core established in Renaissance Venice."[viii] The spread of patent law had urban, regional and territorial impacts that extended beyond the realm of manufacturing and industry, into what Henry Lefebvre terms the "urban society" – a political and technological system of total urbanization.[ix] In this milieu, where science, expertise, and the circulation of knowledge impacted cities, territories, and nations, the patent has played an important but surprisingly surreptitious role. A rereading of English and American patent history is particular telling. Originally English patents, like Venetian, were essentially a mix of monopolies for particular trades and enterprises and rights granted to protect new inventions. Patent monopolies became tools for the English monarchy and guilds to maintain power over goods and labor.

Queen Elizabeth herself granted nearly 80 patent monopolies for a range of goods and expertise, including the creation of white soap, saltpeper, knife handles, musical instruments, dredging machines, and important skills such as glass making, water drainage, and the mining of minerals. This lead to a influx of skilled workers and inventors, including those involved in the drainage, dredge, and reclamation technologies from Venice and the Netherlands. Interestingly, one fifth (1/5th) of all patents granted between 1620-1640 were for methods to raise water and drain land for reclamation, revealing the scope and scale of innovation in this sector of technology.[x] The fens and lowlands of England would never be the same as drainage infrastructure was constructed through a complex process of technology transfer from Italy and Holland using patents.

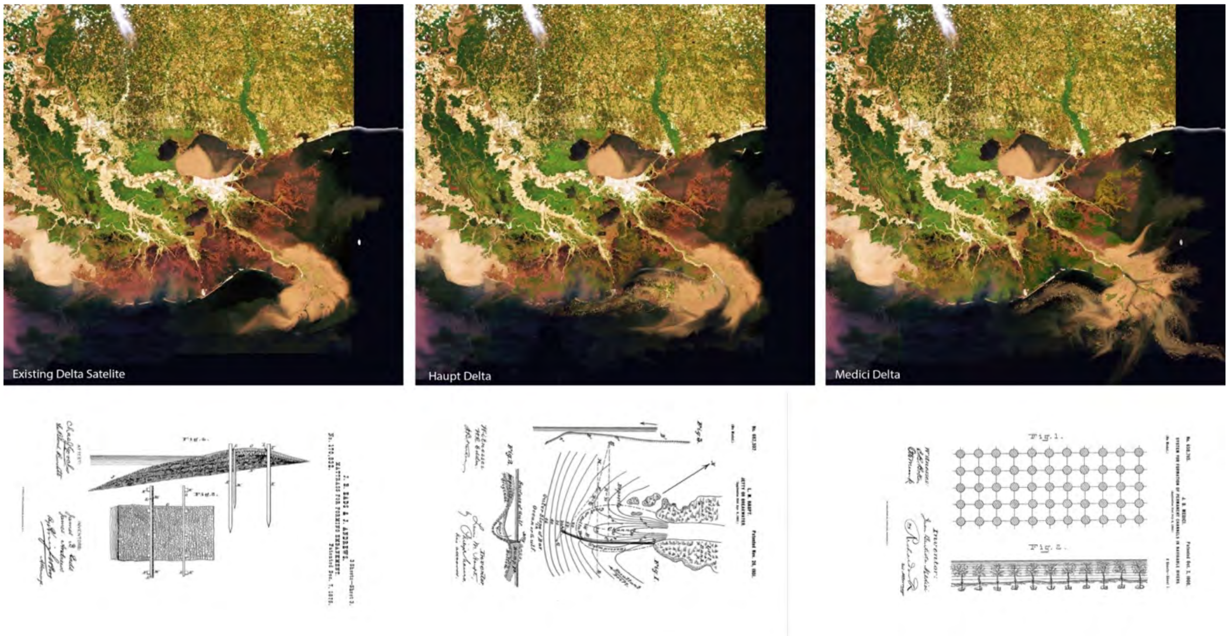

Fig. 2 Patent innovation impacts large-scale environmental systems, including rivers, coasts, and cities. The images above show a series of site-specific inventions patented for the creation of navigable channels at the Mississippi River, Heads of Passes. On the right is the existing satellite image, and the patent by James Buchannan Eads that stabilized the southwest pass of the river.

In America, patents are intimately intertwined with the nation's founding. Prior to the American Revolution colonial patents mirrored European, and specifically English, patent law.[xi] Establishment of a patent system was one of the first orders of business in the newly formed government, and the Patent Act of 1790 charted a distinctly American patent system founded exclusively on rights for new inventions and requiring that patents disclose enough information so that those skilled in any particular art might to make and use the technology.[xii]

The constitutional origins of American democratic ideals and their conflation with patent law provided a nascent US with a hybrid vigor through which statecraft became inexorably linked to progress and innovation. In this manner, western progress and technological frontiers advanced concurrently. The impact of which can be observed in the exponential growth of the American economy, and the geography of North American writ-large, from the barbwire fences of the middle-west to the reclamation of western swamplands.[xiii] Although it is common to associate American patents strictly with objects of commerce, it is important to note that from 1790 to 1849, the USPTO was operated by the Department of State with patents initially granted by the Secretary of State, Attorney General, Secretary of War, and for a brief time the President. The increasing rate of patent submissions and explosion of domestic affairs overwhelmed the State Department and led to the creation of the Department of Interior in 1849. Between 1849–1925 the patent office operated under the auspices of the Department of Interior, spanning an unprecedented period of national growth and development marked by canal building, railroads, electricity, sewers, paved roads, navigable waterways, and the first levee systems.

The Department of Interior was formed through a strategic reorganization of the USPTO, General Land Office, Census Bureau, and Bureau of Indian Affairs and charged with the management of "home" affairs, including wilderness areas and new US territories. The combined interests of the Department of Interior made it the de facto "department of the west," playing a vital role in the expansion and development of western states. Although grand in ambition and scope, the actual footprint of the Department of Interior was remarkably small—initially housed within the patent office building in Washington DC. These two seemingly disparate offices cohabitated for six decades, until the constant flow of tourism to the building and the growing piles of patent models forced the Department of Interior to move out. Richard Andrews, an environmental policy scholar, has argued that in an ideal world, the integration of interior, patent, land, and census departments might have provided the "foundation for integrated planning and management of the nation's environment." [xiv] By 1925, the patent office found its permanent home in the US Department of Commerce, where it remains today.

Dusting off old patents from early American history reveals that the US government was cognizant of the role of patents in the transformation of the built environment. For example, in 1821 Congress waived the residency requirement to grant Englishman Thomas Oxley a patent for his "American Land Clearing Engine," which promised to hasten development. In 1844, while pondering interstate communications, Congress passed acts to construct an experimental telegraph line from Washington to Baltimore following Samuel Morse's patent for invention. And in 1847, James Crutchett was commissioned to prototype and test his experimental gaslight in the nation's Capitol, proving the viability of artificial lighting in the urban landscape.[xv]

The process of patent innovation, expert review, and prototyping technology in the built environment continued in large-scale complex environmental systems. For example in 1845, Congress approved the creation of a panel of experts to test an experimental dredge machine, patented by J.R. Putnam, for the removal of sandbars at the mouth of the Mississippi River.[xvi] And, in the 1870's the world-renowned engineer, James Buchanan Eads, himself had a patent to accompany his proposal for the establishment of navigable channels at the Heads of Passes.[xvii] Congress awarded Eads a contract for 4 years to prototype and test his system, and paid him based on success of the work.[xviii]

An Expanded Field of Landscape Technology: research trajectories and experimental pedagogies

The patent is western civilizations oldest legal and institutional mechanism for incentivized innovation, with a six-century history of facilitating the advent of complex infrastructure. It is often associated with commerce and objects of manufacturing, but, also with the transformation of large-scale and complex environmental systems. As we expand professional boundaries into the unknown realms of the Anthropocene, territorial design, socio-ecological innovation, a strategic reevaluation of patent rights may help advance disciplinary agendas beyond discrete site and building envelopes - offering a prelude to an expanded field of landscape technology.

Landscape technology operates at scales that range from site detail to larger territories and urban systems. The expanded field of landscape technology now arguably includes not only discrete design elements but also larger processes, methods, and machinery, that build infrastructure and armatures at environmental scales. This is substantiated through historiographies of site technologies and analysis of the broader urban and regional landscape chronicled in the patent archive.

An evolving dossier of historical case studies has now facilitated the creation of experimental pedagogies that integrate patent innovation into site and territorial design processes. Integration of patent innovation into pedagogy takes many forms, from heuristic models for problem solving and generative design process, to rigorous innovation studies that situate knowledge and prior art in a specific sector of technology. To illustrate these points two pedagogical approaches will be discussed in this section. The first results from the LAEP Innovation Seminar (LDARCH 226) taught at UC Berkeley (2016-2019), focusing on the fabrication of hard habitats for coastal armoring. The second focuses on an experimental workshop for territorial design at the scale of the Sacramento- San Joaquin Delta in California. Both integrates patent innovation, images, and history in distinctly different ways, with different outcomes.

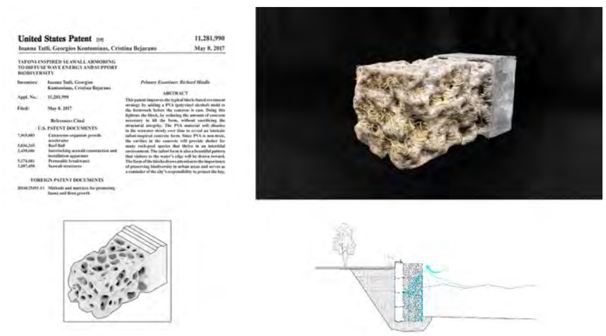

Fig. 3 Outcomes from the LAEP Innovation Seminar include functional prototypes, patent citation searches, mock patent documents, and site design drawings that show how the new "invention" impacts the built environment.

The L.A.E.P. Innovation Seminar (LDARCH 226) at UC Berkeley, explores the habitat potential of hard structures in the urbanized environment, focusing specifically on the design and fabrication of ecological seawalls and vegetated architecture. The course advances in the science, technology, and design of "hard habitats", and speculates about their potential future role in the novel ecology created by cities, buildings, and built environmental systems. The course title Hard Habitats also instigates a design polemic that inverts the notion of 'ecology' as soft and vulnerable, instead suggesting that organisms, and the habitats they seek, may be tough, resilient, and more forceful than a veneer of green or subtle ecological metaphors may suggest. Importantly, the course posits urban ecology as a distinct sector of technology, with the capacity for innovation.

An robust body of scientific research, pilot projects, and patents, support this premise and indicate that specific design criteria may improve the species richness and habitat potential of marine structures.[xix] This type of material and scientific experimentation is particularly well suited to design innovation within the field of landscape architecture given the field's hybridity, and evolving expertise in urbanism, ecology, and material expression.

The course begins with a comprehensive literature review, and then integrates patent innovation mapping techniques with speculate design processes including bricolage and experimental model making. The remaining weeks of the course advance a detailed design project focusing on the prototyping and fabrication new ecological seawall technology (Fig 3). Student projects are situated within a well-defined "innovation landscape" and each project evolves from an understanding of "prior art" existing in patent documents. The course integrates accepted innovation mapping techniques into design curriculum, including keyword searches and citation network searches. Students present their projects alongside existing patents and precedent projects, leading to a robust understanding of this sector of ecological technology.

In the summer of 2016, the author led a workshop, in collaboration with Neeraj Bhatia (CCA) as part of DredgeFest California that centered on sedimentation and earthworks in the California Delta. During the weeklong workshop, participants and workshop leaders were asked by the DredgeFest organizers to develop responses to a series of scenarios that covered the range of possible futures in the delta. Our team of designers were given the challenge of visualizing scenarios for the future earthworks of the delta. Instead of trying to unpack the full complexity of the California's Delta in such a short duration, we focused on the design of discrete technologies (mock patents/inventions) and simulated their territorial effects as bottom-up acts of design speculation. This allowed us to begin iterative design experiments right away using a heuristic model based on patent innovations. And, as the workshop progressed, it enabled us to understand the relationship between a discrete technology and the broader region.

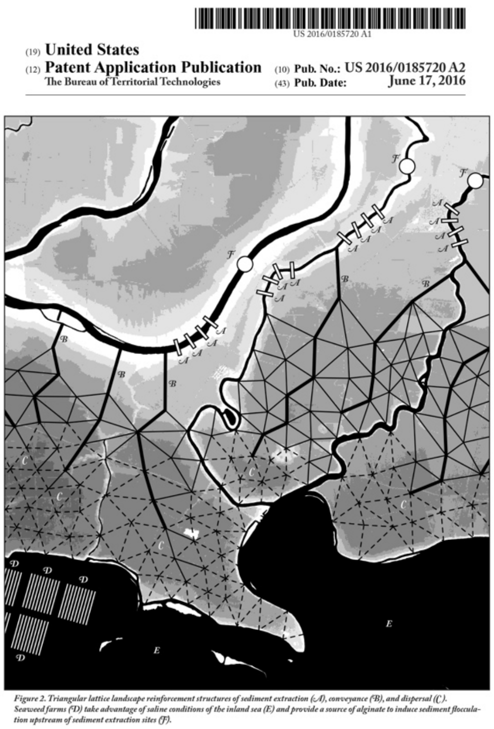

Fig. 4 Outcomes from the Dredgefest workshop (2016) included detailed designs for speculative technologies that impacted the broader regional landscape. Design agency was explored as a cross-scalar framework, operating simultaneously at the scale or the discrete object and the larger territory.

After a short initial exercise exploring existing technologies from the patent archive and extrapolating their territorial impact, four new technologies were "invented". Graphic standards were borrowed from patent documents and included details of how the system operated at the scale of the detail, to the scale of the region. Each addressed issues ranging from subsidence and accretion of sediment, to aquifer recharge and levee reinforcement. For example, the Regional Reinforcement system, created by Michael Biros, addressed the issue of sea level rise and land subsidence in low-lying areas. The object of the invention was to provide a method to convey and disperse sediment through easily deployable sluices that direct water into permeable seepage and dewatering structures (Fig 4).

By developing a specific technology and understanding how it would alter the broader the landscape, it allowed designers to quickly understand the implications of their design proposals, moving back and forth between technological invention, and regional transformation, ultimately facilitated design experimentation at the scale of the territory and at the detailed scale of a specific technology developed by the designer. The difference between these experiments and those of traditional site design and analysis, is the feedback between the micro and macro scale technology. Territorial effects could be explicitly directed and choreographed by acknowledging the cross-scalar relationship between various components. In essence, we posited that singular devices and technologies could effectively reconfigure a large-scale territory. In this sense the patent served as historical source, and projective framework, for future scenarios for the delta.

A Case Study in Landscape Architecture Professional Practice

In 2017 the Resilience By Design Bay Area Challenge was launched in California, with 9 international multidisciplinary teams selected to develop strategies for sea level rise and climate change adaptation. The Common Ground Team, lead by the Landscape Architecture firm Tom Leader Studio selected the San Pablo Baylands, and its adjacent infrastructure and urban fabric, as a site. The team included Tom Leader Studio, SF Exploratorium, Guy Nordenson & Assoc, Michael Maltzan Arch, HR&A Advisors, Sitelab Urban Studio, Lotus Water, Rana Creek, Dr. John Oliver, Richard Hindle, UC Berkeley, Fehr & Peers

Transportation Consultants. The diverse team approach the collaborative design process through charrettes, research, community meetings, stakeholder engagement, and envisioning processes, to develop a comprehensive strategic plan to be enacted over years and decades as climate change impacts the region.

Fig. 5 The project considers a new future for this highway as an elevated scenic byway, creating an iconic “front door” to a vast ecological open space previously known to few, The Grand Bayway will become a Central Park *with more 21st century sensibilities for rapidly expanding North Bay communities*

The site of San Pablo Baylands is among the largest wetland estuaries in California, located between Vallejo and Peteluma. The tidal bay marsh formed over centuries through the fluctuating waters and sediments of San Pablo bay and the freshwater inputs of Napa river and smaller creeks in the watershed. Today the bay edge marsh front is traversed by highway 37, a busy, yet extremely flood prone roadway linking the northern bay area to San Francisco. The design team developed a robust infrastructural plan for the area and roadway, including a new multifunctional elevated causeway.[xx]

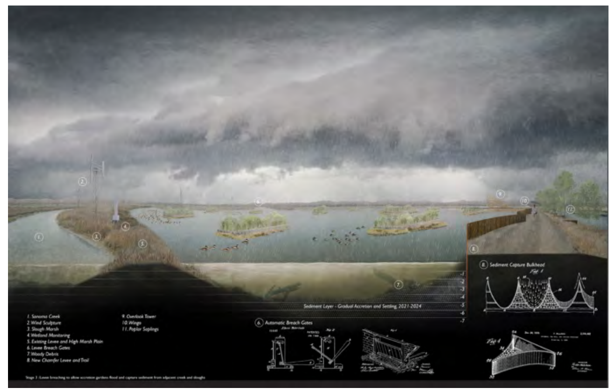

Fig. 6 Image of a flooded hyper-accretion garden structured using specialized technologies selected from patent sources.

A major component of the project was a restoration of the highly degraded, channelized, and subsided wetland now operating as agriculture bound by levees. Some areas of which have become open water though levee breeches, and others remain actively cultivated. Instead of providing a detailed plan for the 50,000-acre site, the contingencies and phasing of the site strategies were linked to specific site timelines and relevant technologies for accretion of sediment, benthic ecology, water regulation, and incremental adaptations to sea level rise. Each landscape condition was the linked to an innovation network of patented technologies that might be used to structure the site. In certain instances, specific site assemblies were suggested, and integrated into the design, showing how each technology would impact the site and future scenarios for the region. The team adapted existing technologies to the design framework, and then made informed suggestions for future needs based on these innovation studies. This led to novel site designs at detail and regional scales, while linking geographical contingencies to technology.

Conclusion

The geographical dimensions of patent innovation spans centuries and reveals the coevolution of technology and environment. Interpreting patent innovation through the lens of physical geography and urbanization has fruitful research and pedagogical potentiality, especially in the context of the Anthropocene as designers address complex environmental challenges. Integrating the geographical dimensions of patent innovation into research, provides a robust dossier through which to analyze the environment. For educators and students of landscape architecture the global patent archive chronicles and expanded field of landscape technology, helping to situate the discipline within a framework of innovation. This expanded field has yet unforeseen implications as we look towards the future of design desiccation and praxis. For example, in territorial design studios and seminars, a focus on innovation may help to frame technological questions related to site history and future transformation, by providing a high-fidelity window into physical infrastructure, mechanized processes, and material site assemblies. At the detail scale of site construction, patent studies can help explain a site's material complexity, or even develop narratives about the future of innovation required to reach a particular benchmark, such as ecological performance. This not only helps students and designers understand site processes, but also facilitates discourse and in-depth research through the lens of design and technology. Speculating on the future of professional practice, the geographical dimensions of patent innovation also suggests a new form of design agency rooted in historical precedent.

Notes:

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Technical Provocations: Material Inventions, Structural Assemblies, and Environmental Responses as Precursors and Design Prompts

Lisa Huang and Bradley Walters
University of Florida

Introduction

In most architectural educations, building technologies and design studios are taught as separate sets of courses where neither may fully impact the other until the design student is immersed in an integrative[1] studio. When technologies and design are addressed as separate lines of study, the concern is that students start to think of building technologies – materials and construction methods, structures and environmental systems – as disciplines that are considered <u>after</u> the design proposal is determined. Or students, particularly those who do not have significant experience in professional practice, can get overwhelmed by trying to consider all technology issues and design at the same time. Emphasis needs to be place on building technologies as impactful design determinants that can instigate and inspire innovation in architectural design.

This suggests a tighter overlapping relationship between technology disciplines and design curriculum. The technical application must then play a primary role in the construction of the studio design project and in the design of the learning experience. In our architectural curriculum, the integrative studio occurs in the second semester of a Two-year Master of Architecture program (Advanced Graduate Studio 2). In preparation for this integrative studio semester, we have developed and implemented an Advanced Graduate Studio 1 course that examines each building technology as the project design provocateurs. This strategy takes each of the following technology topics: materials and construction methods, structures, and environmental systems, as the focus of three separate projects in order to investigate the conceptual design potential of each discipline.

In typical studio design projects, students are given a program and a site and they design from the large scale down to the small scale. This means determining building forms first before considering infrastructure and detail. Instead, we approach the semester in the opposite directions. We start with the design of a full-scale fragment of a wall or ceiling that captures light but is driven by studies on materiality and assemblies. In the second project, we zoom out to the 1” = 1’-0” scale where structures are addressed at three scales of the building, the wall assembly, and the detail component. In the final project, students must design two small buildings that are designed for two extreme climatic conditions. In these three projects, we implement a conceptual understanding of building technologies in design studios so that the technology disciplines have greater impact in the design process. We were not concerned with specificities in each building technology discipline that would be addressed in their technology courses. Our objectives were to use principles of building technologies as primary motivators for design projects and consequently, to reveal the interconnectivity between these disciplines in hopes of increasing a student’s understanding of the role of infrastructure in integrative design.

The projects for this Advanced Graduate Studio 1 course were developed and first tested in the Fall 2015 semester by two professors who co-taught the graduate class of 28-36 students. We have taught this course curriculum for four years and in each semester, we have been adjusting and refining the projects in order to improve on results. This paper discusses the projects' processes and the issues and problems we encountered in this studio course. Due to this paper's word count limitations, we will refrain from going in-depth regarding the theoretical framework for each project in the studio course.

P1: Meditation of Light and Meditation on Matter

In architecture, matter is the medium through which design ideas become reality. Materials shape spatial experiences and architectural form. In professional practice, architects rarely get their hands dirty in the construction process. Instead the role of the architect during construction is to observe and note if the work is being built as per the design documents. In most innovative architectural practices, material considerations are integral to conceptual ideas from the start of the design process. To investigate and communicate material concepts, they proactively fabricate their own full-scale material studies during a project development. This effort ensures that contractors understand the design intension and also demonstrates how the assembly can be built.

Young designers entering practice often experience a gap between their design intentions and built reality. In order to minimize this distance, it is critical to engage matter hands-on to know its characteristics (weight, dimensions, limitations) and its relationships to other materials (joints, intersections, adjacencies). In this project, we address this issue head-on by designing at a 1:1 scale to investigate the impact of materials and assembly on design intention and the design process. The hands are challenged to tackle the physical and intellectual resistances of working directly with full-scale building materials. The goal is to develop a "seeing hand" that understands the relationships between architectural constraints and material realities. Instead of starting with the design of a whole building, we start with the detail in order to explore issues of tactility, phenomenological effects, and the poetics of material assemblies.

Working at full-scale with their hands, students develop a haptic knowledge of materials and the possibilities in the fabrication processes. There are physical implications with each material choice, so this project intends to also foster flexibility in design thinking. In a construction assembly, building materials are not equally interchangeable. In professional practice, design proposals are often adjusted and reworked through numerous iterations. An initial design proposal may be conceived as a brick building, but then other factors, including cost and availability, may alter the material choice which consequently impacts the design intention. Integrative design requires the seeing hand and the flexible mind in order to reduce the gap between intention and actuality. Throughout the project, we had the students read Marco Frascari's "The Tell-the-Tale Detail', Vittorio Greggotti's *Inside Architecture*, and Giuseppi Zambonini's "Notes for a Theory of Making in a Time of Necessity."

The Full-Scale Drawing

In the first week of the project, each student created a full-scale drawing that captured a design intention for transmitted or regulated natural light. The drawing, with a minimum of 6 feet in one direction, is scaled and positioned in relation to the human body to understand the experience of the light condition (Figure 1). The two-dimensional elevation drawing is understood as part of an implied larger design project. It is a fragment of a façade/interior wall, a roof/ceiling or a corner condition. The program for the drawing is the transmission of natural light, so the students must invent light qualities and the implication of material qualities like textures, color, and three-dimensionality through shadows. The full-scale drawings need to capture dynamic light and not just a static moment in time.

Figure 1. Full-scale drawings of invented light conditions. (Elizabeth Cronin, Sara Vecchione, Fall 2015)

The drawing not only communicates dynamic light and shadows but also reflects exterior and interior conditions. By seeing thorough the enclosure, it creates an implied depth and design intention in the spatial assembly, Within the drawing, students were asked to address scales of information – underlying grids and repetitive elements or texture. The drawings expressed materials and assemblies (seams, overlaps), design intent (narrative, experience), a range of scales (fasteners, surface texture) and measure (proportion, underlying systems of organization).

We encouraged students to avoid the typical window aperture. The drawing had to consider the orientation of the sun and the shaping or forming of light regarding its quality, color, texture, grain, and scale. The drawing explores the construction of an apertures and a wall fragment that lets in light but also whether the fragment allows, denies, or directs views outward. Students could use any media of their choice, but the drawing could not be a continuous sheet of paper. It had to be constructed of at least two pieces so that the full-scale drawing itself was a physical construction. The connection between pieces had to be intentional and meaningful in the drawing.

The Material Experimentation Laboratory

In the following two weeks, the students zoomed into details of the big drawing and experimented with material studies that resonated with their design. For each detail, they would compile a list of possible materials and the processes of working with those materials to achieve their lighting effects. For instance, in Figure 1, the textures and light in green could be made of oxidized copper, fritted tinted glass, concrete reflecting green light, etc. Qualities of transparency, translucency and opacity are vetted in the full-scale drawing.

Our graduate students functioned as a collaborative for this portion of the project. They could work individually or in teams but all their material experiments would be compiled into a materials library for the whole class. Students with similar interests in casting concrete would work together to cover more ground in experimentation and build a larger body of empirical research. The material studies were full-scale and could not be made of representative materials or found objects. The experiments had to be serial in nature to explore a range of possibilities and to investigate connections between materials through research on joints, attachments and anchors. Serial studies are critical in this experimentation process; one material sample does not provide enough information to determine the design intent. The students were asked to empirically interrogate material results and to constantly ask "what if" to determine their next steps. Daily group discussions encouraged the students to engage in more innovative approaches.

At this stage of the project, we also ask the students to speculate on how various material options would affect their original design intentions. Since they are making and working with materials with their hands, learning to use fabrication tools, and refining their techniques to build with precision, it is easy to forget what were the original design intentions. We constantly refered to characteristics in their full-scale drawings in an effort to maintain their awareness of their conceptual ideas.

The Full-Scale Assembly

In the final two weeks of the project, each student decided on materials and proposed an individual 1:1 scale assembly that resonated with their original design proposal (Figure 2). The assembly must be freestanding and address an interior and exterior face. Representative materials were not allowed. During the previous weeks, the students concentrated on the small-scale details. Now to build a full-scale construction, they were challenged to address armature or structure to support a free-standing assembly. Students were permitted to engage local fabricators and they were encouraged to look beyond the big box hardware stores. The final constructions are placed outside for the rest of the semester, alongside their original full-scale drawings, so that we can discuss effects of weathering and their lessons learned.

The issues we encountered in this project stage was many of the assemblies were more like sculptures than wall assemblies. The two-week time frame was too quick and in desperate attempts to finish, students rushed their constructions and left out critical components. Another limitation was that students had to fund their own constructions so issues of cost had a huge impact. In the Fall 2016 semester, the 2015 NCARB Award provided substantial funding for this project and we were able to help subsidize the cost of the students' constructions. We address the issue of material waste by requiring that students must use mechanical connections in their assemblies. At the end of the semester, we disassemble their 1:1 scale construction and save materials for next year's graduate class to use. This also helps to reduce the cost for the students in the next year.

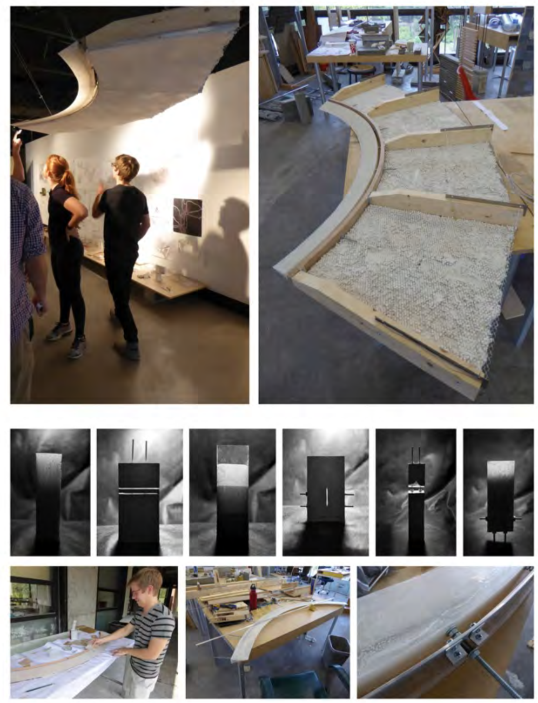

Figure 2. Testing and building the full-scale construction. (Nick Johnson, Fall 2015)

At the end of this project, the most common comment from students was 'it didn't turn out the way I thought it would" which was our motto for this project. This project intentionally embraces failure as a strategy to heighten awareness of the gap between design intention and final construction and the role that materials and construction processes play in the final results. In the lessons learned discussion, the majority of the students were very alert to how they would approach the project if they were to do the project again.

P2: Spatial Intersections

The first project of the semester was rooted in 1:1 material exploration and shaping assemblies in the service of light and space. Whereas Project 1 was framed as a singular moment occupied by a singular authorial occupant, this next project required a consideration of multiple occupants, adjoining and related spaces, and issues of dynamic light, time, and movement. In integrative design thinking, we must acknowledge that structural systems exist at three scales: of the building, of the assembly, and of the component. In Project 1, structure is addressed at the component scale in supporting the materials and the wall fragment. As we focus closer from the building to the detail, we see that every part of the building has structural support that relies on the larger primary structure. In Project 2, students situate their 1:1 scale light and material construction within larger spatial conditions. For the next three weeks, they work at a 1'=1'-0" scale to examine the effects of primary structural systems on their design intentions.

We zoom out to consider Project 1 in the context of a larger fragment of a building space or a spatial interlock between two or more spaces. The students start by determining a primary structure that would shape the building spaces. The larger structural system comes to the forefront. In the full-scale material construction, the students build a structure that is at the scale of the wall or roof assembly. This larger structural system provides overall spatial definition for the building and it must work in conjunction with the material assembly and the control of natural light. The first question the students address Is where primary structure sits in relation – in front of, flush with, hidden within, or up against - their enclosure fragment. At the same time, they also explore the material considerations for the structure and the effects it has on the design intention. They know the quality of light and material conditions for their design but now it was to be design in conjunction with structural implications.

The students design the building fragment through partial plans and sections, axonometric projects, and 1'=1'-0' scale physical section models. The full-scale building materials from Project 1 are now addressed at representative scales so the students are challenged with using representative materials to capture materiality in the physical model (Figure 3). The size of the physical model is critical because of its direct association with the typical scale of building details drawn in professional practice. The physical models needed to be large enough to delve into the assembly and the component scale of structure while also small enough to be manageable for a student to build in three weeks.

Figure 3. Drawings and 1'=1'-0' scale physical models studying structural systems in their design work. (Anggitta Nasutation-Zurman, Fall 2015)

The issues we encountered were fundamental – preliminary struggles with logic and rules-of-thumb for spacing and sizing structural systems. The majority of our students had studied structures as a course isolated from design studio and it was clear that there was a disconnect in how structural applications are integral with design intentions and decisions. The students were accustomed to incorporating structure as an afterthought.

P3: Between Ground and Sky

What we build and how we build are closely tied to the sites and places in which we work. Site informs material selections, formal responses, tectonic assemblies, and structural solutions. A careful understanding of ground is critical in determining how best to touch, engage, mark, or shape it.

When we engage the physical world outside the studio, site and landscape become more than passive tableaus or inert media within which we operate. The natural landscape is, in fact, a complex and nuanced field marked by overlapping and competing systems. Networks of plants, animals, and insects feed, consume, and interact with one another. These living communities are dramatically affected by factors that define the climate of a region, including seasonal variations in light, precipitation, and/or temperature.

When we consider the human condition within these natural systems, there are a number of new issues that arise. Issues of culture, history, belief, social structures, psychology, reason, passion, and memory enter. In one extreme position, all of these issues dominate and overshadow all other concerns, often resulting in fragmented habitat and interrupted ecosystems. At another extreme, the human is identified as fundamentally “non-natural,” excluded from participation in these systems and from occupation of certain places. Between these extremes, there is the opportunity to recognize the human as an active participant in environmental change, positively interacting with changing natural systems.

To work in this way requires simultaneously considering both the human condition and the sites that we occupy, reading both to discover and uncover aspects about them that may not be readily legible. In this last project, we encouraged students to begin to recognize personal attitudes but also learn to meter their impact on their work. The objective of this project was for the student to develop a sensitivity to the places and climates in which they will work in the future. This requires them to distill spatial conditions that transcends their own preferences and become meaningful to others.

In this project, students map and quantify certain aspects of a site, searching for traces of changes that have occurred over time, patterns in vegetation and/or wildlife activity, changes in topography, ground-cover, and soils. This part of the work also engages solar movements, wind, water, and time. Diurnal changes in light, temperature, and humidity intersect with longer-duration seasonal shifts in precipitation and annual fluxuations in temperature.

The first two projects of the semester aggressively engage the issues of light, materiality, joint, assembly, enclosure, structure, and program. The third and final project of the semester brings all of these issues together with the issues of ground, sky, water, and place. However, the work from the first two projects were not necessarily carried into this third project.

Analyzing Site, Climate, and Precedents

For the first two weeks of the project, we focused on climate and precedent studies. In identifying sites, we used maps based on the Köppen-Geiger climate classification system. This system, developed by Wladimir Köppen (1846-1940) and Rudolf Geiger (1894-1981), is the most widely used to classify the climates of places on our planet. It is based on general temperature profiles, latitude, precipitation, and vegetation.

In this project, each student designs two small projects that will each occupy sites in two different extreme climates: hot and cold. To be more precise, they operate within zone A (“humid equatorial climate”) and zones D-E (“humid cold climate” or “cold polar climate”). Within these broad regions, the students divided into teams to research these two climate zones in more detail. At the same time, each student chose one building precedent in each climate zone to analyze.

The climate research focused on specific locations within the selected zones so that the students studied how those places deal with the extreme climatic conditions. The students' research included, but was not limited to, weather patterns, thermal comfort requirements, sun exposure and orientation, and traditional and regional materials and methods of construction.

The precedents research and analysis looked at contemporary approaches to building in these extreme climate zones. The students could compare traditional strategies with more recent strategies to understand changes in technology or methods of operation. The research for climate and precedents was presented and then compiled into a single document as a resource for the studio

Designing in Parallel Two Projects in Extreme Climates

Following the climate and precedent research, the students have five weeks to develop two projects which focused on the construction of a joint, moment, or threshold within a cold polar climate and a humid hot climate (Figure 4). Each project was no more than 1000 square feet of enclosed area. Students had the freedom to choose their sites and they could invent the program for each building. But they had to engage and respond to the particularities of site and the environment, specifically mitigating all forms of water and variable climate conditions.

We focus on environmental technologies in terms of passive strategies and developing a sensitivity to regional conditions and the methods of addressing climatic issues. The two extreme climate zones are design prompts that set up oppositions in almost every aspect of designing a building – the composition of the wall assemblies, the form of the roof, the way the building

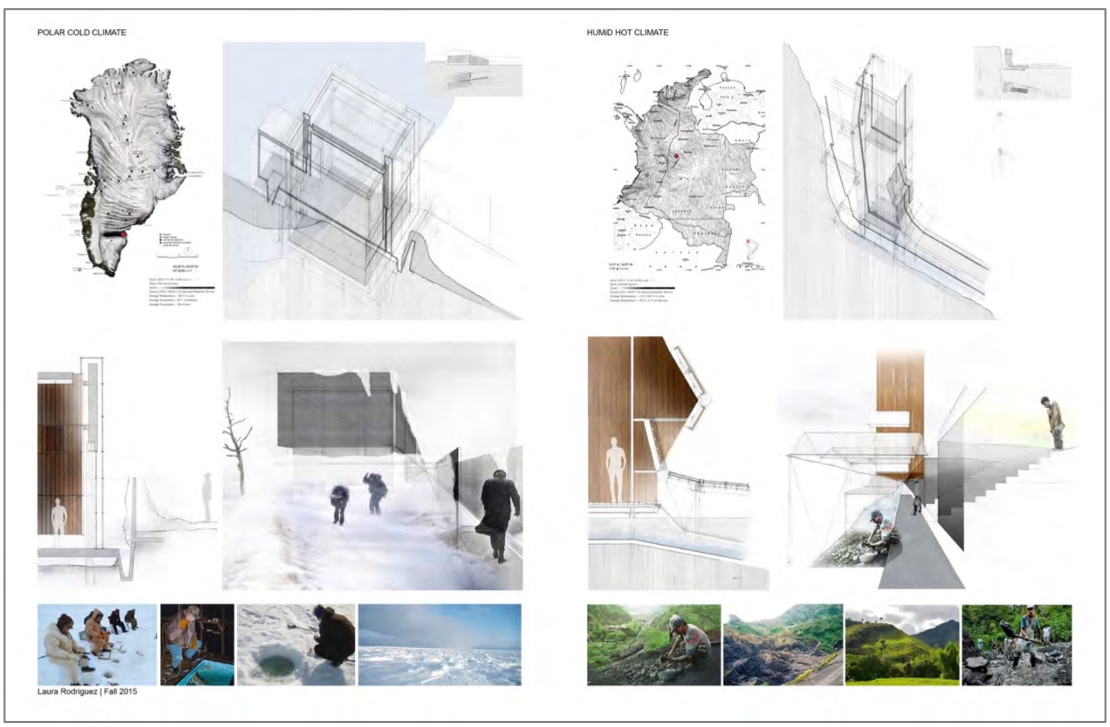

Figure 4. Project studies in the polar Cold and humid Hot climate zones.. (Laura Rodriguez, Fall 2015)

touches the ground. Since these two projects are designed in parallel, it heightens the student's awareness of how differences in climate affects the building design.

The students had the freedom to choose formats and media in developing these projects. This gave them an opportunity to determine their own design processes and to be more specific about their research interests. The character of the place and the distinction between the two projects had to be visually clear in the work. Because the two projects were in contrasting climates, they would have very apparent differences in the designs. Their two projects did not need to be related to one another, but the projects had to be designed in dialogue with each other.

In this project, students zoom out to investigate the buildings as a whole, but also the building as a fragment within a place. Interestingly, the most prominent issue that emerged from this project is that the students, most of which grew up humid hot climates, had a really difficult time comprehending cold weather. Most of them had never seen snow. Despite their research on polar cold climate zones, designing for extreme cold climates was a foreign concept to many. Our original objectives asking the students to step away from only thinking about their own experiences and focus in on how the building must react and respond in its climatic locations.

Conclusion

In all three projects, one of each building technologies takes on a leading role in prompting conceptual design ideas. But inevitably, the other technology disciplines also fold into the projects due to the interwoven nature of infrastructure in buildings. These projects try to explore how building technologies are not just practical issues to address or to integrate after the building design is determined. But instead, they can have conceptual meaning and influence in architectural design. The three studio projects concentrate on the conceptual design realm and not precisely in pure professional practicalities. This is primarily to present to the students that the principals of building technologies can be employed as conceptual design factors and to encourage architecture that is designed with a sensitivity to technology matters.

It is critical to maintain conceptual and abstract design ideas in the integrative design studios. We are concerned with students losing a sense of conceptual thinking in their design work if the technologies are brought into their projects only as practicalities.

Now that we have four years of implementing this curricular strategy, in our next steps, we would like to take a closer look at the effects from this curriculum and to examine whether this curricular strategy is effective as a precursor to the integrative studio and in the students' professional practice experience. We are interested in interviewing the students who have graduated and continued in professional practice for their feedback and thoughts on the course. We are hopeful that our curriculum is meaningful and that we can continue to develop this strategy to greater effect.

Acknowledgements

We received the National Council of Architectural Registration Board's 2015 NCARB Award which funded Project 1 during the 2016 Advanced Graduate Studio course. We had the wonderful opportunity to take students to visit fabricators and manufacturers across the country.

Notes:

1 As defined by Item C.1 in Realm C: Integrated Architectural Solutions in the Student Performance Criteria of the *NAAB Procedures for Accreditation 2015 Edition*.

Folding in Research

Roger Hubeli

Syracuse University

Abstract

The paper describes how the research collaboration between design faculty and the research arm of one of the world's largest concrete and cement manufacturers can serve as a basis for advanced building technology courses and provide internship opportunities for the students to further deepen the knowledge they gained in the class. The larger context of the course is the recent advancement in concrete mix technology and the resulting opportunities to develop novel fabrication and construction techniques.

The paper showcases a professional elective course (seminar) that was structured around an advanced concrete cast technology that allows concrete forms to be poured onto flat formwork that is wet-folded into its final form, reducing the need for complicated formwork to achieve more geometrically complex concrete elements. After the seminar concluded, one of the students had the opportunity to further assist and develop the project during the summer as an intern at the research and development lab of the concrete company that provided the mix for the class.

In an effort to showcase a lineage between course work and student internships, the paper focuses on one of the projects that used the approximation of a shell structure through a folded triangulation (coined 'creased shell'). The geometry was developed and tested in collaboration with the faculty and further developed in collaboration with the industry partner. The results of that project became a key component of the overall research work the course was embedded in. Therefore, the paper will reflect, in the context of such research projects, a collaboration between the material industry and the academy that can offer valuable opportunities for students to gain access to advanced material research through hands-on experience.

This paper showcases how material technology can foster new design strategies where architectural form emerges from a understanding of material properties and processes.

Background

Research Collaboration

The seminar course is part of a larger research collaboration between the professor and his colleague and one of the largest cement and building material manufacturers in the world. This multi-year collaboration has originated from a research lab visit during a study abroad travel course that focused on the intersection of material culture and architecture and has since evolved into a collaboration based on bringing together the architectural design expertise of the professor, his colleague, and the material and technical knowledge of the manufacturer. The broader context of the collaboration is the evaluation of the rapid changes in concrete technologies over the last decade and its possible impact on future architectural applications, in terms of form, tectonics and new construction methods. But it is also an opportunity to combine design research agendas with pedagogical aims; both academically as well as from the role of the manufacturer. The manufacturer is interested in giving future generations of professionals an insight into the mechanisms that form the interaction between the construction and material industry's latest developments and how it impacts design.

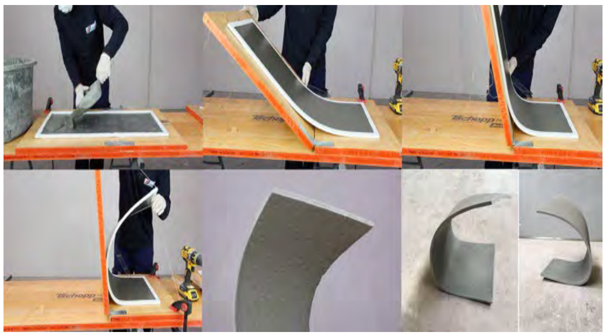

Fig. 1. Demonstration of the basic folding principle.

Advancement in Concrete Mix Technology

The potential impact on design starts with a novel concrete casting technique called 'wet-folding'. Concrete, as a composite material, has a long history of constant improvement of its matter through the reconfiguration of its mix.[1] It is the mix that forms a kind of base matter that has formal and performative qualities embedded within it. And it is the mold that materializes this matter.[2] The 'wet-folding' technique rethinks the mold through folding high strength concrete mixes from flat casts into complex spatial geometries before the mix has cured (*Fig. 1)*. The technique is made possible by a series of innovations that lay in the design of the concrete mix. This includes the use of proprietary high-performance concrete mix designs in combination with precise calibrations between the viscosity of the mix, the acceleration of the curing process and the use of reinforcement fibers.[3] Although the mix design is a crucial component of the success of the casts, the scope of the paper extends beyond the technology behind the mix to speculate on ways to fabricate formwork and what types of forms can emerge from the process. In the context of a professional elective, the mix technology was a starting point to explore novel ideas of formwork; from folding to bending, to popping, to rotating. The student work is, therefore, situated in the realm of design research and was evaluated on the basis of empirical requirements of the mix and what can be achieved with common materials for the formwork as well as aesthetic and formal results.

Advancement in the Relation Between Form and Formwork

To translate from traditional concrete and common formwork to more advanced methods, the students started with a basic understanding of concrete mixes. Traditional formwork has always reflected the negative of the form a designer intends to make; thus complex geometries are dependent on the production of complex formwork. In most cases, this suggests that for each different form made, specific molds have to be manufactured to fit that particular form. While it is possible to cast multiple pieces from the same mold, most often the formwork cannot be altered to cast a variety of similar pieces that change in scale, proportion, etc. The result of making varied forms is an expensive and complicated production of custom-made molds. This is typically avoided, especially in the pre-casting processes, where economy depends on maximizing the output of pieces per mold. Thus, being able to disconnect the form of the formwork from the form of one specific cast has long been a key focus in the development of new concrete construction technologies. The most common solution to this problem is the use of modular formwork elements, such as the PERI System that serves as a basis that is expanded upon with project specific formwork alterations and inlays that are typically used for in-situ construction or complex steel formwork prefabrication that are typically used for high volume production of architectural elements, such as t-beam, columns and stairs. But the formal variety of these systems are very limited and are typically intended for standard construction.

Conversely, the above-mentioned advancements in concrete mix science, and the introduction of digital fabrication and construction over the last two decades have led to a series of different research projects that propose new modes of concrete construction. Gramazio Kohler's TailorCrete[4] project, for example, proposes wax cast formworks that allow for complex curved geometries to be cast with the help of industrial wax inlays that can be re-melted. Or with Fabric Forms, they use a robotic controlled fabric formwork that was developed at UCLA by Sarafian and Culver,[5] to control the final form with less traditional formwork techniques. And there are many different concrete 3D printing projects, such as the RRRolling Stones from HANNAH,[6] to develop a process of making that generates new formal expressions with 3D printing. All these projects take advantage of the changes in mix design and fabrication tools to redefine the relationship between mix, mold and technology.

Similarly, the wet-folding technique also challenges the typical idea of the concrete mold and proposes a concrete that is no longer a heavy and thick material with only great compressive strength but lacks in resisting tensile forces. Contrary, this new concrete mix material has the capability of being thin, light and flexural strength that are typically more closely related to the properties of steel.[7] As these developments challenge the understanding of concrete as it is typically used in construction, advanced seminars offer an opportunity to expose students to these new developments and explore the potential for new formal investigations by collaborating with the material industry.

Exposing students to Industry

Over the last two decades, considerable changes occurred in material science and fabrication that continually find their way into the production of architecture. The research on the implementation of these technologies into everyday architectural production are still predominantly driven by research institutions, startup design firms and entrepreneurs, rather than by established architectural practices.[8] Experiments in materiality often involve innovative approaches to design computation and digital fabrication, and now increasingly rely on interdisciplinary teams of designers and scientists.[9] This new mode of operation will be a fundamental part of the future that current students will encounter in their career. To better understand this future, it is important for students to work with technologies and materials as a hands-on experience and participate in material research that explores what these technologies have to offer. To advance student's knowledge in materials, the study of new techniques in collaboration with the material industry provides exposure to a range of innovative projects that could inspire the design process. Even though it is challenging to integrate such experiences in large lecture courses; professional electives offer an opening in the curriculum to fold pedagogical goals into design research agendas. The open-endedness of the content allows for empirical as well as speculative explorations that are difficult to fit into the framework of other core courses. And the seminars allow, by their very nature, to narrow the scope of investigation so that it is possible to dove tail the course into larger research projects. Which, in the case, the course led to the opportunity for one of the students to further expand the work done in the academic context to the research lab of the manufacturer.

Course Framework

General Structure

The course was divided into two concurrent sections: 'theoretical' and 'practical'. Most of the 'theoretical' content was frontloaded, so that the students had a better understanding of the cultural context of the material and acquired specific technical knowledge needed to productively engage the material. While there is no clear delineation between one and the other, the course is structured so that, towards the end of the semester, the students focused on lab time to dedicate to the iterative production of formwork and casting concrete.

The place of origin for the 'theoretical' section was a series of lectures, readings and case studies. The lectures expanded on the basic knowledge that students have of concrete construction. To provide the students with a more sophisticated understanding of what concrete is, the lectures looked at both the history of the material as well as at its current development and possible futures. Readings, such as Mud and Modernity from Adrian Forty's book Concrete and Culture[10], or Thomas Schröpfer's essay 'The Alternative Approach – Observation, Speculation, Experimentation'[11] helped the students understand that the research they participate in is not simply focused on technology but strives to operate between the technological development of the material and its congruent cultural implications. This was further emphasized by asking the students to prepare presentations that explained the work of architects, such as Felix Candela and Miguel Fisac[12]. In the work of both of these architects there is a very strong connection between structure, form and modes of construction, tied to economy and social concerns and ideas. In contrast to the discursive nature of the 'theoretical' aspect of the course 'practical' section of the seminar was dedicated to the design of a small canopy through exploration of different wet-folding techniques. Reversing the typical design methodology, the students did not design the geometry or the form of their canopy first and then seek to resolve its construction, but rather the design emerged from studying the potentials of a construction and fabrication process. Based on this logic the students were asked to directly work with the material itself and speculate on its potential through their own empirical conclusions and not through referencing literature.

Learning Goals

The learning goals of this course were three-fold. First, the course was intended for students to get a better understanding of contemporary concrete construction. This was accomplished through lectures but also through their hands-on experience, which illustrated that concrete is no longer a heavy, thick material that they typically imagined of concrete. Rather students began to see, as so many other advanced materials can accomplish, that this new concrete material has a wide variety of different uses, performances, fabrication and construction methods with broad architectural uses and expressions. Looking at precedent and working through their own projects, they learned how the recent changes in concrete construction have broader implications on architecture as a whole. This might be a very obvious observation, but it is through combining design research and fabrication with broader design ideas that the students truly started to understand the connection between technological advancements and architectural design. Second, through the development and fabrication of the formwork and casting, the students learned what it means to understand and use construction as part of design research. Answering questions on how you have to construct a formwork for it to operate in an intended way, and how the construction of the formwork relates to the concrete mix are not questions that are only relevant for their specific projects, but are important lessons to understand how engaging with technical questions can advance formal ambitions.

Lastly, and perhaps most importantly, the course allowed students to get an insight into how exploring new materials and fabrication techniques can be the basis of an architectural design process. Working with the actual material, the students were asked to simultaneously develop possible fabrication and construction processes and speculated on the potential structural applications, combining hands-on material explorations with digital design and structural analysis tools. A process that foregrounds design research with a foundation in processes and technical knowhow, the students were provided with the capacity to engage the construction industry not just as a consumer, but as an active participant that helps shape its future.

Methodologies (through samples)

From Folds to Folding

The students were asked to develop a small-scale canopy by using a fabrication technique that would be based on ‘wet-folding’ concrete. To further explore their proposed technique the were asked to build digital models that showcased how their technique could scale up and be imagined as structural system at an architectural scale, building on structural ideas, formal expressions or means of construction that they observed in the work of the architect they presented earlier in the semester. While there were different approaches regarding the use of the folding technique, this paper focuses on one student project that aimed to develop a ‘creased shell’. Especially since this project was further

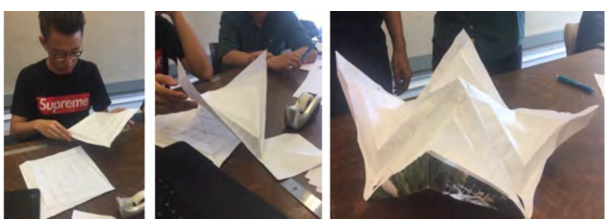

Fig. 2. Initial paper model studies.

developed over the following summer as part of the overall research project and allowed students to see the translation from small-scale material studies to a larger-scale version developed in the context of the concrete manufacture’s professional construction research lab.

Being fascinated by the shell architecture of Felix Candela, this project started with the student’s research on origami techniques in paper that allow to develop ‘shell-like’ forms. Using paper models that were based on single sheets,[13] the student approximated a series of different shell-like forms through different folding patterns (*Fig. 2)*. One of the main concerns was that the chosen folding pattern would allow for the folding to be possible without having folds that would be steeper than 90 degrees, otherwise the mix would slip off the formwork. In addition, the folding pattern should allow for the formwork to be easily foldable under the weight of the concrete with minimal movement and displacement since any unnecessary movement increases the chances that the mix will be overly agitated; increasing its slump and then sliding off the formwork.

Considering these concerns, a pattern was chosen that allowed the form to be generated with just pushing two opposite corners towards each other. While this effect is a result of the geometry of the folds, it was further enhanced by creating some ‘valley’ folds through scores on the one side of the material and the ‘peak’ folds on the other. While this proved to be simple in the paper model, the question was whether this system of folding could be scaled up with similar techniques using less malleable formwork. In other words, could the paper studies be translated into a formwork that can be operated on according to the same principals; even when under the weight of the concrete.

From Folding to Formwork

To transform the paper models into actual formwork, the translation of the folding mechanism was critical in the construction process. Initial models tried to replicate the folds in cardboard but the weight of the concrete required a stronger material, even at a small scale (*Fig. 3)*. The next version of the formwork was constructed from two

Fig. 3. First simple cardboard formwork and cast.

layers of laser cut wood pieces that were connected through a cloth glued between them. While this worked to fabricate a first successful cast, the issue was that there was no front and back side to the formwork that would differentiate between the 'peak' and 'valley' folds.

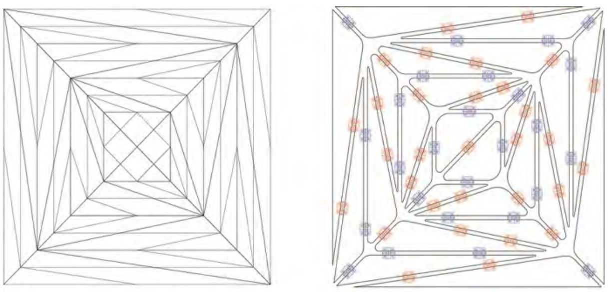

Fig. 4. Redesign of Geometry into hinged formwork (colored hinges indicate valley or mountain fold).

This made the operation of the formwork, at a larger scale impossible, since it lost its ability to fold by just pushing in the corners and needed more manual adjustment. This change, in turn, reactivated the mix and caused slumping. This increase in slumping created inconsistencies in the thickness of the concrete as well as a lack of precise edges and clean lines in the form.

To eliminate these issues, the scale of the test was increased so that the folds could be replicated through a series of hinges between the wooden pieces (*Fig. 4)*. The position of the hinges on one or the other side of the formwork allowed the differentiation between 'valley' and 'peak' folds. To ensure that the mix would not be caught in the folds, a plastic sheet was used as an underlay before pouring the concrete. This helped eliminate some friction that occurred between the formwork and the already cured concrete but the resulting surface quality closely resembled the ripples and folds in the plastic which was not a desired outcome. But the techniques were a success in that the form could move and adjust the way the student anticipated. This setup allowed for a series of initial casts and formed a clear conclusion for the context of the course (*Fig. 5)*.

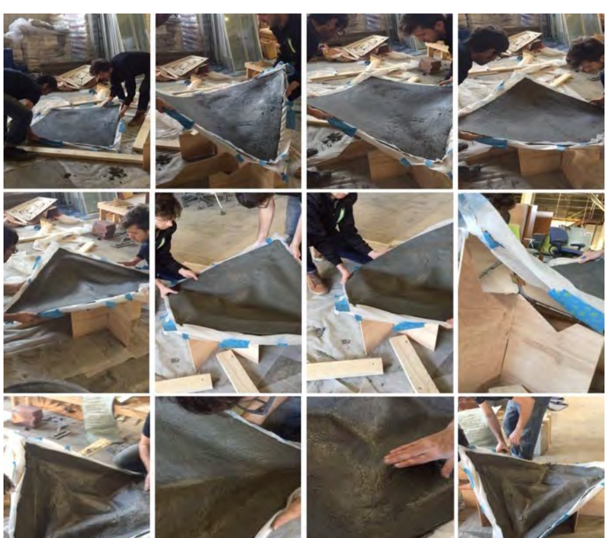

Fig. 5. Folding of "creased shell" at intermediate scale.

Analysis

With the support of an engineering faculty member, the student translated the geometry of the shell-like form into SAP2000. Since the chosen geometry was more complex than a traditional shell, and that the casts were small in scale, the analysis was not intended to provide true feedback since there were many unknowns as to the slight variations of surface angle with the creasing angles of the surface. But this process allowed the students to get an insight into a research processes that combine physical investigations and digital analysis. And while the scope of the course did not allow for a direct feedback loop, the analysis confirmed the need for additional material strength in the folds.

Results

Course

The pedagogical result was perhaps best described in the one student's response to the course:

"I was very happy that I was able to learn more about the historical context and various usages of concrete. But above all, designing something out of a new material was

'cool' and interesting. Dynamics between actual construction, advanced research phases in an industry's research lab, and course efforts to stitch the gap through design (research) really excited me."

The main research result showed that the small-scale tests could be scaled up with a similar fabrication method (*Fig. 6)*. Especially since the models proved that an increase in scale actually helped to ease the fabrication and demolding process, since the ratio between the gaps needed between the pieces for the folds and the bending angle of the pieces were easier to control, resulting in a clearer articulation of the form.

Fig. 6. Final form of student 'creased shell' prototype

Internship

Given the successful tests that were done in the context of the course at the University, we decided, with our industry partner, to explore this technique in more detail at a larger scale. This resulted in one of the students having the opportunity to further develop the 'creased shell' project as part of a summer internship at the manufacturer's research lab. The student worked under the supervision of the professor but was part of the technical fabrication team of the manufacturer.

The major challenge when scaling up the formwork lied in the translation of the hinges into a system that would work when it is operated by a crane due to it no longer

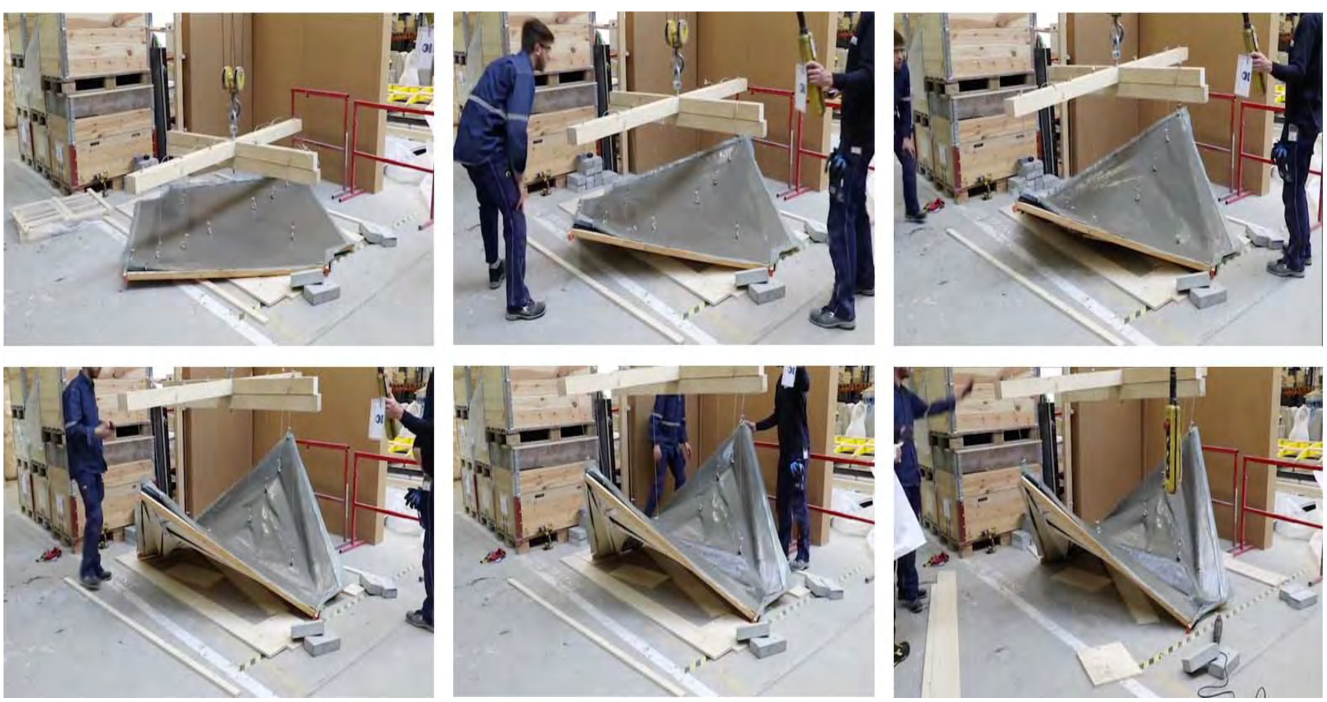

Fig. 7. Crane lift at Manufacturer Lab, done by student in collaboration with technical staff of manufacturer

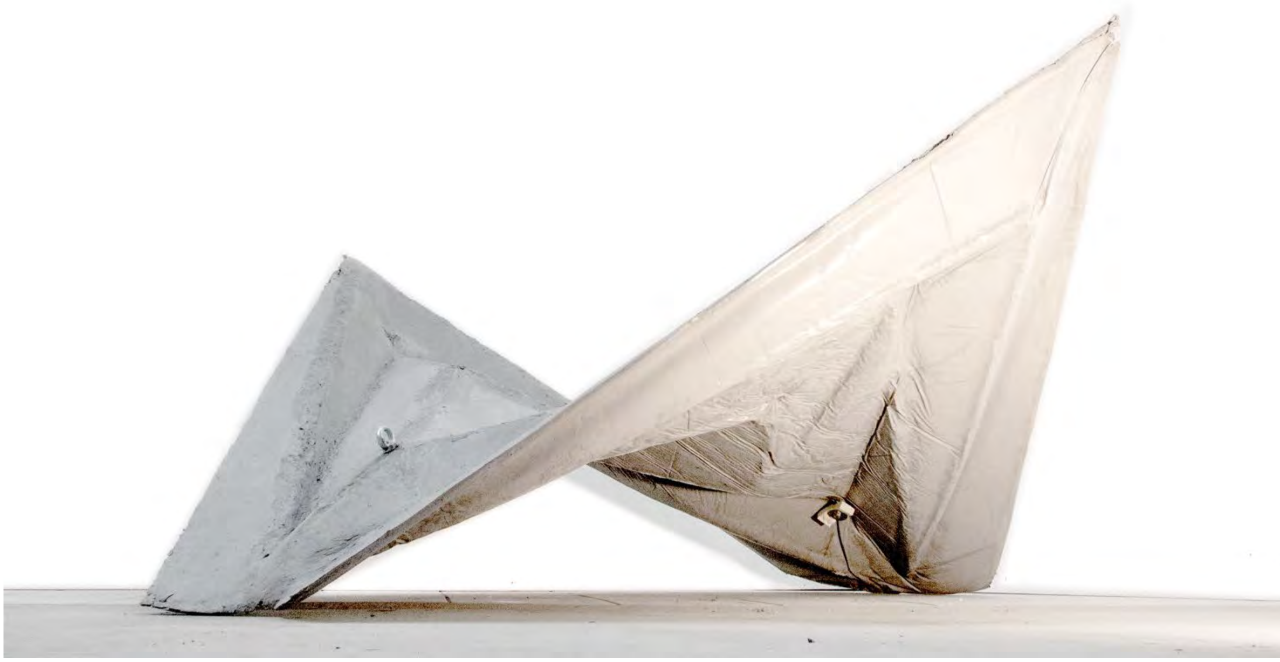

Fig. 8. Scaled-Up version of 'Creased Shell'

being possible to manually manipulate the formwork. But in essence the formwork was able to be fabricated at the larger scale in a very similar manner to the smaller iterations. The angled surfaces, to comprise the 'peaks' and 'valleys,' were CNC routed wood pieces glued with epoxy to a malleable fabric surface. The original fabric was replaced with a geotextile fabric and the hinges were translated into a series of metal strips that were connected either at the bottom or top side of the formwork.

To manipulate the formwork at the larger scale, the movement of the formwork was translated into a series of cables that were pulled up by a crane. In the smaller scaled version, the digital design process was useful to generate the cut sheets for the formwork and preview the general movement of the formwork from its flat to folded state. But in the larger version, the movement of the hoisting points in space where of great importance for the success of the cast. Therefore, a more refined digital model was constructed that traced the points and translated them into hoisting anchor positions and cable lengths that allowed the crane to operate fluidly with the formwork (*Fig. 7)*.

The final cast, at the larger scale of two-meters, was successful in providing a proof of concept of the technique (*Fig. 8)*. It also demonstrated that the increased strength of the mix generated structural forms that, with most standard concrete mixes, would not be able to be cast. Simultaneously the process of scaling up the formwork revealed the limitations of the functioning of the formwork system at larger scales due to the combined weight of the formwork and mix. These observations provided the research team with initial empirical proof that substantiated further discussion to expand the development of the research; enforcing an initial assumption that further explorations of the system might be best situated in the context of prefabrication, where the dimensions and weight remain in a manageable relation.

Conclusion

Given the rapid development of materials as well as construction methods in architecture, it is important to offer students learning opportunities at the intersection of design, fabrication, construction and material science. It is central to architecture that students learn to understand how they can productively act within this fast-changing context, ask the right questions and be responsible designers.

Seminar courses are a great opportunity to embrace new materials and methods in the design process as a form of research for students. Through providing the students with a hands-on insight into the industry, they are able to garner more specific knowledge and know-how than they typically receive from larger technology lecture courses. But to ensure that the students are able to contribute to the research in a meaningful way, it is important that they understand the larger context in which they participate in and be given the access and tools needed to engage in material research in order to have more impact later on in the profession.

Notes:

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Urban Food Systems: Applying Life Cycle Assessment in Built Environments and Aquaponics

Alex Ianchenko and Gundula Proksch
University of Washington

Abstract

As the building sector faces global challenges that affect urban supplies of food, water and energy, multifaceted sustainability solutions need to be re-examined through the lens of built environments. Aquaponics, a strategy that combines recirculating aquaculture with hydroponics to optimize fish and plant production, has been recognized as one of "ten technologies which could change our lives" by merit of its potential to revolutionize how we feed urban populations. To holistically assess the environmental performance of urban aquaponic farms, impacts generated by aquaponic systems must be combined with impacts generated by host envelopes. This paper outlines the opportunities and challenges of using life cycle assessment (LCA) to evaluate and design urban aquaponic farms. The methodology described here is part of a larger study of urban integration of aquaponics conducted by the interdisciplinary research consortium CITYFOOD. First, the challenges of applying LCA in architecture and agriculture are outlined. Next, the urban aquaponic farm is described as a series of unit process flows. Using the ISO 14040:2006 framework for developing an LCA, subsequent LCA phases are described, focusing on scenario-specific challenges and tools. Particular attention is given to points of interaction between growing systems and host buildings that can be optimized to serve both. Using a hybrid LCA framework that incorporates methods from the building sector as well as the agricultural sector, built environment professionals can become key players in interdisciplinary solutions for the food-water-energy nexus and the design of sustainable urban food systems.

Keywords: open, life cycle assessment, urban agriculture, aquaponics

Introduction

Urban environments rely on an interdependent network of food, water and energy that stretches beyond city limits to sustain its inhabitants [1], [2]. In 2006, 70-80% of all environmental impacts incurred by EU-25 countries originated in three areas interconnected by their use of food, water and energy - food and drink consumption, housing, and private transport [3]. Agriculture in particular is a key driver of climate change, water depletion, habitat change and eutrophication [4], exacerbated by the need for food production to increase by at least 70 percent to meet demands by 2050 [5]. In recent years, urban agriculture has gained momentum as a potential alternative to traditional food systems - aiming to reduce the distance from farm to consumer, recycle waste streams, and provide food security to underserved populations [6].

While urban agriculture has gained significant ground through small-scale recreational and educational uses, operating large-scale agricultural businesses within city bounds is still a young practice that often relies on technological innovation to produce market-competitive crops. In particular, aquaponics has been recognized as one of "ten technologies which could change our lives" by merit of its potential to revolutionize how we feed urban populations [7]. In a coupled aquaponic system, combining recirculating aquaculture with hydroponics optimizes nutrient and water flows for simultaneous production of aquatic animals and plants. With the help of nitrifying bacteria, nitrogen-rich wastewater from aquaculture tanks supplies nutrients for growing crops, which then filter the water to a state where it can be safely returned to the beginning of the cycle [8]. While there are many ways to practice aquaponics using a wide range of aquatic animal and crop species, this paper will primarily refer to systems that contain fish (often tilapia) and leafy greens (lettuce, kale, and various herbs). As aquaponic systems attempt to simultaneously balance the complex needs of fish and plants, they are often practiced in controlled environments such as greenhouses, which offer a degree of protection from unfavorable climate conditions and pathogens. The relationship between the aquaponic system and the surrounding envelope has the potential to be beneficial for both - a building-integrated aquaponic farm can improve host building performance, while a well-designed envelope can raise farm productivity [9], [10].

Figure 1 Ouroboros Farms, Half Moon Bay, CA

The urban integration of aquaponics is a multifaceted sustainability strategy that can simultaneously address water use, food production, energy use, and built environment performance in cities. To holistically evaluate how urban aquaponic farms perform in comparison to existing food systems and built environments, life cycle assessment can be used as a systematic methodology that is common to both architecture and agriculture; it has potential to bridge the gap between the two in the pursuit of sustainable cities.

Life cycle assessment (LCA) enables researchers in different fields to understand environmental impacts incurred by a product for the purpose of improving product performance and informing decision-makers and consumers. LCA is a standardized method regulated by the International Standards Organization [11, p. 2006], [12, p. 2006]. An ISO-compliant LCA study contains four phases - goal and scope definition, inventory analysis, impact assessment and interpretation (see *Figure 2*). In order to maintain comparability, LCAs must define a *functional unit* as the object of analysis - a unit including quantity, quality and duration of the product or service provided [13]. The methodology framework is intentionally flexible to accommodate assessments of different industrial processes and product types.

LCA is an attractive tool for both built environment and agriculture professionals because it is comprehensive - the life cycle of each system component is documented using emission data, from manufacture to operation and eventual disposal. Recently, some LCA methods for assessing environmental impact have been integrated with parametric design tools already familiar to building professionals through software such as Tally for Revit or One-Click LCA [14], [15]. This paper outlines the opportunities and challenges of using life cycle assessment to evaluate urban aquaponic farms with the aim of motivating collaboration between built environment professionals and aquaponic experts in the interest of assessing the food, water and energy implications of scaling up aquaponic production in cities.

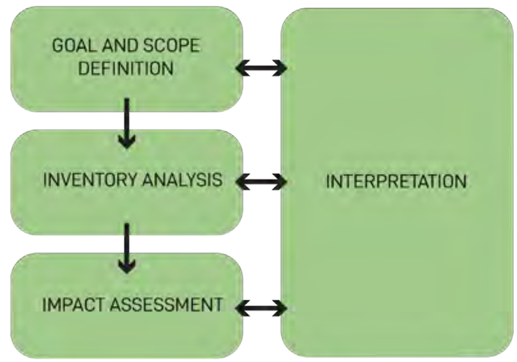

Figure 2 General LCA framework (adapted from ISO 14040:2006)

Literature Review

LCA in the building industry

In the building sector, LCA is used to evaluate both individual construction components and whole building systems [16]. The life cycle of buildings consists of material extraction, component manufacture, construction, operation and eventual demolition. Operational impacts caused by maintaining occupant comfort throughout the lifespan of the structure tend to outweigh embodied impacts caused by component manufacture and assembly in conventional buildings; although embodied impacts of high-performance buildings can be significantly higher [17]. Due to the dominance of the operational phase, LCA in the building sector is often used to detect opportunities for optimizing energy use. In both hot and cold climates, climate control systems often account for a significant proportion of total energy costs. Building professionals can take advantage of LCA as a design tool to make informed material and configuration decisions that affect the operation of each project throughout its lifespan before it is constructed [13].

LCA in the agriculture industry

The agricultural sector uses LCA to legitimize ecolabeling certain food products and pinpoint optimization opportunities in growing, harvesting, processing and distributing food to consumers. The life cycle of an individual crop is often considered from seed to harvest, omitting the preparation and disposal of food by consumers due to uncertainty. An assessment of a particular crop can include soil preparation, planting, irrigation, fertilizer and pesticide application, harvest, storage and transport. The application of chemicals to reduce risk is particularly significant in the life cycle of a crop due to inadvertent leaching of toxins into the surrounding environment that can cause erosion and eutrophication [18].

LCA Challenge	**Building sector**[1]	**Agricultural sector**[2]
Determining functional unit	Buildings have multiple functions	Agriculture often produces multiple co-products at once
Determining site-specific impacts	Lack of local data	
Representing model complexity	Many non-standard components	Variable practices
Acknowledging scenario uncertainty	Long lifespans	Seasonal variability
Locating data	Lack of data on recycling	Lack of data on fertilizer dispersal

[1] Adapted from [16]

[2] Adapted from [19]

Table 1: Common challenges in building and agricultural sector LCA

LCA in aquaponics

Since aquaponics is a young, yet rapidly-growing field, the author was able to find only seven published studies of environmental impact in aquaponics that use the LCA approach. Most focus on small research facilities, and exclude the built envelope of the aquaponic farm from the scope of the assessment.

A study performed at the University of Ca' Foscari in Venice, Italy used LCA to compare impacts caused by two simulated aquaponic farms located in greenhouses in Northern Italy - one using deep water culture (also known as the RAFT technique), in which plant roots are submerged in troughs containing nutrient-rich water and one using a media-filled bed system (MFBS), where water is pumped through beds filled with substrate such as clay pellets [20]. More recently, a simulated small-scale aquaponic system was compared to traditional tilapia and lettuce production [21]. On the smallest scale, a classroom aquaponic kit was assessed and compared to the impact of other educational supplies [22]; on the largest, an LCA of an outdoor 500 m^2 aquaponic research facility on the U.S. Virgin Islands was conducted [23]. Using collected data from a research facility, a small aquaponic system was compared to a hydroponic system of the same size in a greenhouse located nearby Lyon, France [24]. Similarly based in collected data, an earlier LCA attempted to simultaneously address environmental impact and profitability of an aquaponic system in Iowa [25]. Finally, a dissertation from the University of Colorado compiled a life cycle assessment based on data from the operation of a 297 m^2 aquaponic system 'Flourish Farms', a part of the GrowHaus urban food hub in Denver [26]. The compiled comparison of previous aquaponic LCA literature can be found in *Table 2.*

		Impacts considered												
Study	**Year**	Abiotic Depletion	Global Warming Potential	Acidification	Eutrophication	Ionizing Radiation	Mineral Resource Scarcity	Water Consumption	Human Toxicity Potential	Energy Use	Land Competition	Net Primary Production Use	**Farm enclosure size**	**Farm enclosure type**
Xie and Rosentrater	2015		●					●		●			288 sf	Greenhouse
Forchino et al.	2017	●	●	●	●								430 sf	Greenhouse
Boxman et al.	2017		●	●	●			●	●	●	●		5,381 sf	Outdoor
Hollman	2017		●					●		●			3,196 sf	Greenhouse
Cohen et al.	2018		●		●	●	●	●					None	None
Maucieri et al.	2018	●	●	●	●								None	None
Jaeger at al.	2019		●	●	●			●		●	●	●	2,421 sf	Greenhouse

Table 2: Comparison of previous aquaponic LCA studies

Existing literature on aquaponic LCA reflects the early stage of research in this field - most studies are based on life cycle inventories constructed from hands-on data, collected at a small research facility. However, to effectively assess how aquaponics will perform in the complex urban fabric of North American and European cities, other enclosure types besides greenhouses need to be assessed and incorporated into the LCA methodology. Integrating practices from both the building and the agricultural sector in LCA is essential to assessing the sustainability of future urban food production systems such as aquaponics.

Hybrid LCA methodology

In order to assess the environmental footprint of a commercial-scale urban aquaponic farm, CITYFOOD intends to conduct an LCA. The following outline describes the steps that will have to be developed to conduct a hybrid LCA study that bridges built environment expertise with aquaponic knowledge. This approach follows recommendations laid out in ISO 14040:2006 and ISO 14044:2006 [11], [12].

Goal and scope

The goal and scope phase of an LCA sets the trajectory of the study by modeling the selected product system as a series of discrete unit processes, defining the functional unit, and clarifying data assumptions and limitations. A prototypical commercial aquaponic farm system can be described by a process flow diagram represented in *Figure 3*.

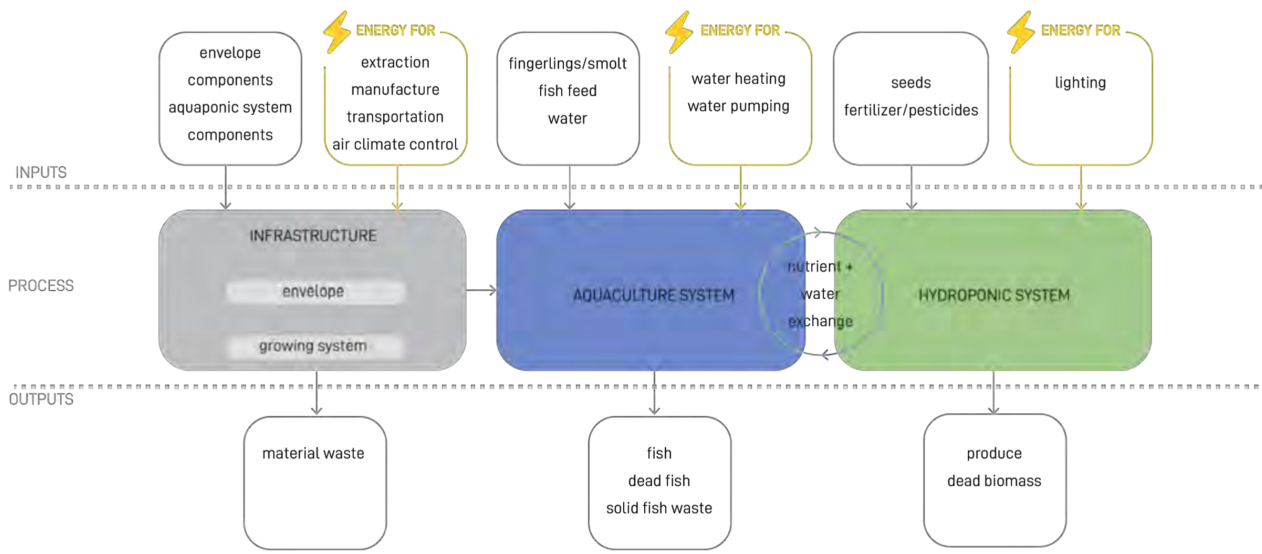

Figure 3 Process flow diagram describing an aquaponic farm system.

Many aquaponic studies done by aquaculture and horticulture scientists omit infrastructure - materials used for tanks, pipes, water troughs, surrounding structure and cladding in each farm. However, including infrastructure and enclosure is essential to understanding the impacts incurred by aquaponic farms in most temperate and colder climates, where aquaponic systems need a controlled climate to operate year-round. Infrastructure occupies a unique place in the process flow diagram, since it is both an ongoing process (requiring energy to maintain the interior climate, and occasional material inputs for component repair and replacement) and an input for the operation of the aquaponic system. Understanding that the contribution of the building sector to global environmental impacts is comparable in magnitude to the agricultural sector, envelope design for urban aquaponic farms becomes an opportunity for optimizing overall environmental performance of urban food systems.

Determining a functional unit is a challenge in both building and agricultural sector LCA (see *Table 1*). To assess the aquaponic farm, the LCA practitioner needs to first specify the intended application for the study. To compare results to conventional aquaculture, 1 ton of live-weight fish produced for the intended duration of the farm may be used [23]. For comparing aquaponics in terms of horticulture, fish may be treated as a co-product and the functional unit may be set to 1 kg wet-mass crop harvested [20]. To compare the performance of an aquaponic farm to other types of enclosures, 1 square foot of farm operated for the intended duration may be analyzed - however, accounting for the production of both fish and plants in the facility poses an impact allocation challenge which may be solved through system expansion [28].

Inventory analysis

The inventory analysis phase of an LCA involves quantifying inputs and outputs defined in the scope of the study through data collection about each resource flow within the system. Although in a realistic scenario all resource flows are connected within the aquaponic farm, collecting and analyzing data will be described in terms of infrastructure, aquaculture and hydroponic inputs and outputs.

Infrastructure inputs and outputs - This category of resource flows includes material and energy expenditures for constructing and maintaining a farm envelope and aquaponic equipment. Building-specific LCA databases and tools can be used to obtain unit process flow data for material extraction, component manufacture and disposal. Some examples include Athena Impact Estimator, BEES, and One-Click LCA; for an extensive list of building-specific and generic LCA tools and databases that support built environment studies, see the report generated by the Efficient Buildings study at the European Commission Joint Research Centre [29, p. 2]. To obtain material unit process data to represent aquaponic equipment, generic LCA tools and databases such as OpenLCA, OpenLCA Nexus, GREET, USLCI Database, GaBi, ecoinvent and SimaPro can be used. For transportation data within the U.S., the Argonne GREET tool can apply.

As a comparison of multiple farms in Australia shows, high-tech soilless farm LCA results correlate strongly with energy use [30]. If interior energy needs of the aquaponic system are carefully calibrated to exterior climate pressures, overall energy expenditures for operating the farm can be reduced. Species selection in the horticultural component of aquaponic systems determines the climate setpoint for the entire enclosure - for example, head lettuce thrives in cooler temperatures (60-70°F), whereas tomatoes grow most efficiently when the surrounding environment is warmer during the day (70-80°F) [31]. This is an important point of interaction between the aquaponic system and the surrounding envelope – selecting a crop that is better-adapted to exterior climate conditions can reduce the overall energy demand for the farm enclosure.

The selection of climate control systems and building assemblies also contributes to the energy demand of each aquaponic farm, and simultaneously influences farm productivity. Some aquaponic farms employ evaporative cooling or fog cooling systems in place of energy-intensive air conditioning; alternatives to forced-air heating also exist, such as passive solar design and radiant floor heating. Considering energy expenditure for establishing climate control, cladding material choice becomes important - whereas aquaponic farms in transparent enclosures can benefit from solar light and heat, opaque farms in warehouses can save energy by blocking heat loss with highly-insulated envelopes. These architectural decisions influence the productivity of the aquaponic farm – the ability of the cladding material to transmit sunlight directly impacts the availability of photosynthetically-active radiation (PAR) for plants' growth, and the temperature and humidity levels maintained by heating and cooling systems impact the rate of evapotranspiration and biomass accumulation in plants.

One unique consideration for aquaponic farms is the need to control humidity. The addition of fish tanks into the enclosure raises humidity, which both supports better plant growth and introduces a higher risk for the spread of pathogens [34]. In future LCA studies of aquaponic farms, energy expenditure for humidity control and associated temperature adjustments may play a more significant part than in hydroponic alternatives.

Energy-modeling tools such an EnergyPlus can be applied to calculate overall energy expenditures for climate control in aquaponic farms [32]. Additional energy exchanges from rearing fish and plants have been modeled under the project Virtual Greenhouse [33].

Aquaculture inputs and outputs - This category includes material and energy flows needed to grow fish. Agricultural LCA databases such as Agribalyse and Agri-footprint can be used to obtain limited data on fish feed unit processes and smolt production; no dedicated LCA database for fish production exists. Much like crop species, fish species selection determines the setpoint for the entire system, since different species thrive at different temperatures [9].

In most aquaponic systems, liquid fish waste is treated as an asset since it provides nutrients for crop growth; however, solid fish waste is disposed from the system. There is little data on the treatment of solid fish waste, so it is difficult to determine its relative environmental impact. This may change - aquaponic researchers propose reintroducing solid fish waste into the process of the aquaponic farm as a valuable asset by remineralization or the use of anaerobic digesters [35], [36].

Figure 4 Urban Organics, St Paul, MN

Hydroponic inputs and outputs - This category of resource flows includes material and energy flows needed to grow plants. Limited data on seed production is available through agricultural LCA databases as well as generic ones (Agribalyse, Agri-footprint and USLCI). Commercial-size aquaponic facilities often supplement nutrients derived from fish waste with synthetic fertilizers in order to ensure a stable rate of crop production. Data on generic fertilizer production can be similarly accessed through agricultural LCA databases, although finding unit process flow data for the production of liquid fertilizer solutions specific to soilless growing systems poses a challenge.

Energy required for lighting is largely dictated by the needs of the cultivated crop and the enclosure of the farm. Operating a farm in an indoor, insulated environment may reduce the need for climate control energy expenditure, but necessitates the installation of artificial lighting arrays. The energy trade-off between operating climate control and lighting in different urban farm designs can have a significant impact on the overall environmental performance of the farm [37].

Impact assessment

Most previous LCA studies of aquaponics have considered global warming potential, eutrophication, energy use and water use as impact categories (see *Table 2*). From the built environment standpoint, energy use is a highly valuable impact category to include in an LCA study, since the existing building stock in the United States is responsible for 40% of national energy consumption and 72% of national electricity use [38]. Water use is another impact category that is relevant for both sectors - in a recent study analyzing the water impact of a typical residential building in Australia over a 50-year lifespan, direct water consumption accounted for 12% of the inhabitants' demand, whereas the water embodied in producing consumable goods such as food represented 46% [39]. If water-recirculating growing systems like aquaponics tap into alternative urban water sources such as rainwater and greywater from residential use, the cumulative water footprint of living in the city could be reduced both due to diminished direct water demand and diminished implicit water demand embodied in food production. Some impact calculation methodologies available to LCA practitioners in the building and agricultural sector include the CML method, ReCiPe midpoint and endpoint approaches, and TRACI, among others [40].

Interpretation

Understanding the implications of infrastructure design for growing system efficiency is the next step in realizing urban aquaponic farms that are competitive and sustainable. The challenges that lie ahead for built environment professionals interested in using LCA to design sustainable urban food systems include:

(1) Energy modeling - using a variety of simulation tools from both built environments and agriculture to represent the climate control and lighting energy expenditures in a large-scale farm.

(2) Data availability - secondary inventory data for aquaculture and soilless horticulture is often lacking in open-source LCA databases.

(3) Data validation - as aquaponics is a young field, simulation results will have to be compared to real performance data from farms to be validated.

Previous hybrid LCA work focused on a hydroponic rooftop greenhouse located in Barcelona serves as a good example of incorporating data from the built environments and horticulture to develop a comprehensive assessment of a new sustainable technology [41].

Conclusion

Life cycle assessment is a valuable tool for both the agricultural and building sectors to address global challenges in the sustainable management of food, water and energy. Quantifying the impacts of multidisciplinary solutions such as urban aquaponic farming requires expertise from built environment professionals. For architects, engineers and planners looking for sustainable solutions, constructing LCA studies that bridge the building sector with agriculture can result in unexpected discoveries of synergies within urban resource flows. In this way, new hybrid LCAs can become not only a retrospective assessment tool, but also an aid for decision-making during the design stage.

Investigating the relationship between innovative food production and building construction through hybrid LCAs that incorporate multidisciplinary knowledge can alleviate the environmental impact of both. Although urban aquaponic farms are currently few and far between, results from existing LCA studies are promising. Scaling up aquaponic farms to a commercially-viable size within cities can be an exciting step towards sustainable urban food systems which prioritize closing resource loops.

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Bridging the Gap between Architecture and Engineering: a Transdisciplinary Model for a Resilient Built Environment

Michelle Laboy & Annalisa Onnis-Hayden
Northeastern University, Boston, MA

Abstract

As the focus of environmental engineering increasingly shifts to landscape-based, decentralized solutions to energy and water; and as architecture increasingly shifts its attention to resilience, ecological connectivity and independence from centralized infrastructure, these two disciplines find themselves closer in scale than before. This paper presents a collaborative project between upper level architecture and environmental engineering students focused on the design of sustainable and integrated water systems. Critical features of transdisciplinarity included: the engagement of stakeholders in the process at multiple moments; the speculative nature of working on very distant futures, the multi-scalar requirements of the collaboration, and the expectation of balancing quantitative and qualitative performance criteria. The curriculum was successful by many measures of work quality and impact. Students reflected on expectations and outcomes at two points of the semester, providing insights on challenges and opportunities. Relying on a shared responsibility for the project and well-aligned touchpoints, rather than daily-integrated studio-format, overcomes administrative constraints, but made misalignments more evident. While initially students had higher expectations of learning about the *other* discipline's role than about their own, later results clearly show many more thought they had learned more about *their own* discipline, and expressed more confidence on their joint work. This is an encouraging finding about the power of transdisciplinary educational experiences.

Introduction

Calling the term overused, architect Bernard Tschumi was quoted as saying that collaboration worked well when everyone had defined roles –"not one of those artificial things where everyone is being creative together".[1] While perhaps cynical, this comment highlights that effective interdisciplinary work is built on deep disciplinary expertise. Nonetheless, today's context of crisis presents designers with complex problems that necessitate integrated solutions. A recent historiography of architecture and science defines interdisciplinarity as vocational cracks that happen in moments of crisis, "opening up alternative lines of inquiry that in turn enrich our vocational understandings;" [2] a suggestion that professionals learn more about their own discipline by understanding the work of others—a provocative idea for educators. Bringing different disciplines into a project team early in the design process is required to build that understanding, but it alone may not lead to the integration necessary to address the more complex contemporary problems. This is especially true if design professionals do not have the skills or understanding to adopt each other's methods of inquiry and forms of knowledge. While interdisciplinary collaboration can begin to break down the silos in design education (architecture, engineering, urban planning, etc.) its shortcomings become more evident when well-intentioned efforts rely on self-contained modes of research, which are then brought together. To address this shortcoming, design education could engage with the notion of transdisciplinarity, which promises to hybridize knowledge and modes of inquiry to move "beyond putting things together." [3].

A transdisciplinary approach should result in more than the sum of the individual disciplinary knowledge,[4] thus new pedagogies for design education should make evident how traditional curricular approaches are opened up to new questions and forms of input. For example, transdisciplinary research expands the idea of different disciplines working jointly with the addition of external non-academic or non-professional perspectives from society.[5] While this has the potential to better address the more challenging and complex social and environmental problems in practice, it represents a challenge to design educators that usually rely on defining a more narrow and speculative problem to provide more clear learning outcomes. That being said, there is momentum building around the idea that design education needs to, and is well positioned to, embrace a higher level of complexity and hybridization. Architecture and urban planning are considered fertile territory for transdisciplinary work because they are action-oriented and focused on multi-dimensional problems.[6] Similarly, calls for engineering to engage transdisciplinarity emphasize their focus on design, process and systems in the application of skills and knowledge to unstructured problems. Scholars of teaching and learning in design disciplines can advance transdisciplinary teaching and practice by testing and disseminating innovative pedagogical experiments, building a body of evidence for when, where and how to most effectively create hybrid curricula. This paper presents findings about teaching methods, learning opportunities and overall challenges that were discovered while implementing and assessing a transdisciplinary design project between two courses in architecture and environmental engineering.

When reviewing the literature, a few characteristics of transdisciplinary research pointed the teaching team towards key elements to effectively bridge between architecture and engineering education, including: a focus on real-world problems and their solutions; acceptance of uncertainty and local constraints from social, organizational and material contexts; the bridging of theory and practice; and the connection of research and societal decision-making.[7] Two capstone design courses mapped shared learning goals and milestones for team projects focused on sustainable development, specifically addressing the nexus of water and energy, which operate at multiple scales from buildings to urban infrastructure. The goal was to systematically observe how students hybridize knowledge through collaboration on a complex and multi-scalar design problem; and to evaluate how this pedagogical model may better prepare future professionals to build more resilient environments.

Urban water: a context for transdisciplinary design

This collaboration was inspired by a student-initiated extracurricular project at Northeastern University for the Rainworks competition of the Environmental Protection Agency in 2015. The student team, mentored by the authors of this paper, won an honorable mention—ranking 3rd out of 48 projects nationally. The project engaged multiple disciplines and community stakeholders, providing a transformative experience for everyone involved. This water design problem generated a level of student motivation and effort that inspired the faculty to experiment with more transdisciplinary models within the core curriculum.

Global patterns of urbanization demand new paradigms for sustainable urban water resources, emphasizing integrated water management for environmental quality, economic prosperity, and social development; and requiring improved coordination between engineers, urban planners, architects, and city administrators to replace water import and export with more localized supply and reuse.[8] As a result, the focus of environmental engineering increasingly shifts to landscape-based, decentralized solutions to energy and water; while the focus of architecture is increasingly shifting towards resilience, ecological connectivity and independence from centralized infrastructure through site- and district-scale solutions. These disciplines traditionally operated at two extremes in scale but are now closer than before.

According to the National Academy of Engineering, the multifaceted and multidisciplinary challenges of sustainability can introduce students to interdisciplinary learning by working to solve complex, interdependent, global problems.[9] However, a review of the literature on design education found only a few truly interdisciplinary collaborations focused on sustainable development; which included civil, construction, environmental, agricultural, biosystems, electrical, computer, chemical, and mechanical engineering, as well as landscape architecture and organic agriculture; [10,11,12] but not architecture. This is surprising considering the significant role that buildings play in the consumption of energy and water. On the other hand, most known collaborations in architecture are with structural engineering, as evidenced in detailed accounts from practitioners.[13] Many of these documented examples are limited to the building scale, working with allied disciplines of architectural and structural engineering; arts, landscape, and health; while other examples that expanded to urban scale issues worked with landscape architecture, urban geography or planning, but not engineering.[14,15,16] Similarly, interdisciplinary capstone projects are not a new or innovative practice in engineering education;[17] but few engage environmental engineering with other disciplines.[18] Indeed, cross-disciplinary design in civil engineering is often limited to its sub-disciplines of environmental, structural, geotechnical, transportation and water resources. This suggests that a curricular experiment between architecture and environmental engineering would not only be motivating to students and potentially relevant to the future of practice, but that it also demanded a careful analysis of learning outcomes.

Methodology

There are two methodologies to describe about this project: the teaching methodology and the research methodology, which happened concurrently and informed each other. The first involved designing a curriculum, documenting challenges and opportunities, and making observations from the outcomes of the student work. The second part involved understanding current practices, identify existing evidence, and refine remaining research questions; as well as measuring both student interest in and perceptions about their learning. We surveyed the students at the start and at the end of the collaboration, asking the same questions to both disciplines. We analyzed the distribution of responses to quantitative questions and coded ideas emerging from qualitative/ written answers; making comparisons between initial and final surveys, as well as between disciplines. These two parts of the work, the teaching observations and the student surveys, provided the foundation for a pedagogical research analysis. The following sections of the paper explain the design of the curriculum to provide context; followed by key observations from the faculty about important moments of learning, specific challenges, potential solutions and/or opportunities for future research; and finally an examination of the results from student learning surveys.

The faculty's prior experience in project-based teaching, their alignment of interests, and the ability to make changes in the curriculum is critical to the feasibility of this type of experiment. In this case, the Architecture professor is a researcher on architectural aspects of socio-ecological resilience, who teaches and coordinates Comprehensive Design Studio, and has taught collaboratively with landscape architects on ecological issues. The environmental engineering professor is a researcher on sustainable wastewater treatment solutions and integrated approaches to water, who teaches the environmental engineering capstone and previously had included building developers as clients in student projects. The students in these courses were a combination of seniors and graduate students from architecture, and seniors from the Bachelor in Science in Civil & Environmental Engineering. In these required courses, the students in these particular sections were only a subset of the two classes, and therefore were self-selected. This allowed the faculty to gauge initial interest and perceptions of students opting into the project, but also allowed students to be aware of and motivated by the experimental nature of the curriculum.

A pre-semester survey measured whether there was student interest in collaborating with other disciplines. Nineteen of the twenty-one civil engineering students that registered for the Environmental Senior Design Project answered the question: “Are you interested in being part of a multidisciplinary team?” Six responded “yes”, twelve responded “maybe”, and one student responded “no.” This survey showed significant curiosity about this type of collaboration, but the large percentage of students that responded “maybe” indicates that there was some uncertainty about what it would entail. In architecture, fifty-five students were already divided into twenty seven groups (mostly pairs) and given a description of five different sections of Comprehensive Design Studio, including two interdisciplinary collaborations with engineering (the subject of this paper with environmental engineering and another with structural engineering). Nearly half of the class (48%) expressed interest in one of the two interdisciplinary sections. Just over a quarter of students (26% of the total class) expressed interest in the collaboration with environmental engineering. These numbers are remarkable considering the experimental nature of the studio, in what is already considered an extremely challenging semester. Ultimately, thirteen engineering students were paired with ten Architects in two sub-groups of twelve and eleven; although the formation of transdisciplinary teams did not happen until a month into the semester, as will be explained.

Curriculum Design: Mapping Shared Learning Goals

For building technology educators in architecture, project-based teaching within the design studio can be a powerfully-effective learning experience that increases student motivation through more formative assessments that closely resemble their personal interests and future professional practice.[19] While in engineering education, project-based learning has become standard practice and an accreditation requirement;[20] design is not as central to their daily experience as it is in architecture. Therefore, the nature of design education in each discipline is one of the first challenges to overcome. The studio model in architecture, based in a shared physical space for creation, instruction, meetings and feedback, is not typically found in engineering. The typical capstone course in engineering is the closest to the architecture studio: with precursor courses on project-based learning, sequential assignments, and strong group project emphasis.[21] While these are natural places in the disciplines’ curricula for this type of collaboration, both the teaching methods and deliverables can differ substantially. Engineering capstone courses rely on written reports with a significant amount of quantitative analysis, while the architecture studio relies on graphic visualizations and physical models. This can be a source of misunderstandings and misperceptions, but also an opportunity to build understanding.

To hybridize methods, it is necessary to identify shared learning goals. For example, the connection to “reality” of the design project has both similarities and potentially productive differences between disciplines. Active stakeholder involvement is an important aspect of engineering capstones, which is essential to transdisciplinarity, but less common in architecture education. On the other hand, the architects’ speculative approach to projects helps expand the goals of involved stakeholders and the performance criteria of the engineering project by imagining alternative futures. These alignments and differences can be found in the course learning outcomes. The syllabus of the environmental engineering capstone course requires *"understanding the problem from a client's perspective."* The architecture studio syllabus invites students to think how building systems will *"meet unknown future spatial, structural, and energy needs in response to a changing context and climate."* While most goals in the engineering syllabus are focused on professional skills (applying engineering standards and computing tools, writing effective proposals and technical reports, and giving effective presentations of technical material), one goal explicitly connects with transdisciplinary approaches: "Consideration of economics, aesthetics, sustainability, manufacturability, impact to the natural environment, ethics, social impact, political context, public health and safety."

The early focus of both courses on systems, their sustainability and resilience, proved to be a productive alignment of learning goals; a way to focus the early research on how systems and their performance may need to change over time. This prevented the architects from jumping into design too quickly following their traditional approaches while encouraging the engineers to think beyond existing conditions as governing parameters of design. Both groups of students, as will be explained, were at different points uncomfortable with or anxious about aspects of this approach, but it was important to create space for new ways of thinking. This was made possible because the Comprehensive Design Studio in the School of Architecture at Northeastern consists of four phases that reverse the typical studio sequence to foreground building systems as generative of long-lasting buildings, delaying site or program, in that order, so that solutions can follow the life cycle of systems from longest to shortest.[22] The approach moves away from "applying" technology to solve an already defined problem; instead using research-based principles on systems performance to guide the design process. Similarly, it is increasingly more central to environmental engineering capstone courses to consider the changing parameters of climate change in the systems that they design. System life cycles and changing environmental conditions are a perfect context to suspend traditional design approaches and engage in hybridized thinking.

When working within the constraints of each discipline's teaching methods, especially in courses that are so central to the accreditation of the program, it is important for the faculty to not only identify shared learning goals and opportunities for hybridization, but also to map the alignments of learning goals in the schedule, identifying moments for deep engagement, and moments to retreat into disciplinary expertise. The goal should be to clearly identify the appropriate timeframe for students to work together, and the degree of integration that is expected. This considers a unique challenge of collaboration in education: that in order to be transdisciplinary, students need to first attain a high level of disciplinary expertise that they don't yet have. The faculty hypothesized that testing the effectiveness of hybridized modes of inquiry can be better tested in the quality of the final deliverables of each individual discipline, rather than a combined deliverable where the impacts to each discipline would be more difficult to discern. With those goals in mind, the organization of course schedules and deliverables was adjusted to reserve a critical amount of time at the beginning of the semester for the students to prepare for and build confidence in their roles in their future interaction; and to provide some space at the end of the semester for the disciplines to reflect on their past interaction and develop detailed deliverables specific to their discipline.

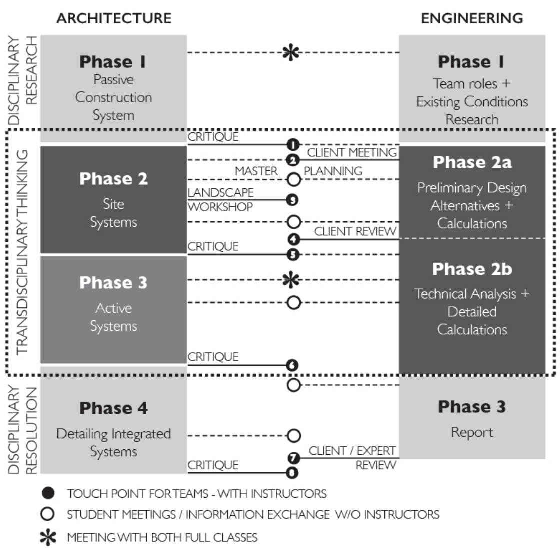

Fig. 1. Example of mapping alignments and goals for a transdisciplinary curriculum between an architecture studio (left) and the engineering capstone course (right).

As seen in Figure 1, what we called “transdiscipinary thinking” happened in the middle zone of the semester. The goals and schedules of both courses were adjusted slightly to align at the beginning of Phase 2, and for the classes to meet at important *touchpoints*, which included: (1) the forming of teams at the review of phase 1, (2) meeting with the client to listen to aspirations and set project goals, (3) a workshop with professional landscape architects to review preliminary urban design and site planning concepts, (4) Preliminary presentation to the client (5) Phase 2 critique of projects (site design) with external professionals, and (6) Phase 3 critique of architecture projects with professional architects and the engineering students as critics. Students were also expected to meet other times without the faculty and collaborate on exchanging information for the final deliverables (Fig.1).

Observations in the classroom

The projects required comprehensive master plans for sustainable districts or developments with ambitious environmental goals in Boston and Gloucester, Massachusetts; and identified a few critical building sites within the district/development to be designed in more detail either as district service buildings or as prototypes for key parts of the plan (Figure 2). Students had to negotiate the goals and requirements of individual sites with those of the master plan, develop quantitative and qualitative analysis; and model the requirements, contributions and performance of prototype buildings within the district. Architects and engineers co-authored the most critical design decisions. The faculty made observations about the dynamics of this collaboration at individual class meetings and at joint touchpoint meetings.

A joint lecture and discussion kicked off Phase 1, before architecture and engineering students formed teams. It covered important background on the topic of the projects, including the urgent global challenges and compounding effects of rapid urbanization and climate change, and design opportunities in coastal cities at the water/energy nexus through the use of inspiring examples of integrated projects. This proved to be an important teaching strategy to address the initial uncertainty. However, during the group discussion that followed students were asked about the potential of working together, and the answers were fairly predictable. The responses included ideas from the engineers about how projects with architects may be more: *holistic, inspiring, aesthetically pleasing*; and responses from architects about how projects may be more: *realistic, feasible, stronger, measured*. After that group discussion, engineering students researched and documented existing and projected future conditions of potential sites, while the architects worked intensely on researching and designing construction systems that expand what architecture can do with water. The five pairs of architects developed site-less structural prototypes for, for example, rainwater collection and storage through the structure (concrete umbrella columns), robust masonry walls thermal mass that supports heavy vegetated surfaces, folded plate structures that channeled water from the roof to rain gardens along the building edge, (Fig. 2a-c) glulam timber for long-span greenhouses housing living systems amongst uninsulated buildings, and a timber frame with south-facing atriums housing biotopes for water treatment. These prototypes were catalysts for teams to form, and to find alignments between engineering research on site projections and architectural ambitions that could structure the parts of the urban master plans (Figure 2).

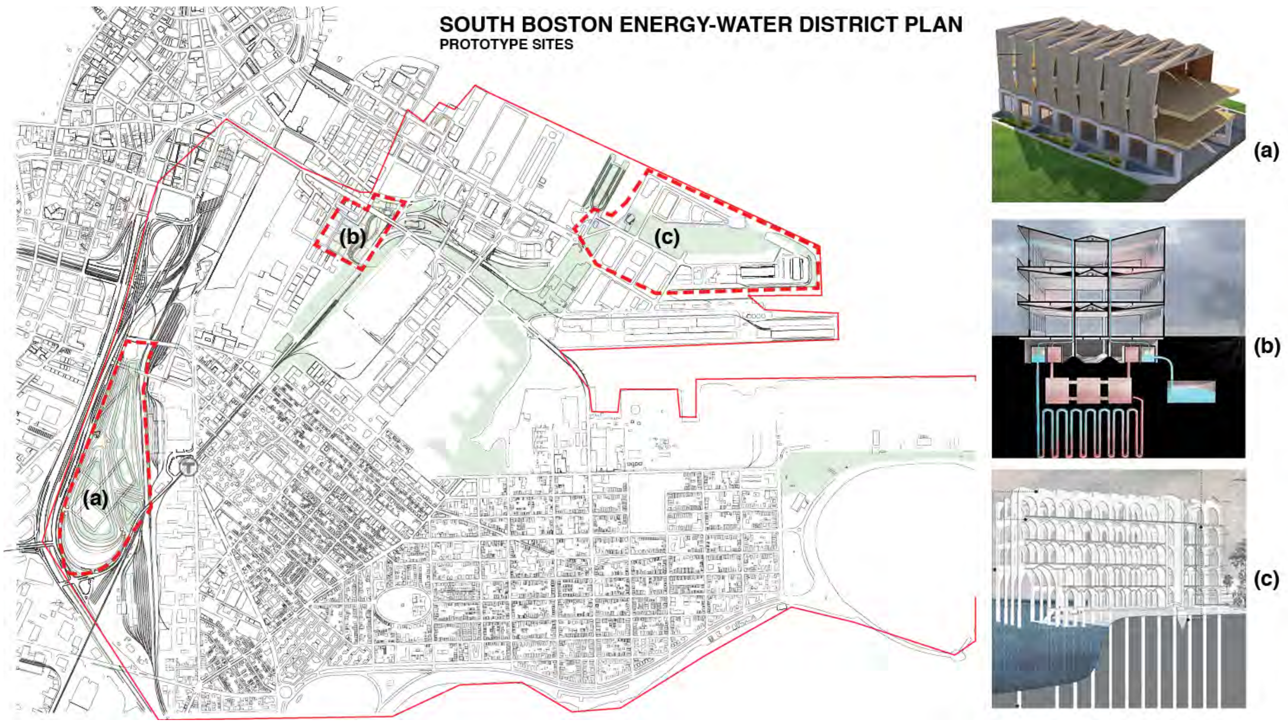

Fig. 2. Student team's master plan for Boston's Seaport district, with three architectural prototypes developed for three critical sites: (a) the Community Water and Energy Center, (b) the Green Street building of water-collecting umbrella columns, and (c) the remote grid-disconnected building that manages all water on site and is designed for storm surge.

The following phase involved intense transdisciplinary collaboration on master planning. This is where points of tension were observed. Architects moved quickly through design iterations based on preliminary data, site observations and intuitions, while the engineers were non-committal until full site data was available. The design critique with external landscape architects, an atypical format for engineering students, was a helpful touchpoint that modeled how to work diagrammatically with informed assumptions that could later be refined. Similarly, architects proposed alternatives to the client's initial requirements, based both on performance and experiential criteria; but engineers resisted the idea of not giving the client what they asked for. At one of the touch points, the faculty facilitated a group discussion about recognizing clients priorities and often competing goals, and encouraged the teams to think about ways to educate the client by presenting and contrasting multiple options for the design playing out over longer time frames. This represented a challenge for engineers who rely on fixed criteria for selecting equipment and making calculations, and for architects that usually follow a program brief. Both architecture and engineering students modeled different scenarios to design ways to enable changes in program, equipment, technologies, and engineering processes over time. Students were uncomfortable with the unavoidably slower pace of progress in a more complex process. In these expected situations, it is helpful for the faculty to provide assurances that the immaturity of the design at that stage was necessary and expected in order to later achieve more integrated thinking.

The second type of challenge involves finding shared responsibility on the project when the students traditionally operate at very different scales. The approach to this challenge was to make the larger teams jointly responsible for the urban scale planning, but architects were divided in sub-groups responsible for specific sites within each district; and the engineers were divided into sub-groups responsible for different technical components. Like a metaphor for transdisciplinarity, students had manageable projects to apply specialized expertise to, but also higher-level goals and responsibilities that extended beyond the boundaries of their individual sites.

Survey Findings

We asked the students what the other discipline brings to the table and how the interdisciplinary collaboration will make their project different than if they worked only within their own discipline. The engineers anticipated that the architects would bring creative ideas and perspectives about the culture of the project site. They expected a more *well-rounded* and *interactive* design that would better integrate design with the rest of the community (the existing buildings and the people living within), more *aesthetically pleasing* and more *fluid* and *interesting* than what they would have come up with on their own. For example, one student said "the buildings would just be squares on the plan without any real substance and stormwater structure would be mere oblong element without any other function than holding water". The architects expected more rigor and accuracy in quantifying impacts using "real" data and technical information to increase the options, capacity and scope of the architects more "diagrammatic" projects. They also expected a necessary simplification and increased focus for what otherwise would be overcomplicated or unrealistic ideas; designs that were more *functional, realistic,* and *complete*.

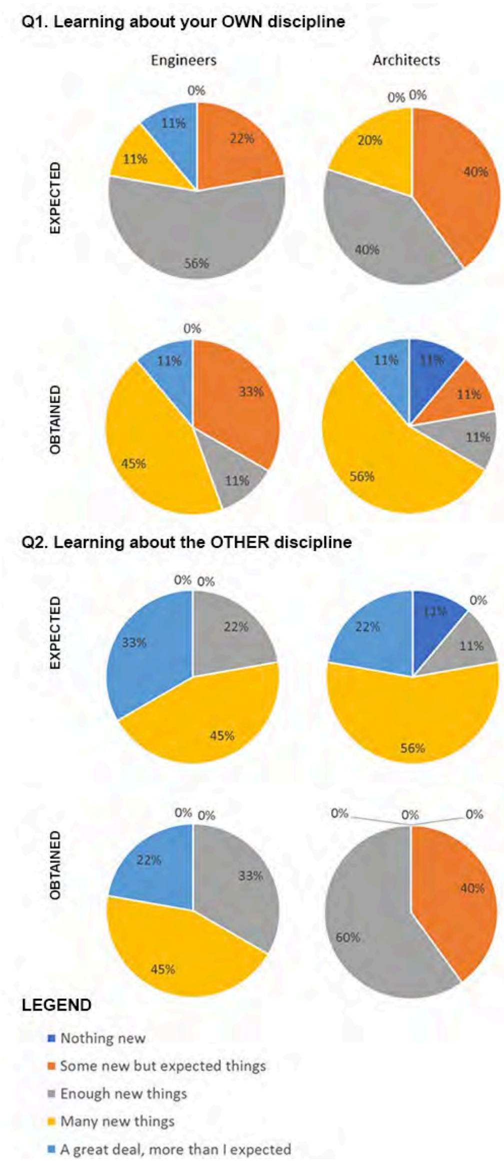

Figure 3: Survey results for learning questions about the role of the disciplines, before and after the collaboration.

When asking the students early on to quantitatively rate how much they expected to learn about the role of each discipline, the survey reveals that both the engineers and architects had higher expectations of learning about the *other* discipline's role than about their own (fig.3). Later results clearly show that the students felt that they learned more than originally expected; and most interestingly, many more thought they had learned more about *their own* discipline. This was especially true for the architects, who seemed to have improved sense of the importance of their role in these seemingly technical problems. This is an encouraging finding about the power of transdisciplinary educational experiences.

Conclusion

This collaboration was successful by many measures. Students self-organized and engaged with people from communities, including water taxi drivers in the seaport district, fishermen and food processing workers, developers, land owners and environmental groups. While slower to develop, the projects in the end achieved a higher level of technical development than previous iterations of both courses. Projects earned multiple recognitions: two awards at the Northeastern University RISE competition: an Innovation Award but also a Graduate Humanities Award; and a 3rd place in a national wastewater competition. The two departments recognized the potential for more collaboration between these two disciplines, and the need to develop hybrid practices. Two new combined majors between Civil Engineering and Architecture, and between Environmental Engineering and Landscape Architecture were proposed and approved for the coming year.

Shortcomings are to be expected with a first iteration; and should be addressed in future iterations in this institution or others. Relying on a shared responsibility for the project and touchpoints, rather than daily-integrated studio-format, overcomes administrative constraints and requires more independence and initiative on the students; but misalignments of schedule and differences in learning goals between the two disciplines were still evident impediments to more cohesive projects. Students acknowledged that the other discipline contributed to their confidence in their proposals. This type of experience is more likely to teach students something they do not expect about themselves and prepare them to negotiate new methods of working. It also provides opportunities for taking bigger risks in projects. There were a few critical features of the project that enabled transdisciplinarity: the engagement of stakeholders in the process at multiple moments; the speculative nature of working on very distant futures, the multi-scalar requirements of the collaboration, and the expectation of balancing quantitative and qualitative performance criteria. This capstone project represented a challenging but worthwhile effort for all those involved, and the quality of the proposals that emerged suggest that there is fertile territory to continue to explore transdisciplinary collaborations between architecture and engineering.

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'Partners in Light:' How Plastics Enabled Fluorescent Lighting and the Modern Office."

Thomas Leslie, FAIA
Iowa State University

Abstract

Writing in 1946, Charles Breskin, the editor of *Modern Plastics*, suggested that designers were emerging from the "dark ages" of commercial lighting. While construction in America had lagged during the Depression and World War, scientific advances in many areas of building technology had surged, and new demand for residential and commercial space was matched by the desire for more efficient, comfortable, and mechanized buildings. While advances in building cladding and servicing have been well-covered, one key development—matching chemical developments in plastics with electrical and illuminatory advances in fluorescent lighting—had equally revolutionary impacts on building interiors.

Fluorescent lighting as a technology dated to the late 19th century, but it only saw commercial development with the expiration of incandescent patents in the 1930s. Keen to develop a new market for a product that they could still claim as exclusive, General Electric pushed early fluorescent systems to market by 1934. These lamps offered cool, energy efficient light that was ideal for factories, but they also saw early use in office buildings. Among their benefits was the ease they offered in controlling and directing their light. While incandescent lamps ran hot, requiring heat- and ignition-proof housings of metal, fluorescents could be paired with diffusers, reflectors, and housings made of more easily molded plastic. Underwriters Laboratories approved the first polystyrene holders for fluorescents in 1945, which allowed lighting designers wide latitude in the way fluorescent light could be focused, reflected, directed, and shaded. The first systems to provide truly even light distribution over wide floor and desk areas followed. Along with the ubiquitous sealed curtain wall and perimeter air conditioning units, office buildings of the 1950s quickly took advantage of fluorescents' easy pairing with scientifically designed housings that enabled regular, gridded ceiling layouts—a key influence in the development of the open plan, modular office.

Introduction

Writing in 1912, illuminating engineer Louis Bell stood at a turning point in architectural lighting. Carbon-filament electric lamps, which produced faltering light of around 16 candlepower and that burned out within a few hundred hours, had been the industry's standard for over a generation. Tungsten filaments, which had debuted in 1907, offered brighter longer lives, "driving out" carbon filaments from the market despite their greater cost. (2) General Electric, which traced its corporate ancestry to Thomas Edison, established a near-monopoly on tungsten lamp production. It absorbed the National Electric Lighting Association in 1911, taking over its research and industrial center east of Cleveland, Nela Park, where GE went on to improve tungsten alloys, wire coiling, and bulb atmospheres, bringing the cost of incandescent lighting down while increasing its efficiency.

Incandescent fixtures had two intractable comfort problems, however: one visual, and one thermal. To heat tungsten to the 2300°C necessary to achieve incandescence, a narrow filament had to be subjected to a high current, creating resistance. Radiance relies on the physical quantity of tungsten, but resistance requires a narrow cross section. Filaments must, therefore, be long and thin, but they also have to be protected from the outside atmosphere to prevent oxidation. Over time, engineers settled on a tightly wound tungsten coil within a spherical bulb—at first evacuated, but later filled with a neutral gas to prevent the filament from evaporating. (3) This turned long, linear filaments into intense point sources of light that could reach 1000fc of intrinsic brightness. Such a powerful source was uncomfortable to view directly and had to be shaded from direct lines of sight by diffusers, louvers, or reflectors, all of which decreased the lamp's effectiveness. The heat that these fixtures emitted, however, was even more problematic. Most of the energy radiated from an incandescent filament is heat—only 7-10% of the electricity that went in to a typical tungsten filament emerged as visible light. (4) Even at its maximum theoretical luminous efficiency, at its melting point of 3655°K, a tungsten filament produced just 53 lumens per watt. Incandescent lamps, however, had to operate at much lower temperatures, since the melting point of the solder that held their base wires together was only 345°F; at this temperature, tungsten filaments produced 16 lumens per watt. (5) The electricity that did not produce shortwave, visible light produced longwave radiation, or heat, some of which heated the surrounding glass bulbs, but most of which was transmitted, along with the visible light, to heat surrounding materials, room fixtures, and occupants. This added to the temperature of surrounding rooms and it restricted manufacturers' options for lamp holders and shades; any material that intercepted and absorbed visible radiation also absorbed radiant heat, which could cause scorching, melting, or even ignition close to hot bulbs and filaments.

General Electric and their closest competitor, Westinghouse, responded to these problems by matching more powerful lamps, which offered modest improvements in efficiency but had shorter filament lives, with features that reduced direct glare including silvered caps or frosted bulbs. Incandescent fixtures, typically surrounded a lamp with metal or glass enclosures that diffused or reflected the filament's piercing brightness. But these were only marginally successful. By 1939, Architectural Record shared the frustration of illuminating engineers and architects with the limitations of incandescent lighting. "Efficiency of the tungsten-filament lamp," it noted, "is now approaching its practical limits." (6) This frustration was already being addressed, however, by the spectacular debut of new "firefly-like" lamps at the New York World's Fair and the Golden Gate International Exposition San Francisco. (7)

Fluorescent Lamp History and Principles

Since the 1860s, engineers had known that certain gases—neon in particular, but also helium and sodium vapor—emitted visible radiation when energized. The Cooper-Hewitt lamp, which debuted in 1901, relied on this effect, as did sodium-vapor lamps, which appeared in commercial form in 1931. (8) Pure electric discharge lamps were inefficient and difficult to operate, however, and the light they produced was limited in color. They were appealing since they contained no fragile filaments, but saw little use outside of advertising and industrial applications. French scientist Alexandre Edmond Becquerel noted in 1859 that adding 'luminescent solids' to discharge lamps added impressive candlepower. He suggested that such solids could be spread on glass bulbs' inside surfaces to boost the lamps' efficacy. (9) As early as 1896, Edison himself experimented with electric discharge lamps using bulbs coated with an oxide of tungsten that fluoresced when bombarded by energized gas particles. This produced similar intensities of light but at lower energies—and thus cooler temperatures—than either incandescent or pure electric discharge lamps. The difficulties of producing these coatings and the popularity of incandescent lamps had left Edison unenthusiastic.

To provide rapid starting and consistent operation, fluorescent lamps consist of glass tubes lined with phosphor-rich powder and filled with a low-pressure inert gas and a small quantity of mercury, which vaporizes in the near-vacuum of the tube. Electrodes at each end pass an arc through this gaseous mixture, which causes the mercury to emit radiation across the spectrum, with a particular ultraviolet intensity. While this alone produces some visible radiation—the electric discharge effect—the invisible, ultraviolet radiation that accompanies this excites phosphors in the tube's coating, which in turn produces visible light. By adjusting the phosphors' chemistry, engineers can adjust the emitted light's color and intensity. While electric discharge lamps required several ounces of mercury to produce adequate light, fluorescents required only a few milligrams. Argon serves as a 'starter' for the tube and, as it becomes energized mercury floating in its midst also begins generating radiation. While the principle of fluorescents was thus simple and efficient, the actual process required technical innovation and some engineering finesse. Because fluorescent lamps became more efficient conductors as they energize, they require electric ballasts to prevent runaway electric currents. Starting requires a precise mixture of argon and mercury vapor, and fluorescent lamps are sensitive to temperature—mercury emits radiation most efficiently at 45°C (113°F).

Despite the delicate engineering required, fluorescent lamps offered three advantages over incandescent lamps that kept researchers interested in the principle during the incandescent era. First, by spreading their output over the larger surface area of a bulb instead of concentrating it in a single point-source filament, they addressed incandescent lamps' persistent problems of glare. Second, whereas incandescent lamps' maximum life peaked at 1000 hours, lifespans of fluorescent lamps averaged between 2500-5000 hours, reducing maintenance and replacement costs. (10) Finally, fluorescent lamps offered improved efficiency over incandescent lamps. By 1943, improved tungsten filaments still converted less than 7% of their electricity consumption into useful light in standard, 100-watt lamps. A 40-watt fluorescent lamp, by comparison, converted more than 18% of its energy into visible light, producing between 50 and 70 lumens per watt, or three to four times that of incandescent lamps. (11) This reduced the amount of electricity needed to illuminate any given space, but each watt represented a fixed quantity of longwave radiation—3.415 British Thermal Units of heat for every watt-hour of energy consumed—being discharged by the lamp. (12) 100-watt Incandescent lamps produced bulb temperatures of 250°F, compared to 100°F to 120°F for a 40-watt fluorescent lamp that produced roughly the same output. As thermal comfort became an area of scientific study and concern with the advent of air conditioning in the 1920s and 1930s, heat produced by incandescent lighting proved to be a troublesome factor in environmental engineering. In 1950, Progressive Architecture estimated that each incandescent lamp in a building added between $14 and $23 of increased air conditioning capacity. (13)

Fluorescent lamps' advantages would only reach the market, however, with dedicated engineering and experimentation. There was little momentum to research a better solution while General Electric and its licensees saw comfortable growth in the incandescent market. As late as 1935, with no viable alternatives on the market, domestic and commercial customers remained "quite satisfied" with incandescent technology's gradual—but slowing—improvements in efficiency and cost. (14) Over the next few years, however, advances proceeded rapidly, sparking anticipation among designers and frustration with incandescents' stalled-out technical advances. GE and its primary licensee for tungsten-filament lamps, Westinghouse, had enjoyed a near-corner on the lighting market, with 78% of the nearly 700,000,000 lamps sold in the United States coming from one of the two manufacturers. But the two companies had mounting concerns. The American patent on tungsten filaments—filed by two Austrian citizens, purchased by General Electric, and granted in February 1912—expired in 1929. (15) Agreements with glass suppliers such as Corning kept the two companies ahead of their competitors, but independent manufacturers such as Salem, Massachusetts-based Hygrade posed a growing threat. Hygrade merged with a radio manufacturer named Sylvania in 1931, obtaining a formidable research and development team that sought new avenues into the still fast-growing lighting market.

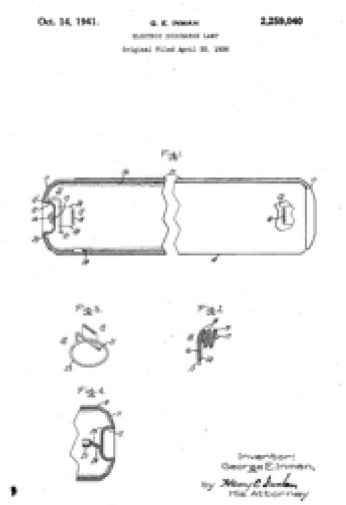

Fig. 1. G.E. Inman's patent for a commercial fluorescent lamp, filed 1936.

General Electric's research farm at Nela Park remained the premiere site for lighting innovation, though, and in 1934 they began work on alternatives to the newly competitive incandescent marketplace. In October of that year, physicist Arthur Compton saw a rudimentary fluorescent lamp in an English laboratory and, as a technical consultant on retainer to GE, he urged executives at Nela Park to pursue the idea commercially. Researchers led by George Inman began work that November, building on tentative but fruitless experiments with fluorescence in electric discharge lamps done by GE engineers in Schenectady, by those that Compton had seen in England, and by French scientists who had sought to correct the green color of mercury discharge lamps. By December, the GE team developed a working 10-inch lamp that proved fluorescent's feasibility and the company launched parallel initiatives to develop ballasts and manufacturing tools. Westinghouse and Sylvania followed GE's lead, as did Dutch manufacturer Philips. Three years of fine-tuning followed GE's prototype; internal correspondence revealed that the prodigious performance promised by fluorescent technology only occurred with a frustratingly delicate balance of conditions:

"Within the range of acceptable bulb sizes, the designer (of fluorescent lamps) must compose the electrical characteristics to produce the desired lumens per foot, brightness per square inch of tube, and over-all efficiency. He must adjust the electrical relationship of current, voltage, lamp loading (which is the wattage-diameter-length relationship), and related gas pressures so as to provide reliable starting and satisfactory regulation under operating conditions as to temperature and humidity." (16)

General Electric demonstrated prototype fluorescent lamps at the Illuminating Engineering Society's annual meeting in Cincinnati in September, 1935, at a dinner celebrating the centenary of the U.S. Patent Office in Washington, D.C., in November of that year, and at the American Institute of Electrical Engineering's annual meeting in 1936, though the company's publicists described these in restrained terms, as "a laboratory development of great promise." (17) After work by Philip Pritchard and his team on the precision manufacturing necessary to produce thin, coated, tubular bulbs and to fill these with a near-vacuum of argon and mercury vapor, GE announced in April, 1938, that fluorescent lighting's "efficiencies heretofore unobtainable" would reach the market that spring. Along with Westinghouse, they offered three sizes of lamps—18, 24, and 36 inches—

ranging from 15 to 30 watts. The new lamps' debuts at the World's Fairs in 1939 proved to be a sensation; the New York Times reported that thirty percent of the New York fairgrounds were illuminated by fluorescents offering a visual 'softness' and nuance that contributed to the Fair's signature 'Wellsian fantasy of color.' (18) Much of the Golden Gate Exposition's billion-and-a-half candlepower came from fluorescent lamps as well, in particular the soft pink light that bathed the 'Court of Reflections.' Public response was so enthusiastic that the three companies scrambled to increase production. GE obtained key patents in 1941 and along with its prime licensee, Westinghouse, saw sales increase from 200,000 units in 1938 to 1.6 million in 1939, 7.1 million in 1940, and 21 million in 1941. (19) Upstart manufacturer Sylvania pursued a parallel set of patents, spurring competition that reduced prices by 2/3, raised average lumens-per-watt across the industry from 35 to 50, and increased options in color and size, all by 1942. While GE and Westinghouse concentrated on the lamps themselves, Sylvania offered a "complete unit of light" to its customers, matching their lamps with fixtures that could manipulate, direct, or diffuse their output. (20)

World War II had two determining effects on the fledgling industry. While few of the materials needed for the lamps themselves were embargoed in the U.S., wartime restrictions on metal limited manufacturers' ability to supply fixtures. At the same time, rapid expansion of materiel production for the war effort brought with it increased industrial demand for illumination and here fluorescent lighting proved itself. Industry had already been an early adopter of fluorescent lighting. Large, open factory floors could take advantage of its efficiency, and its diffuse light meant that it required less elaborate fixtures to cast an even illumination over work areas. Perhaps most important, however, plant designers recognized that fluorescent lamps' cool operation matched the increasingly sophisticated climate control systems demanded of precision manufacturing. In 1940, the Austin Company matched one of the country's largest and most complex air conditioning systems with three-lamp fluorescent fixtures throughout General Motors' Allison aircraft engine plant in Speedway, Indiana, citing lighting load as a major factor in their cooling calculations. The factory's ambient temperature—held between 70°F and 78°F throughout the year—and its even, reliable illumination offered by the cooler, efficient fluorescent fixtures enabled "high-speed quantity production methods to the manufacture of airplane engines—which require many precise operations." (21)

Fig. 2. Austin Company's design for the Allison division of General Motors was among the first to use fluorescent fixtures throughout. Architectural Record, February, 1940. 91.

A nearly-contemporaneous factory, also designed by the Austin Company, for Simonds Saw in Fitchburg, Massachusetts, made this pairing explicit. A Carrier air conditioning system provided 400,000 cfm of conditioned air to areas as diverse as sales offices and a forge room. (22) While designers originally planned to illuminate production areas with 650-watt incandescent fixtures when first planned in 1931, a depression-related delay until 1939 made fluorescent lighting's efficiencies available to the project and the factory was ultimately outfitted with 1400 100-watt Cooper-Hewitt fluorescent tubes that provided an even 20 foot-candles throughout. (23) This "manufactured north light," a reference to the desirable, glare-free daylight that factory skylights are often designed to maximize, worked well enough that the entire Simonds complex was designed without windows, its thermal and visual environments both entirely artificial. “The scientific superiority of artificially controlled environment furnished the basis for designing this completely windowless plant,” reported Architectural Record. “Air, light, heat, humidity, and sound are all regulated to provide the best attainable working conditions for employees, and a maximum of efficiency in manufacturing processes.” (24) Simonds estimated that the combination of air conditioning and fluorescent lighting, along with improvements in acoustics, increased worker efficiency by 35%.

These benefits—cooler operation, diffuse illumination, and lower electricity consumption—made fluorescent lighting the system of choice for wartime factories. The Simonds example showed, too, that fully enclosed, windowless factories were feasible, an important design aspect when fears of Axis bombing raids led to blackout conditions at night. “One of the recent romances of American industry is the development of fluorescent lighting,” wrote Lester Smith of the Wall Street Journal in 1942. “Not since Thomas A. Edison invented the incandescent lamp has the art of lighting undergone as radical a change as that which has occurred in the past few years.” (25) Workers in factories during WWII enjoyed more than double the amount of illumination on their tasks as had those in WWI, and in some cases, the new lamps provided up to ten or twenty times the candlepower of previous installations. Ford’s plant at Willow Run used more than 100,000 fluorescent lamps, allowing greater levels of precision and faster production times on bombers manufactured there. “The brightest lights today aren’t found on dimmed-out Broadway,” noted the Journal. “They are in the arms factories where vastly improved illumination is helping war workers chalk up impressive production records.” (26) Some measure of fluorescent lighting’s value to the war effort can be seen in the shelving of persistent anti-trust complaints against GE by the Department of Justice in 1942; continued manufacture of lamps and fixtures was deemed critical by the military, and the case was only resumed in 1953.

Postwar introduction

Fluorescent lamps were limited to military production through the war, but their benefits were anticipated for residential and commercial use. When the war ended the lighting industry had a tremendous overcapacity, bringing costs down and forcing GE, Westinghouse, Sylvania, and other competing manufacturers to find new markets for lamps and fixtures. Manufacturers saw limitless potential in the energized postwar economy; industry produced nearly 41 million fluorescent lamps in 1945, but it also manufactured nearly 800 million incandescent lamps. (27) Department stores were quick to take advantage of the soft, soothing diffuse light of fluorescent fixtures and enthusiastic designers foresaw “handfuls” of “daylight” fluorescent lamps replacing the “dozens” of incandescent lamps in a typical American home. Residential adoption proved slower, but fluorescent lighting’s unique qualities and quirks of their geometry offered a powerful new approach to office lighting, matching radical changes in the way offices were being organized. While the “fireless light” made inroads in homes and stores throughout America in the 1950s, it was in offices, and especially high-rise offices, where it found its most robust market and its ideal architectural application.

Fluorescent lamps were accepted quickly for several reasons. Their efficiency, measured in watts of electricity per lumen of light, continued to improve, average lamp life increased, and prices came down as competition between manufacturers intensified. But their thermal efficiency made them, through a long chain of technical developments, ideally suited to open workspaces such as factories or open-plan offices. Crucially, their lower operating temperatures gave fixture designers a broader palette of materials. Incandescent lamps’ high bulb temperatures limited the materials that could be used to shade, focus, or diffuse their intense output. A glass globe could diffuse an incandescent lamp's brightness, but glass was heavy and expensive, and a globe trapped and converted more of the lamp's luminous energy into heat. More efficient louvers or baffles had to be fabricated from materials that could handle constant high temperatures. Glass and metals formed the basic material vocabulary for luminaires throughout the early 20th century, but material science in the 1930s offered new possibilities, in particular plastics. Here, the heat from incandescent lamps proved limiting; thermoplastic resins such as Bakelite, acetate, and polystyrene soften and deform at temperatures ranging from 127°F to 212°F—polystyrene's melting point is 248°F, just below the bulb temperature of a tungsten filament lamp. Thermosetting plastics such as melamine and acrylic can withstand higher temperatures without softening, but here, too, the high heat of incandescent lamps creates issues such as discoloration and brittleness; even acrylic has a service temperature of just 195°, making it unsuitable for incandescent luminaires. (28)

Architectural Record recognized the potential for plastics within cooler fluorescent luminaires in 1939:

"Plastics are lighter in weight than glass or metal, permitting savings in structural details, and greater safety in the use of overhead fixtures. They are less breakable than glass and less likely to crack from sudden temperature changes. Thickness, color, and shape can be controlled with precision, and optical characteristics can be varied to suit requirements as to transmission, reflection, and diffusion; but they are not practical for control by refraction. Some plastics can transfer light by internal reflection, like diffused quartz. The use of plastics with the larger filament lamps and with electric discharge sources is still limited because of inability to withstand the temperatures developed. They will probably be used more widely with the cooler fluorescent lamps." (29)

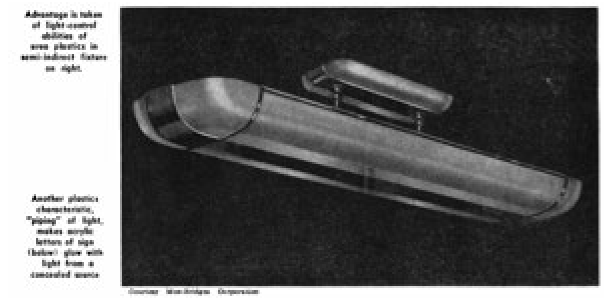

Fig. 3. Scientific American *was among the first to report on the possibilities of plastic in diffusing and directing the cool light of fluorescent lamps. "Partners in Light,"* May, 1946, 199.

Manufacturing technology for plastics developed during the war increased the range of possibilities in lighting design. By 1946, Underwriters Laboratories determined that "polystyrene and…other slow burning plastics" were suitable for use in fluorescent lamp fixtures. Thermoplastic materials offered great versatility. They could be produced in a range of opacities and could be molded or extruded into more precise, complex shapes than glass. This presented opportunities not only for shades and louvers, but also for lenses and diffusers that could take the place of the heavy, thermally massive glass globes that had surrounded incandescent lamps. Acrylic louvers and diffusers were matched by aluminum louvers and reflectors. Both materials were lighter and, after the war, less expensive than glass or steel. Scientific American predicted that plastics would "guide, blend, transport, and control light" in ways that would "be a stimulus to production, worker morale, and safety." (30) At the International Lighting Exposition in Chicago the next year, where fluorescent fixtures of all kinds demonstrated the surge of new applications and public acceptance of the new diffuse, cool light, exhibitors told the Chicago Tribune that "Plastics have largely replaced glass in fluorescent fixtures."

Plastics were critical in developing strategies for visual comfort in open work areas because of the lingering problem with glare from exposed lamps. While fluorescent lamps spread their light output over a greater area than incandescent lamps—a reduction of nearly 98% in direct foot-candles, according to one source—they remained too bright for office tasks. Such "light out of place" had been acceptable in factory installations where workers moved around, but for continuous visual tasks even minimal glare was deemed distracting and inefficient. Lighting designers addressed this by manipulating fixture locations relative to the ceiling and tuning fixtures to distribute some lamp light upward, recruiting bright white ceiling surfaces as giant reflectors. This indirect approach could be supplemented by louvers that blocked direct light at angles—suggested by experts to be anywhere from 15° to 45°--but that permitted light to directly illuminate surfaces below. This worked well in theory, since diffuse background lighting reduced eyestrain for more intensely-illuminated visual tasks, but in practice it proved difficult to balance the quantity of light emerging from the tops of fixtures with that directed downward. Research in the late 1930s suggested that, while a ceiling that was half as bright as the work surface would be most comfortable, louvering the bottom of a fixture and allowing lamps to illuminate the ceiling produced lighting levels there that were up to fifteen times brighter than desks below. (32) This was a consequence of simple room geometry; fixtures suspended from above needed to be placed well above head height, and building economics limited the potential for ceiling heights tall enough to balance interior lighting. In typical offices with ceiling heights of less than 10'-0", a light located at the accepted minimum for headroom, 6'-8", would be closer to the ceiling than to a 29"-high desk, and would therefore illuminate the ceiling more intensely. This imbalance was worsened if ceiling heights were lower, and high-rise construction, where every inch of building height is critical, placed particular pressure on these dimensions.

Luminaire design thus balanced several factors: preventing direct glare, balancing direct and indirect illumination, distributing light over work surfaces, and limiting impact on room cooling loads. Manufacturers responded with dozens of new fixtures that worked with fluorescent lamps' narrow, tubular geometry. While manufacturers and consumers had "become…accustomed to circular-shaped lighting equipment," the new lamps' long, narrow proportions, determined by the need to limit the distance from activating mercury vapor to fluorescing phosphorescent coating, created "more dominantly linear" solutions that suggested "lines of light," rather than points. (33) Fixtures incorporated reflecting and diffusing elements that could be extruded along the lamps' lengths, matching industrial processes of manufacturing plastics to the linear nature of the tubes themselves. Distribution of their light thus became a geometrical exercise in cross section, and a louvering or shielding one longitudinally. Aluminum, when polished, provided a lightweight, thin reflective surface that could be bent into precise parabolic shapes to focus light. It could also be cut into shading blades. Plastics such as acrylic could be molded or extruded into lens-like or prismatic patterns that could diffuse a tube's light evenly over a flat surface. Aluminum was lighter and allowed more specular surfaces and tighter detailing than steel while plastic matched aluminum's light weight with a range of opacities and colors that surpassed that of glass. Manufacturers began producing fixtures tuned to mounting locations below and within ceilings that either diffused or concentrated light in reliable patterns along their axes.

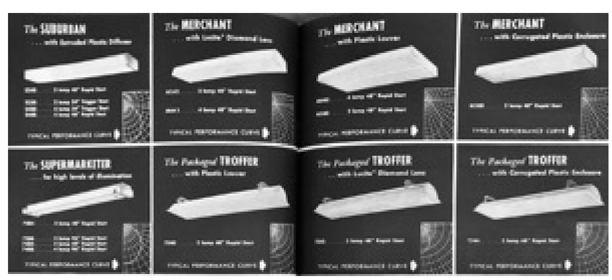

Fig. 4. The combination of easily extruded and molded plastic with the linear, diffuse nature of fluorescent lighting led to new fixture types that could be easily matched to the needs of new, open plan offices. Miller Company advertisement, Architectural Record*, May, 1955. xi.*

Standardized charts and tables of light distribution for individual fixtures enabled designers to accurately assess how many foot-candles could be thrown onto work surfaces or ceilings at varying angles. Lighting design became more of a science than art, with precise, predictable effects that could be obtained through a growing array of aluminum and plastic fixtures that focused, diffused, baffled, or concentrated light from fluorescent tubes.

The resulting precision was matched by a huge array of architectural possibilities. Linear fixtures could be arrayed in coves or cornices, for instance, providing even lighting over ceiling and wall planes. Attention focused, however, on the use of "troffers," or flush-mounted ceiling units that combined a "trough" fixture with the intent of "coffer" lighting to provide an illuminated ceiling. These units could be arrayed in linear ranks across open offices and tuned, with lenses, reflectors, or adjustments in how many lamps each contained, to provide ideal background and task lighting along work surfaces and surrounding walls. Their regular march provided ceilings that were bright but comfortable, a key factor in the diffusion of the open plan offices and integrated, 'power membrane' ceilings that became trademarks of the next decades.

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29 "Trends in Light Sources," in "Design Trends: The Control of Light." Architectural Record, Sept., 1939. 84.

30 "Partners of Light." Scientific American, May, 1946. 197-200.

31 "Exhibit More Fluorescent Light Fixtures." Chicago Daily Tribune, Nov. 4, 1947. 30.

32 "The Control of Light," op. cit., 79.

33 Amick, op. cit., 108.

Expanding Strategies towards Architectural Design and Building Technology Integration

Carolina Manrique
University of Idaho

Abstract

Our architecture program mission statement establishes that we "value design excellence centered in the poetic merging of the arts and technology". This objective frames current curriculum and pedagogical strategies being implemented which aim to integrate the building technology sequence with architectural design studios at key moments in our undergraduate and graduate programs. Described as a "multifaceted integration model" in a recent publication by the author, a summary of strategies focused on our undergraduate Bachelor of Science in Architecture degree program was presented. These included introducing design thinking in materials and methods and the structural systems one-year sequence, integrating structures and building assemblies in design studios, industry partnerships to enhance courses, and research initiatives at the program and college levels.

This paper takes a more in depth look at the specific initiatives developed to expand curriculum and pedagogical strategies aiming towards better integrating and coordinating the Integrative Design Studio and the Technical Integration Seminar in the first semester of our NAAB-accredited Master of Architecture degree program. Both courses are taught during the same semester at each of our campus locations. Changes in faculty teaching the courses have provided a varied set of approaches and resources introduced to recent generations of students. Challenges and opportunities of delivering the two courses and their relationships as co-requisites are discussed. Collaborations among faculty teaching these courses in each location (or both through distance learning) have explored focused areas as themes for the design projects such as mass timber structures and assemblies, or lighting and green design strategies.

This paper describes the integration strategies implemented in our curriculum and pedagogical approaches, collaboration models between faculty, initiatives engaging industry and academic research partnerships to strengthen theme-based directions in our courses and program (e.g. wood), and ongoing discussions on learning outcomes and evaluation criteria at this level.

Keywords: Pedagogy, Curriculum, Assessment, Integrated Architectural Design, Technical Integration

Introduction

Curriculum and pedagogical strategies are being implemented in two courses in our NAAB-accredited Master of Architecture (M.Arch) degree[1] program at University of Idaho: Arch553-Integrated Architectural Design and Arch568-Technical Integration in Design. These strategies aim towards bridging the gap between architectural design and building technology courses at the graduate level. Strategies implemented in our undergraduate program were discussed in a recent publication (Armpriest & Manrique, 2017)[2].

Our Architecture Program offers three M.Arch degree tracks. A seamless BS.Arch Bachelor of Science (4-years) and Master of Architecture (2-years); a 2+ M.Arch (summer studio plus 2-years) for BS. Arch or BA. Arch Degree holders; and a 3+ M.Arch (summer plus 3-years) for BS or BA Degree holders. Arch553-Integrated Architectural Design and Arch568-Technical Integration in Design are offered as co-requisites in the first semester (fall) of the academic year in the first, second and third years of each program (table-1).

Table 1 Arch553 and Arch568 in M.Arch degree tracks (fall)

B.S. + M.Arch	Seamless	G-1 year
2+ M.Arch	BS. Arch or BA. Arch Degree holders	G-2 year
3+ M.Arch	BS or BA Degree holders	G-3 year

In addition to efforts for bridging the gap between architectural design and building technology courses, on-going discussions addressing assessment requirements at the university level are being used to identify (measurable) student learning outcomes.

In our current draft (February, 2019), "Design Integration Skills" has been identified as a learning outcome in our M.Arch program where students will demonstrate "effective design synthesis skill, including the integration of material, structural, environmental control, and other building systems"[3]. This learning outcome has been identified as to be measured in both our Arch553-Integrated Architectural Design and Arch568-Technical Integration in Design courses. Specific methods for measuring this learning outcome are also being discussed. The development of a Studio Evaluation Form is being proposed for Integrated Architectural Design and course evaluations/grading for measurements in Technical Integration in Design.

As a recent faculty in the architecture program at University of Idaho (joined in fall 2015) I have been interested in recognizing the variety of methods used by faculty and the opportunities for collaboration (internal and external). This exercise constitutes an internal (and personal[4]) critique and assessment of ongoing efforts towards architectural design and building technology integration in our graduate program. This first stage towards developing an integration framework in our graduate program aimed to document these efforts (otherwise lost due to faculty turnover), and identify and discuss key lessons suggested.

Expanding strategies towards architectural design and building technology integration

The strategies toward architectural design and building technology integration discussed in this paper are used to document pedagogical approaches explored by individual faculty and some collaborations which have been developed through common interests in spontaneous ways. Strategies are organized by addressing two goals:

The first goal, "strengthening theme-based design studios", aims towards developing topics that enhance our presence as architects addressing key aspects in our community and region. For example, a key theme refers to the re-emergence of the use of timber and manufactured wood structural products in recent years.

The second goal, "reinforcing design thinking", aims towards developing approaches that contribute to "activate the disciplinary power of architecture" which requires going beyond the "tendency of looking to science to substantiate design and design research" (Teal, 2018)[5]. This goal is targeted to prepare students in their first year of our NAAB-accredited Master of Architecture degree program for more advanced work developed through the Graduate Project Seminar.

Table 2 Summary of Integration Strategies in the Master of Architecture (Integrated Architectural Design and Technical Integration)

Goals	Strategies	Tactics
1-Strengthening Theme-based design studios	a) Developing and expanding internal collaborations	Full integrations
		Collaborative integrations
		Explorative integrations
	b) Developing and expanding external collaborations	Expanding presence of current partnerships
		Expanding connections with Industry to enhance field trips
		Expanding sponsorships through existing partnerships
		Expanding network through existing partnerships
2-Reinforcing Design Thinking	a) Expanding references	Exploring connections to the 'poetic' nature of tectonics
	b) Calibrating precedent studies	Integrating through precedent studies
		Enhancing field trips
	c) Introducing design thinking to building technology courses	Using a design challenge approach in Technical Integration

1. Strengthening theme-based design studios

Wood and light are selected as two themes that have been used recently by faculty in our Integrated Architectural Design studios and relate to priorities in our program. These themes have triggered opportunities for developing and expanding internal and external collaborations requiring to revise course objectives and learning outcomes, and refine exercises and experiences (e.g. field trips).

a) Developing and expanding internal collaborations:

The Internal collaborations discussed below (full, collaborative and explorative) refer to opportunities between faculty and resources in the architecture program, and other programs at University of Idaho.

An example of a full integration between Integrated Architectural Design and Technical Integration in Design was developed when one faculty was in charge of both courses. In fall 2012, the Integrated Architectural Design studio was sponsored by the Idaho Forest Products Commission (IFPC) to develop a design competition exploring "design opportunities using Idaho wood species (solid wood or manufactured wood products)" (Armpriest, 2012)[6].

In addition to the seamless integration between both courses and the development of the partnership with IFPC (which would extend until today through a design competition in our third year undergraduate studio), the competition worked with the College of Natural Resources to define the topic of the design challenge: The Pitkin Nursery Learning Center, a building for their forest nursery and seedling research facility. In 2013 this project was designed and constructed by Patano Studio winning AIA and National Green Building awards in 2014 and 2015 respectively (Patano Studio Architecture, 2017)[7]. The model used for this competition was translated to the undergraduate level from a full semester to a half of a semester duration (8-weeks).

The full integration model provided a convenient way of guaranteeing co-requisites working well together. At some point it was discussed in our program creating a full 9-credit course merging Integrated Architectural Design and Technical Integration to oblige this model for future semester programming. One challenge identified to implement this approach was that it would reduce the flexibility in the distribution of courses among faculty. In our program flexibility is a key aspect. Every faculty is able to teach design studio at both graduate and undergraduate levels, in addition to lecture-based courses in their area of expertise. Furthermore, increasing flexibility needs are being required to cover the delivery of courses in both campus locations (Moscow and Boise, Idaho).

An example of a collaborative integration between Integrated Architectural Design and Technical Integration was developed in fall 2018 when both faculty in charge of these courses decided to agree on discussing and sharing points of convergence during the semester.

Integration between a structures faculty (Manrique, 2018)[8] and a construction and building assemblies faculty (Armpriest, 2018)[9] who had previously worked collaboratively in the third year undergraduate Architectural Design studio developing two competitions sponsored by the Idaho Concrete Masonry Association (ICMA) and the Idaho Forests Products Commission (IFPC). This previous experience of working together, which started in fall 2015, allowed for an easier communication and agreement in key coordination aspects such as cross-themed selection of case studies in Technical Integration focusing on wood as a theme to be developed in Integrated Architectural Design, and final submission requirements being complementary (e.g. wall section model developed from the final project). Challenges in this model were mostly related to registration issues such as students not taking both courses at the same time (courses are defined as co-requisites but not enforced). This generated clear differences in the Integrated Design Project outcomes making visible gaps in building technology topics provided in the Technical Integration course.

Some efforts towards implementing this collaborative integration model were explored in fall 2018 between two faculty teaching the Integrate Architectural Design course in both or Moscow and Boise locations, and faculty teaching Technical Integration from Boise for both campuses (online to Moscow). Most of the conversations focused on sharing general information (e.g. syllabus, general schedule and first project descriptions) in order to coordinate general topics between co-requisites. Despite the interest in sharing information between faculty, the distance between campus locations did not promote a natural opportunity for further discussions during the semester. However, through sharing exercise briefs and following up with students taking both courses key information was gathered.

An example of an explorative integration refers to opportunities initiated by faculty teaching Integrated Architectural Design in our Boise campus using “light” as a theme. This theme, defined in the class syllabus for fall 2018 as “an art for mapping and detailing light” (Montoto, 2018)[10] encouraged students to use resources and design tools from our Integrated Design Lab (IDL)[11]. This opportunity was enabled by having the IDL Director at the time teaching the Technical Integration course for both Boise and Moscow campus locations (Cooper, 2018)[12].

Challenges related to these integration model are tied to facilities not being close enough to stimulate the use of resources. For the students in Boise, the IDL is located in a different building. The building is not far away but only students directly involved in projects (e.g. as research or teaching assistants) access the facility regularly. For the students in our campus in Moscow (295 miles away), the connection with IDL is mostly as an online reference. Opportunities to encourage this integration model are currently being discussed. For example, increasing the teaching role of the IDL Director will contribute for students in the Boise campus to perceive the resources in this facility as available and approachable. As delivery of distance courses from Boise to Moscow increase and improve, the use of online resources and communication will encourage a more seamless approach. Faculty teaching environmental systems in our main campus location have also explored "light" as a theme and use the Daylighted Artificial Sky project, built in our architecture building, as a resource for design studios and building technology courses (Haglund, 2019)[13].

b) Developing and expanding external collaborations:

External collaborations refer to opportunities to develop new and expand existing partnerships between our programs at University of Idaho and Industry.

Expanding current partnerships: Student work examples when our Idaho Forests Products Commission (IFPC) competition was held in our Integrated Architectural Design graduate course (Armpriest, 2012) suggest evaluating if this is a better level for this experience. This competition was moved to our second-half of the semester in our third-year undergraduate program. Expanding the collaboration would suggest proposing to develop a second competition in order to expand wood as a theme in both our undergraduate and graduate programs. A possible collaboration with the competition held at the graduate level can be discussed with our structural engineering program which started to offer a "Timber Design" course in fall 2018 and developed, for the first time the same semester, a "Best of Idaho Wood" Engineering Design Awards competition (IFPC, 2018)[14].

Other opportunities include expanding connections with Industry to enhance theme-based field trips. In spring 2018 the Integrated Architectural Design studio explored wood as a theme (Manrique, 2018) and developed a visit to exemplar wood buildings (e.g. Kengo Kuma & Hatcher, Portland Japanese Garden) and architectural firms at the forefront of development in the use of this material (e.g. Lever Architecture at Albina Yard). Expanding sponsorship through existing partnerships can reinforce theme-based studio approaches (e.g. funding field trips for students), and research work to enhance courses (e.g. research assistant sponsorships). Other possibilities include expanding our network through existing partnerships (e.g. Woodworks through our IFPC contacts).

2. Reinforcing design thinking

Three strategies aiming to reinforce design thinking are discussed: expanding references, calibrating precedent studies, and introducing design thinking to building technology courses.

a) Expanding references:

Typical references used in our design studios aim towards bridging the gap between architectural design and building technology (e.g. Allen's Studio Companion, Ching's Building Construction and Structures Illustrated, etc.) which are known by students who are coming to our graduate program from an undergraduate program in the United States. Some of these references are not known by students coming to our master program from abroad so our Integrated Architectural Design and Technical Integration courses have the role to introduce these references. References used in Technical Integration (Cooper, 2018) include "Architectural Detailing" (Allen & Rand, 2016)[15], "Integrated Buildings: The System Basis of Architecture (Bachman, 2003)[16] and "Integrated Design in Contemporary Architecture (Moe, 2008)[17]. In addition to these resources, "The Architectural Detail" (Ford, 2011), was a reference used in the two

Integrated Architectural Design sections, in both Boise and Moscow locations, and in Technical Integration. This reference was required as an effort to stimulate more advanced understandings of the role of details and tectonic expression in the design process. References such as "Model Perspectives: Structure, Architecture and Culture" (Cruvellier et al., 2017)[18] and "Introducing Architectural Tectonics: Exploring the Intersection of Design and Construction" (Schwartz, 2017)[19] are currently being considered to explore further connections to the 'poetic' nature of tectonics.

b) Calibrating precedent studies:

Both Integrated Architectural Design and Technical Integration use precedent studies as key exercises. The example in figure-1 illustrates connections explored in Project-1 "Study on the Architectural Detail" (first image in figure-1) and structural model and rendering of an interior view for the final project (second and third image in first row of figure-1). This exercise was developed in previous editions of the Integrated Architectural Design and was shared as part of the collaborative integration effort described previously so it was used as the starting project in both our Boise and Moscow locations (fall 2018).

The exploration through this first project in our Boise campus focused on examining "the detail material systems of a prominent building; identifying its design vocabulary based on how it maps light through architectural detailing" (Montoto, 2018)[20]. In our Moscow location the purpose was using a "well-known building precedent, where wood is the main material used for the structural system, in order to study the way in which design goals were achieved through the development of construction systems integration and detailing" (Manrique, 2018)[21]. Detail design drawings and models (1/2"=1'-0" scale) were required to demonstrate an understanding of designed goals and observed architectonics of the precedent used. "The Architectural Detail" (Ford, 2011) was a required reference in this process.

Initiating the Integrated Architectural Design course with this first project provided a solid starting point for students. One aspect referred to acknowledging the level of detail that would be required for the final project. From simply recognizing the various information to be developed at each scale to establishing an understanding of the rationale their projects should demonstrate. Another aspect referred to getting familiar with the theme of the project (e.g. light or wood) through rigorous research and observation. As an assessment tool, the exercise also provided keys to understand the variety of knowledge students arrive to the course from their diverse undergraduate backgrounds (e.g. design communication skills, building technology).

c) Design thinking to building technology courses:

A design challenge approach was used in Technical Integration in fall 2018 (Cooper, 2018). The examples shown in figure-2, student work for "Research Assignment Five", required a composite drawing using design from the concurrent (or previous)
Integrated Architectural Design project demonstrating the integration of several systems (e.g. envelope, structure, etc.) through various simultaneous points of view (e.g. plans, sections, perspectives, etc.).

This approach would require further coordination between both co-requisite courses due to the risk of student work being used twice (especially if both courses are in different locations). However, in the last experience (fall 2018) most of the work showed to be complementary for students enrolled in both courses, and contributed to advance in their final projects.

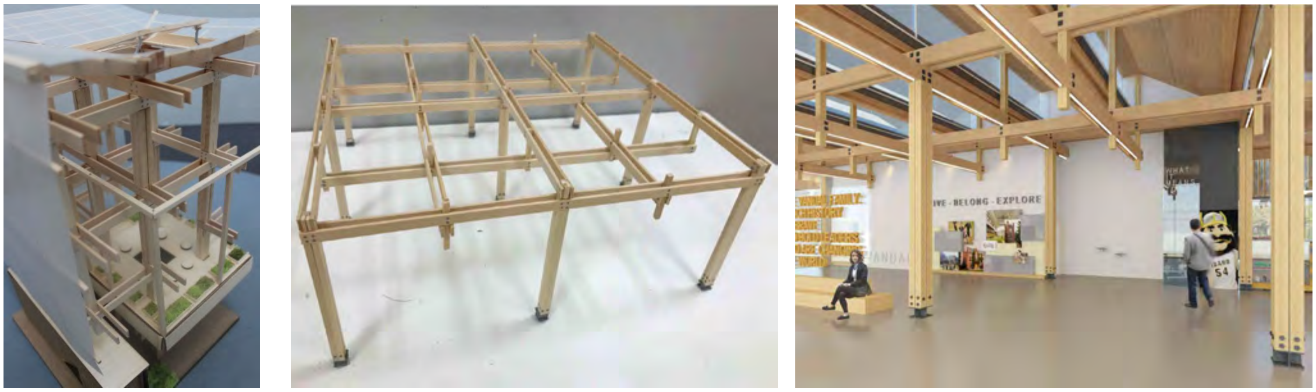

Fig.1 Examples of student work (Swager, D.) Project-1 (1), final project (2, 3) in Integrated Architectural Design (Manrique, 2018).

Fig. 2 Examples of student work (1-Belnap, R. and 2-He, S.) from Technical Integration for Assignment-5 (Cooper, 2018) based on work developed for Integrated Architectural Design from Montoto (2017) and Manrique (2018).

Conclusion

This paper summarizes some of the strategies implemented and identified towards Architectural Design and Building Technology Integration in the first year of our Master of Architecture professional degree. Some to these strategies and the possible ways in which they have an effect in our students can be traced in explorations done during the last year of our Master of Architecture program. An example is illustrated in the student work below (figure-3).

Relationships between architectural technology and design process where explored through an architectural detail precedent study and the development of a main project in Integrated Architectural Design in fall 2017. Means of exploration such as the use of physical models used in this course were taken further in the process of defining a thesis project in the Graduate Project Seminar in fall 2018. The topic started by proposing a study into the effects and possibilities of architecture that defies “tectonic expectations” (Belnap, 2018)[22].

Physical models (and the angles in which they are documented through photographs) are used for exploring ways to express the use of materials that seem in opposition to basic understandings, and for studying precedents that suggest “deceptive methods” to achieve a design goal. For example, the physical model developed for the Sainsbury Center for Visual

Arts (Norman Foster), and the photograph showing only part of the frame, is used to study the deceiving role of "the detailing strategy" of vertical glass mullions reading as non-structural (Ford, 2011:70)[23]. Ford's "The Architectural Detail", introduced in Integrated Architectural Design as a required reference, became the main source for initial understandings and selection of precedents for further studies.

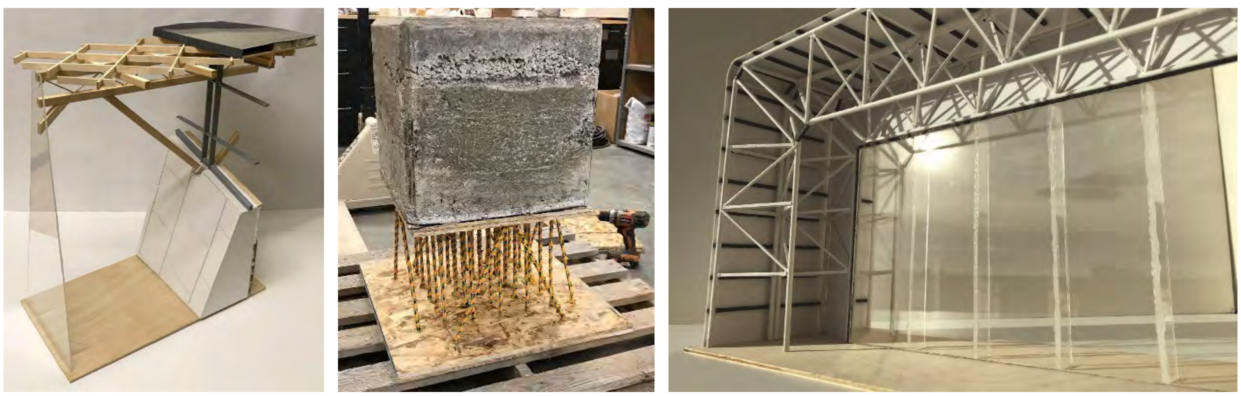

Fig.3 Examples of student work by Ryker Belnap from 1-Architectural Detail model for Integrated Architectural Design (Montoto, 2017), 2- "Concrete in Tension" model for Graduate Project Seminar (Teal, 2018)[24] and 3- "Sainsbury Center for Visual Arts" model for the Graduate Project Studio, coordinated by Randall Teal (2019)[25] with Carolina Manrique (2019)[26] as major professor.

One of the main challenges towards integration efforts, in general, is being able to track the process of students' work throughout the different courses in order to identify connections and potentialities. Providing the example of the student above has required tracing back the process from which his current graduate project topic emerged. Where did these connections suggested by the student come from? What triggered each of the steps? (e.g. an author, an exercise, a lecture, a conversation, etc.). In other words, what other strategies should we implement to trigger more creative integrations? Through the process of tracking back the work of this student and gathering the information of course guidelines and other work examples provided both by faculty and students has provided valuable information on methods and references.

Tracking these efforts establishing the opportunities towards integration also contributes to minimize the loss of continuity of positive approaches due to faculty turnover. Two faculty providing information from their courses for this paper are no longer in our program (one retired and the other is pursuing a PhD program abroad), and a third will leave at the end of spring 2019 to another institution. This paper serves the purpose of documenting some of the valuable efforts for further improvements to be developed by remaining and new faculty taking over these courses in the future.

Some of the opportunities towards integration strategies include minimizing the divide between knowledge areas. Our program makes a good effort in having all architecture faculty teach design studios in addition to lecture-based courses in their area of expertise. Most faculty also teach both in undergraduate and graduate levels, and participate in each other's reviews. This interaction has allowed to understand how others are approaching their courses and have provided important feedback to improve processes and outcomes.

Key feedback usually comes with reference to specialized resources that faculty in their area of interest keep track off. For example, a faculty specialized in building performance recommends a textbook from Kiel Moe as required for the Technical Integration course[27]. Increasing collaborations with our program, with other programs in our college and the university, as well as expanding current partnerships with industry, will provide access to more technical and design resources for both faculty and students. Access to these resources are key to strengthen our theme-based design studios.

Other opportunities for more seamless integration efforts are related to the increasing use of references in courses that bridge the gap between architectural design and building technology. Some of the references used in our undergraduate structural system courses include "Form and Forces" (Allen, 2009)[28] and "The Structural Basis of Architecture" (Sandaker et al., 2011)[29]. Other references used in our structural systems courses are also required in architectural design studios coordinated at the same level such as "The Architect's Studio Companion" (Allen & Iano, 2017)[30] and "Building Structures Illustrated" (Ching et al., 2014)[31]. These textbooks are usually recommended in graduate architectural design studios in addition to more advanced readings aiming to provide further understandings of architectural technology and its relation to the design process. Other references suggesting opportunities for increasing integration efforts explore intersections of design and construction (Schwartz, 2017)[32] and relationships between "structures and the form and spaces of architecture" (Cruvellier et al., 2017)[33]. Expanding these references will contribute for reinforcing design-thinking as a goal.

Notes

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A Framework for Performance-Based Facade Design: Approach for Multi-Objective and Automated Simulation and Optimization

Mahsa Minaei, Ajla Aksamija
University of Massachusetts, Amherst, MA, United States

Abstract

Buildings have a considerable impact on the environment, and it is crucial to consider environmental and energy performance in building design. In this regard, decision-makers are required to establish an optimal solution, considering multi-objective problems that are usually competitive and nonlinear, such as energy consumption, financial costs, environmental performance, occupant comfort, etc. Sustainable building design requires considerations of a large number of design variables and multiple, often conflicting objectives, such as the initial construction cost, energy cost, energy consumption and occupant satisfaction. One approach to address these issues is the use of building performance simulations and optimization methods.

This paper presents a novel method for improving building facade performance, taking into consideration occupant comfort, energy consumption and energy costs. The paper discusses development of a framework, which is based on multi-objective optimization and uses the genetic algorithm in combination with building performance simulations. The framework utilizes EnergyPlus simulation engine and Python programming to implement optimization algorithm analysis and decision support. The framework enhances the process of performance-based facade design, couples simulation and optimization packages, and provides flexible and fast supplement in facade design process by rapid generation of design alternatives.

Introduction

Buildings account for about 40% of the global energy consumption and contribute over 30% of the global carbon emissions [14]. Energy used in building sector for heating, cooling and lighting comprises up to 40% of the carbon emissions of developed countries [14]. A large proportion of this energy is used for meeting occupants' thermal comfort in buildings, followed by lighting. The building facade forms a barrier between the exterior and interior environments, and has a crucial role in improving energy efficiency and building performance. Therefore, this research focuses on performance-based facade design, appropriate simulation and optimization tools and methods for design analysis and support.

Building performance simulation (BPS) provides relevant design information by indicating potential (quantifiable) directions for design solutions. BPS tools and applications facilitate the process of design decision-making by providing quantifiable data about building performance. BPS tools are an integral part of the design process for energy efficient and high-performance buildings, since they help in investigating design options and assess the environmental and energy impacts of design decisions [1]. The important aspect is that simulation does not generate design solutions, instead, it supports designers by providing feedback on performance results of design scenarios.

Optimization is a method for finding a best scenario with highest achievable performance under certain constraints and variables. There are different methods for optimization, requiring use of computational simulation to achieve optimal solution, or sometimes requiring analysis or experimental methods to optimize building performance without performing mathematical optimization. But in BPS context, the term optimization generally indicates an automated process that is entirely based on numerical simulation and mathematical optimization [13]. Integrating BPS and optimization methods can form a process for selecting optimal solutions from a set of available alternatives for a given design problem, according to a set of performance criteria.

This paper first focuses on identifying the role of BPS and design optimization methods, and outlines potential challenges and obstacles in performance-based facade design. This part is primarily based on literature reviews. Then, a new framework for performance-based facade design is presented. This framework takes into account occupant comfort and energy cost optimality, and implements BPS and relevant optimization methods to achieve a proper process for performance-based facade design. The components and development of the framework are discussed in detail. The last part of the paper offers conclusions and presents steps for testing and validating this framework.

Literature Review

There are many existing studies that provide literature reviews about whole building performance simulations and optimization methods. In this research, building facade was selected because of its influence on energy consumption, thermal and visual comfort of occupants. The literature review focuses on the role of BPS, optimization and tools, applications and methods in facade design.

High performance buildings require an efficient performance-based design process that integrates optimization methods into building performance simulations. Coupling simulation tools and optimization algorithms are aimed at removing the existing barriers between optimization and building simulations. Efforts to implement some optimization algorithms into EnergyPlus simulation program have been conducted [17]. Another effort aimed to develop ArDOT program to automate the coupling of existing simulation engine (EnergyPlus) with formal optimization method through neutral data standards [13]. An effort to develop a zero energy building design tool that facilitates the use of building performance simulation in early design stage in hot climate has also been conducted [1].

Role of Building Performance Simulations in Different Stages of Facade Design

The role of simulations in design process has evolved, and simulation models are used in different design phases to predict energy consumption and comfort levels of buildings. These methods are used at the conceptual, schematic and design development phases to optimize building performance, during the occupancy phase to monitor and control the performance and during the retrofit to decide about the benefits of different alternatives and interventions. Therefore, understanding the effects of design decisions and outlining a framework in which the simulation models should be used is crucial to achieve high levels of performance.

Simulation is an integral part of measuring and quantifying performance criteria. Defining the interface between physical building element and performance criteria plays an important role. For instance, the existing building or the reference building (i.e., in case of new construction) can be defined in BPS software programs, including thermal envelope and the HVAC systems, operation, schedules, material properties, etc. Then, the parameters that most affect the energy performance can be identified as design variables, such as different materials, efficiencies of HVAC system, characteristics of thermal envelope, etc.

The biggest challenge of simulation in performance-based design is to provide a variety of normative calculations when an advanced simulation cannot provide a more accurate answer, either because of the presence of uncertainties, the lack of available information, or the context of decision that demands it [9].

Computational building performance modeling and simulation is multidisciplinary, problem oriented and wide in scope. Simulation is one of the most powerful analysis tools for a variety of problems, but it does not provide solutions or answers, instead it supports user understanding of complex systems by providing (relatively) rapid feedback on the performance implications of design scenarios [2].

Role of Optimization in Facade Design Process

There are several methods that can be used to improve building performance, and to achieve an optimal solution to a problem. For example, computer building models can be created by repetitive method, constructing infinitive sequences of progressively better approximations to a solution. These methods are known as “numerical optimization” or simulation-based optimization [8]. For example, one study focused on optimizing building engineering systems, where the direct search method in optimizing HVAC systems was used [10].

In conventional optimization study, this process is usually automated by the coupling between a building simulation program and an optimization engine, which may consist of one or more optimization algorithms or strategies [1]. Genetic Algorithms (GA) are well suited to solve multi-objective optimization problems. GA-based multi-objective optimization methods that are frequently used in building research include Multi-Objective Genetic Algorithm (MOGA) and Niched Pareto Genetic Algorithm (NPGA). These methods aim to produce subset of the optimal set, from which decision-makers can select the most appropriate solution to the problem at hand.

One of the earliest studies used multi-objective optimization in building design and performed a Pareto optimization using dynamic programming [7]. Objective functions included thermal load, daylighting, usable area and cost, and the variables covered massing, orientation and construction. The authors provide an important concept of Pareto optimality applied to building design by calculating process and optimization method. It is shown that computational feasibility depends on the ordering of stages in the formulation to minimize the dimension of Pareto sets [7]. Other study shows that fenestration and its design have a significant impact on the energy use associated with the artificial lighting, heating and cooling of a building [15]. This study described an approach in which a building facade is divided into a number of cells, each cell having one of two possible states, a solid wall construction, or a window. GA search method was used to optimize the state of each cell, selecting a desirable number or aspect ratio of the windows while minimizing building energy use [15]. In other study, a GA was combined with human judgment to minimize energy use. It presented both optimal and near optimal design in visual manner, and enabled users to choose based on their preference [5].

Another study used a GA to minimize energy use; where authors varied thermal conductance and thermal capacity for each zone in model [3]. Presentation of both optimal and near optimal designs in a visual manner enabled the user to choose, based on preference that need not be formalized as constrains or objectives [11]. The study brought “virtual enclosure” concept that describes the building skin based on thermal and visual properties. In this approach, multiple actual realizations were used to map a single virtual enclosure and allow optimization algorithm to solve only the core underlying problem, without conflicting information relating to its realization.

Tools, Applications and Methods

Providing an overview of BPS tools and the methods to quantify the objectives (performance criteria) in design process is important, since designers need to choose appropriate and efficient methods among several number of available approaches. The core tools in the building energy field are the whole-building energy simulation programs, which provide users with key building performance indicators, such as energy [4].

A large number of BPS tools currently exist, and these tools can evaluate many aspects of building performance, such as capital and operating costs; energy performance and demand; human comfort, health and productivity; illumination; electrical flows; water and waste; acoustic design; renewable energy; and atmospheric emissions [4]. Because the number of simulation tools are large, this research focuses only on human factors, energy performance and energy cost.

BPS tools have essential role in the process of building design to achieve energy performance, environmental impacts, cost and etc. Number of simulation engines exist and are often used in different stages of building design process, but out of 406 BPS tools, less than 19 tools are for building performance optimization [13]. According to existing surveys and interviews with professionals, users and participants, findings reveal that Matlab toolbox and GenOpt are effective optimization tools, and the most used simulation tools are EnergyPlus and IDA ICE, followed by TRNSYS and Esp-r [1].

Optimization tools for building design can be divided into three categories: custom programmed algorithms, general optimization packages and special optimization tools for building design. First category requires advanced programming skills and the main benefit is flexibility. Second category often includes a graphical user interface, and consists of many effective optimization algorithms and capabilities. In this category, a commonly used optimization tool is GenOpt, which is a generic optimization program. In order to automate simulations and comparison of several design building variables, a number of researchers have coupled energy simulation tools with optimization techniques through self-produced tools, commonly based on MATLAB [12], or other dedicated software [16].

Current Gaps in Research and Literature in Performance-Based Design of Facades

A limited number of studies have focused on the performance-based design process for building facades which integrate simulations and optimization methods. There is lack of workable framework that implements both simulation analysis and optimization methods for facade design, taking into account performance criteria specific to this building system. Discussions are no longer about software and tools' features, but about the integration and increased use of simulations in design process. The future performance-based design approaches and simulation tools for facades should increase effectiveness, speed, quality, assurance and users' productivity.

Energy modeling and simulations in design process are usually limited to analysis of few different scenarios. It is not possible to simulate and analyze all possible design scenarios because of time constraints. Therefore, this research focused on developing a framework that couples simulation and optimization processes, and allows multiple design scenarios to be tested rapidly. The framework was implemented by coupling Python scripting with EnergyPlus simulation engine, enabling users to consider more variables during the design process.

Benefits of the Developed Data-Driven Framework

The basic characteristics that differentiate the developed framework and improve decision-making process can be summarized as:

- Automation and Speed: The framework enables users to automatically send the design scenarios to simulator and gather the outputs, and then screen out and sort these outputs to find optimized results. The advantages of this automate process are efficient testing methodology, consistency, reliability and increase in the number of possible design scenarios. Also, by implementing this framework, simulation time will be decreased for thousands of design scenarios.

- Variety of variables (multi-objective variables): This framework enables users to test multiple variables at the same time during the design process.
- Modularity: The framework is designed in multiple modules, which work independently. The key benefits of modularity in this framework are distinct functionality and manageability. Each module provides a distinct function and can be combined to provide entirely new collective function. The separate modules make it easier to test and implement this framework in design process or detect the errors.

Methodology: Framework Development for Performance-Based Facade Design

The new framework for performance-based design approach, aiming to minimize building energy consumption and energy cost with considering occupant comfort level, was developed as part of this research. This is a modular framework, consisting of independent scripts that represent modules, steps and function of application under test. The modules are used in a hierarchical fashion to apply the framework, consisting of four steps:

1) Defining goals, performance criteria, facade variables, and their properties, acceptable range in strategies for high-performance facade design
2) Generating the database that includes all possible design scenarios based on the variables with permutation in Python and selected outputs after simulation in EnergyPlus. This is module 1.
3) Coupling Python script with simulation engine (EnergyPlus) to automatically perform simulations for scenarios from database (measurements methods) to quantify variables and generate the needed outputs. This is module 2.
4) Filtering and narrowing down the results by implementing Python script, GA and reinforcement

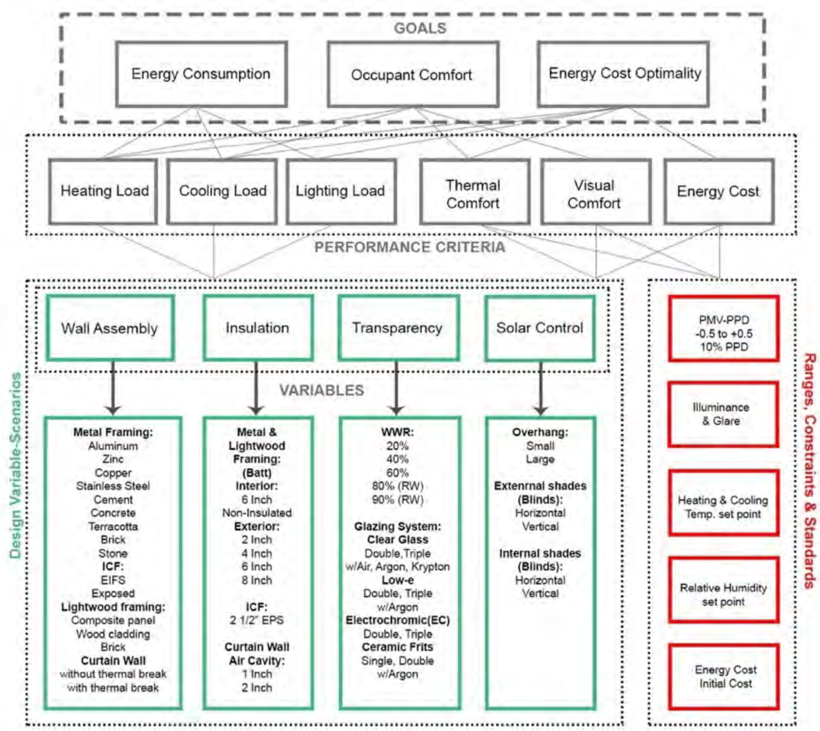

Fig. 1. Conceptual diagram, showing components of the framework.

learning to evaluate outputs and find the optimal scenarios. This is module 3.

The next sections discuss the components of the framework and its implementation in detail.

Step 1: Defining Goals, Performance Criteria, Facade Variables

Figure 1 shows the components of the framework. Performance-based facade design requires a holistic approach, considering performance indicators, such as energy performance and human comfort. These performance requirements (variables) must be quantified. The goals for this framework are to aid the design decision making process, where energy consumption and cost are minimized, and occupant comfort (thermal and visual) is maximized. The energy requirements for heating, cooling, and lighting of buildings are strongly driven by the performance of the facade, especially glazing parts. The objectives for reducing energy consumption are to reduce heating, cooling and lighting loads. Performance requirements (variables) to meet this objective are window to wall ratio (WWR), wall assembly, insulation, solar control, and glazing system. Performance-based facade design objectives that are related to human factors and contribute to occupant comfort and satisfaction in buildings include thermal comfort and visual comfort. The variables that relate to facade design include: air temperature, mean radiant temperature, air movement, relative humidity, clothing levels and activity levels. The predictive mean vote (PMV) suggested by Fanger [6] predicts the effects of these six factors on thermal comfort. Predicted Percentage of Dissatisfied (PPD) persons predicts the percentage of people who would feel discomfort with certain thermal conditions.

Step 2: Creating the Database

After setting all variables and parameters for facade design, all possible scenarios are generated using Python programming. With permutation in Python script, design scenarios are generated and added to database with specific scenario ID. In this study, we have 38,400 scenarios to investigate for the test cell, described in the next section. After running simulation in EnergyPlus, all outputs in step 3 are populated in this database with identical scenario ID. EnergyPlus provides wide range of outputs, but for this purpose, the following results are obtained: cooling, heating and lighting loads, Energy Use Intensity (EUI) for electricity and gas, PMV and PPD, and total energy costs for electricity and gas. Module 1 is responsible for generating all scenarios with defined variable and populating these scenarios in database. Module 2 is responsible for sending automatically these scenarios to simulation engine and for populating the selected outputs in the database. Data Flow Diagram (DFD) in Figure 2 shows the overview of the framework system that represent the flow of data through this process.

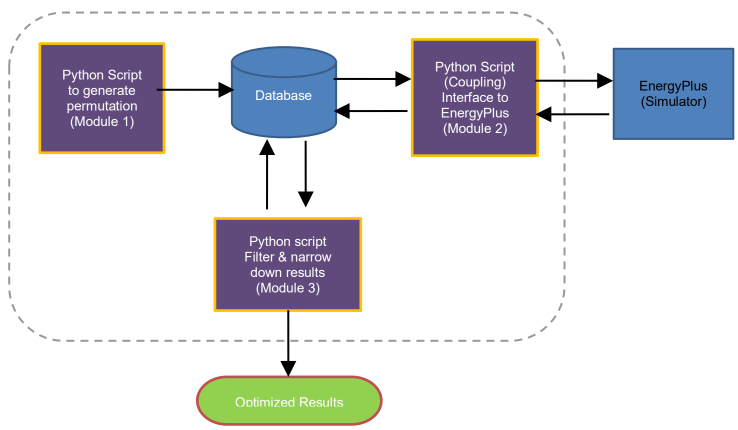

Fig. 2. Data Flow Diagram for the framework.

Step 3: Coupling Python Script with Simulation Engine (EnergyPlus)

EneryPlus 8.5 is used in this research as an energy modeling engine. EnergyPlus has been chosen as BPS tool for two main reasons: (a) this program allows reliable modeling of both building and HVAC systems, and, (b) it works with text-based inputs and outputs, and these facilitate the interaction with Python scripts. EnergyPlus can investigate discussed variables as inputs and simulate envelope related outputs in the study. Thermal comfort is calculated based on PMV and PPD. The formulas for both PMV and PPD are built into EnergyPlus and their values can be obtained directly from the simulation output file.

Initial simulation test cell considered a single office space (40'x40'x10'), located in Atlanta, Georgia. The south-facing facade was used to develop different design scenarios, varying WWR, materials, glazing system and shading control. Defining related parameters as inputs and setting data needed for outputs are the primary method for connecting design scenarios in the database with the simulation engine. Python script works as an interface to call scenarios from database and to send them to simulator. Each parameter must identify a well-defined relation with discussed variables, which reveals facade behavior in relation to performance aspects being analyzed.

Step 4: Filtering and Narrowing Down the Results by Implementing Python Script, GA and Reinforcement Learning

This optimization method in this study is a combination of GA and Reinforcement Learning. The GA in combination with flood fill algorithm and path planning create a new technique to find a relation between the outputs, to assign weights and dynamically adjust the target position. For this framework, three indices are defined for consumption, comfort and cost as indicators. Indicators are combined values that are used to measure performance, achievement or the impact of changes.

The flood field algorithm takes three parameters: start node, target and replacement, and determines the area connected to our target. This algorithm facilitates the optimization by sorting the highest indicators and decides which scenarios have to be simulated, based on the specific scenario ID. Using this algorithm decreases the process time, because it is not necessary to simulate all scenarios—rather, only scenarios that are closer to the target. The comparison is based on the assigned indicator value. In dynamic system, it is necessary to scale indicators to represent the impact of the indicators, so as to configure following tasks, and converge the results to the goal based on these scores. Figure 4 shows a sample for scoring total EUI electricity indicator.

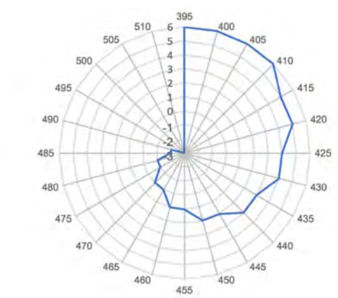

Fig. 4. Total EUI-Electricity (MJ/m^2) and indicator scores.

The initial population is generated randomly, based on the range of possible design scenarios. It is sent to the simulator to run the initial calculations, and then results are returned to the database to compare with the goals and standards. Then, design scenarios that have results closer to the goals are kept, and others are removed. In this framework, goal is summation of three indicators, for energy consumption, comfort and cost. The indicators are dynamically updated based on the range of results. Figure 4 shows an example, where indicators from 6 to -3 are used for the initial test cell energy consumption results. Occasionally, the solutions may be "seeded" in areas where optimal solutions are likely to be found. Individual solutions are selected through a fitness-based process, where fitter solutions (as measured by a fitness function) are typically more likely to be selected. This method accelerates the simulation process and the results give us clusters of optimized scenarios for analysis in next phase of optimization. Figures 5 and 6 show how optimization algorithm selects and sorts the fitted results for this framework.

Figure 5 shows the results before applying optimization for 2,061 scenarios and Figure 6 shows the result of 18,103 scenarios with assigning the first step of optimization. In this case, we have 1,627 scenarios that scored 20 and more than 20 (1,591 scenarios at 20 and 36 more than 20). Next step of optimization will analyze and evaluate these selected results.

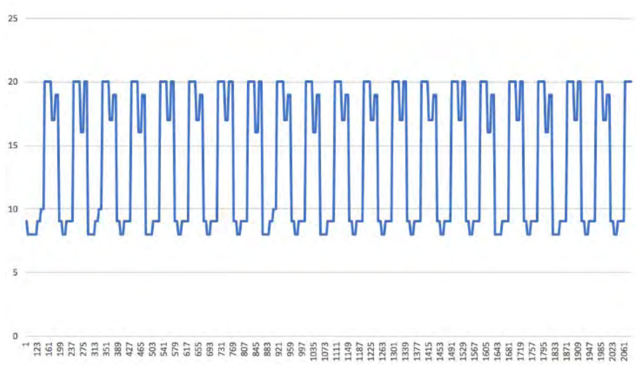

Fig. 5. Total Indicators vs. Scenario IDs (for 2,061 scenarios).

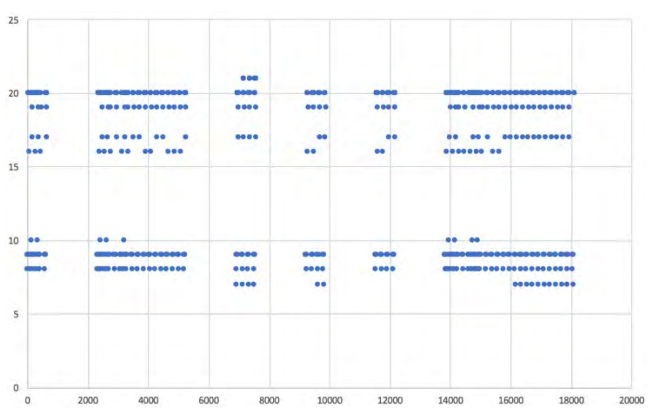

Fig. 6. Total Indicators vs. Scenario IDs (for 18,103 scenarios).

Conclusion and Future Work

This paper discussed the role of simulations and optimization in design decision-making process.. Then, a novel performance-based facade design framework was described, where different performance criteria and variables have been defined for achieving energy efficiency, occupant comfort and cost optimality. The framework has been implemented by coupling EnergyPlus as a simulation engine, and custom scripts using Python programing language. The paper describes the components and functionality of this framework in detail. Future research will focus on testing and evaluating efficiency of this framework, as well as its application for facade design.

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Concrete: Computation and Optimization

Nik Nikolov
Lehigh University

Abstract

New materials require new design and construction methods. Even old materials are being continually developed with new properties that challenge the way we use them. A recent cycle of innovations has led to concretes with considerable and effective elastic limit in tension and flexural strength. The possibility to design in concrete as a single orthotropic material with both tensile and compressive properties create an opportunity for new products but also require new design approaches.

Topology optimization as an architectural design tool is largely unexplored, in contrast to its wide use in the field of mechanical engineering. Topologically optimized shapes are fundamentally different from standard structural shapes and require highly customized means of fabrication. The resulting members can be lighter, use less material, yet still be as strong. Perhaps of greatest importance is the observation that the topologically optimized shape simultaneously manifests a structural optimum and an emergent aesthetic.

This presentation will introduce the basics of structural topology optimization, existing software, and show how it was used in architectural technology coursework. The assignment in view, given to intermediate architectural students, is to design and optimize a structural beam and to subsequently fabricate it in ultra-high-performance concrete using consumer level CNC-milling of polystyrene casting formwork. Computer stress simulations were compared to physical crush tests.

An increasing number of architects and engineers are well-versed in emerging digital fabrication and computation technologies. The presentation will posit that the materials with emerging properties and accessible computation tools provide a platform for both architects and engineers to engage in the problem of combining structural efficiency and aesthetic.

Keywords: Computational analysis, optimization, Pedagogy, Concrete, Fabrication

Integration of Aesthetics and Structural Engineering

Architecture and structural engineering are professions that have a historically close relationship. Today, however, a common sentiment is that architects contribute attractive yet costly solutions and engineers are considered of a dull and practical mindset. A main point of distinction between the two disciplines is the issue of cost[1]. While often a secondary consideration for architects, economy is one of the central goals of structural design. Great works of structural engineering integrate economy, efficiency, and elegance[2]. Designers who successfully integrated aesthetics and structure, like Robert Maillart, Pier Luigi Nervi, Gustave Eiffel, John Roebling, and Felix Candela, demonstrated a focus on low cost by also integrating a thoughtful or innovative approach to construction in their works[3]. Now professionals on either side of the architecture/engineering divide see the other as superfluous to their design process. This diminished respect for each other may in part be due to the decreasing emphasis on structures in architectural education. For instance, in 1965 architecture master's students at Yale were required to take six semesters of structures courses. Those were reduced to three in 1975, and two in 1999[4]. Similarly, there is a lack of instruction on aesthetics and design history in modern engineering curricula, whose accreditation criteria do not include any mention of ethics or aesthetics[5]. The wide adoption of digital technologies in the AEC professions gives rise to the opportunity for both architects and engineers to be effectively equipped to share the building design realm in both structural and aesthetic terms. An increasing number of architects and engineers are well-versed in emerging digital fabrication and computation technologies. The ease of use and accessibility of topology optimization tools provide a platform for both architects and engineers to engage in the problem of combining structural efficiency and aesthetics. It is now possible on a given project with typical time constraints to evaluate many more design proposals and gain much deeper insights into theoretical concepts than ever before.

Introduction to topology optimization

Topology optimization is a computational process by which a surface or a volume of a member under load is subdivided in a number of finite small areas or volumes, called *finite elements*. Each finite element is assigned a density that corresponds to the density of a structural material, such as concrete or steel. A density of zero would signify a void. In the beginning of the optimization process all finite elements in the body are given the same starting density, but during the optimization sequence densities are distributed according to the optimization objectives – in structures, that objective could be to maximize the stiffness of the member under load while taking into account the mechanical properties of the material. At a chosen end of the optimization process structural material is redistributed and a new *optimized* topology is generated.

The ultimate goal of topology optimization is to find the best structural layout, or material distribution of a structure, to fulfill its function in an optimal manner while fulfilling a set of behavior constraints early in the design stage[6]. The conventional approach to incorporating structural considerations in pre-design such as desired shape, size, and strength is to parameterize an existing design and find its best fit. Usually this process limits the design outcomes to the choice of precedents and the creativity of the designer. Topology optimization as an early design tool dramatically expands the design possibilities. The optimization algorithm presents to the designer's evaluation a wide array of design features, such as overall shape of the structure, the location, shape and size of holes, supports, etc.

Significance of topology optimization

Topologically optimized shapes are fundamentally different from standard structural shapes, which are derived from casting or extrusion methods of fabrication and assume a degree of structural redundancy. In comparison, topologically optimized shapes require highly customized means of fabrication and the resulting members can be lighter, use less material, yet still be as strong. Perhaps of greatest importance is the observation that the topologically optimized shape simultaneously manifests a structural optimum and an emergent aesthetic[7]. Topology optimization as an architectural design tool is largely unexplored, in contrast to its wide use in the field of mechanical engineering. Present mass-customizable fabrication technologies, such as CNC-milling, vacuum forming, and 3d-printing, make the wider deployment of topologically optimized architectural and structural members economically viable. As a design approach, topology optimization holds a significant potential for design innovation and can lead to novel structural morphologies that transcend classical typological classification.

The offices of Skidmore, Owings & Merrill (SOM) are leaders in reinforcing the trans-disciplinary collaborations between architects and engineers. Their increased use of optimization algorithms and visualization of the flows of forces give architects a powerful intuitive understanding of the distribution of stresses and magnitudes of displacements, which in turn informs decisions about how the overall shape of the buildings affects its structural frame.

SOM designers and engineers have found that, like the graphic statics analytical methods conceived decades earlier, the visualization of the structural forces … can often lead designers to possible design solutions which can be directly inferred from the visualizations[8].

Examples of large-scale implementation or structural topology optimization are the tower projects in the TransBay Transit Center in San Francisco and Shanghai Center in Shanghai (both 2010) where the optimization process iteratively redistributed a fixed amount of structural material in order to realize the most efficient use of that material. More notably, for the Commercial development project, Shanghai, China (2011) topology optimization revealed a novel way in which the multi-span bridge element connects three towers – the irregular pattern for an optimal structural system for the bridge component of this project was incorporated as part of the architectural tectonics.

Recent analysis of Catalan and Guastavino domes, carried out by John Ochsendorf at MIT, utilizes a combination of graphic and finite element optimization models, while the continued construction and reconstruction of Gaudi's Sagrada Familia is another great example of advanced application of structural topology optimization tools.

Method

There are multitudes of approaches to computing topology optimization, more popular among which are *homogenization-based*, *power-law*, and *evolution-based*[9]. While most approaches have found useful and established application in mechanical engineering, few have found consumer-level applications. The TopOpt plugin for the NURBS modeling program *Rhinoceros*®[10] and its compendium parametric design module *Grasshopper*™[11] utilizes an optimization procedure based on the paper "A 99-line topology optimization code written in MATLAB" by Ole Sigmund[12]. TopOpt is written by the TopOpt research group at the Technical University of Denmark (DTU) and is one of few tools that are specifically geared towards designers, engineers and architects who experiment with design-related methodology and research[13]. One feature of the TopOpt procedure is the ability to interactively configure the optimization setup, such as supports, loads, solids and voids, while the optimization is in progress. Other interesting features is the inclusion of specific procedures that allow for tension and compression prioritization of a single material. These features make the software extremely versatile for analytical experimentation with single linear-elastic orthotropic materials. An obvious material application for this feature is concrete, for which the optimization routine should prioritize load-carrying capability in compression.

There are a number of software packages available on the market that compare to TopOpt. *SolidThinking Inspire*, *Abaqus Topology Optimization Module* (ATOM), *Tosca Structure*, and *Nastran* are among the more popular. What sets TopOpt apart are two important characteristics: for simpler shapes and loading conditions TopOpt requires minimal set-up and the optimization routine is carried out relatively fast. A limitation to its wider applicability is that it is not well suited for working with more complex and irregular shapes under varied loads. This was deemed of no consequence for the goals of this study. What distinguished TopOpt in our view was that the interface allowed for interactive changes of the design parameters while the optimization was still in process – the designer does not need to wait until the optimization routine is complete before decisions on new optimization parameters can be made. Its speed and interactivity allowed us to almost instantaneously get feedback on design decisions and change the direction of the optimization in nearly real-time.

Concrete and Topology Optimization

The predominant model of analysis of concrete shapes is the so-called *strut-and-tie* model and was initially developed in the late 1800s by Wilhem Ritter and Emil Moersch. The strut-and-tie model of analysis assumes reinforced concrete (RC) beams, for instance, to exhibit truss-like behavior. This truss analogy provides a convenient visualization of the flow of forces and identified steel locations. Extensive research in support of the RC truss model has led to its prevalent method of structural analysis and its inclusion in the *Canadian Concrete Design Code* (1984), the *AASHTO* bridge code (1994), and the *American Concrete Institute* (2002) building code. The free form nature of topology optimization, however, enables the discovery of solutions with higher efficiency that are not straight and appear organic. These solutions tend to be complex, requiring curved rebar or rebar with varying thickness[14]. Due to the highly diverse optimization patterns developed for the compressive material (concrete) and tensile material (steel) and their complex geometric relationship, many topologies are simply impractical to fabricate on a mass scale. Reinforced concrete is a complex composite material and no current topology optimization methods are capable of accounting for transverse tensile stresses that may develop in compression members caused by force-spreading. Current work on steel-reinforced concrete optimization focuses on the application of parallel models of analysis – an orthotropic material is assumed for concrete and the tensile stresses are assumed to be carried out by steel in a truss-like fashion. Rebar is therefore placed in linear segments, while the compressive loads within the concrete part are allowed to take any shape[15].

In view of a growing body of research in allowing the selective application for compressive and tensile forces to separate structural materials that are in composite action with each other, our experiment does not aim to substitute standard methods of structural topology optimization of reinforced concrete. Rather, we borrow optimization methods used in mechanical engineering with applications involving polymers and metal alloys and take advantage of emerging properties of concrete that allow us to treat it as an isotropic elastoplastic material with distinct compressive and tensile strengths.

Current developments in ultra-high-performance concrete have challenged the traditional assumptions associated with concrete. For instance, a common ultra-high performance concrete (UHPC) product currently on the market, has an elastic limit in tension of up to 10 MPa (1,450 psi) and flexural strength of up to 40 MPa (5,800 psi)[16], while compressive strength can run up to 200 MPa (29,000 psi)[17]. As a comparison, normal strength Portland cement concrete, which is commonly used in residential structural construction, has an average tensile strength of 3.5 MPa (500 psi), an average flexural strength of 4 MPa (580 psi), and an average compressive strength of 30 MPA (4,300 psi)[18]. The possibility to apply both tensile and compressive properties to a single orthotropic material make UHPC particularly suited for TopOpt's TenCom.1Mat procedure.

Example

Topology optimization was carried out on a simply supported ultra-high-performance concrete beam with a uniformly distributed load, Fig. 1. This loading and support configuration can easily be analyzed and

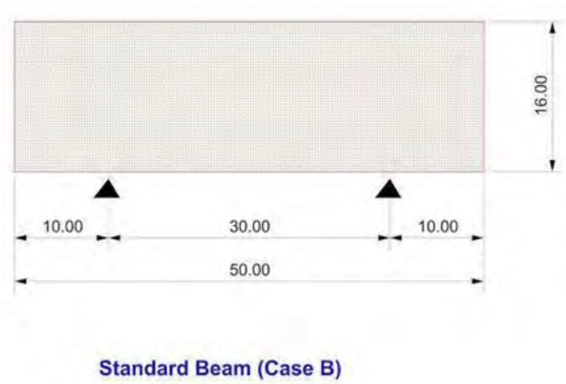

Fig. 1 Standard beam, elevation (drawing not to scale)

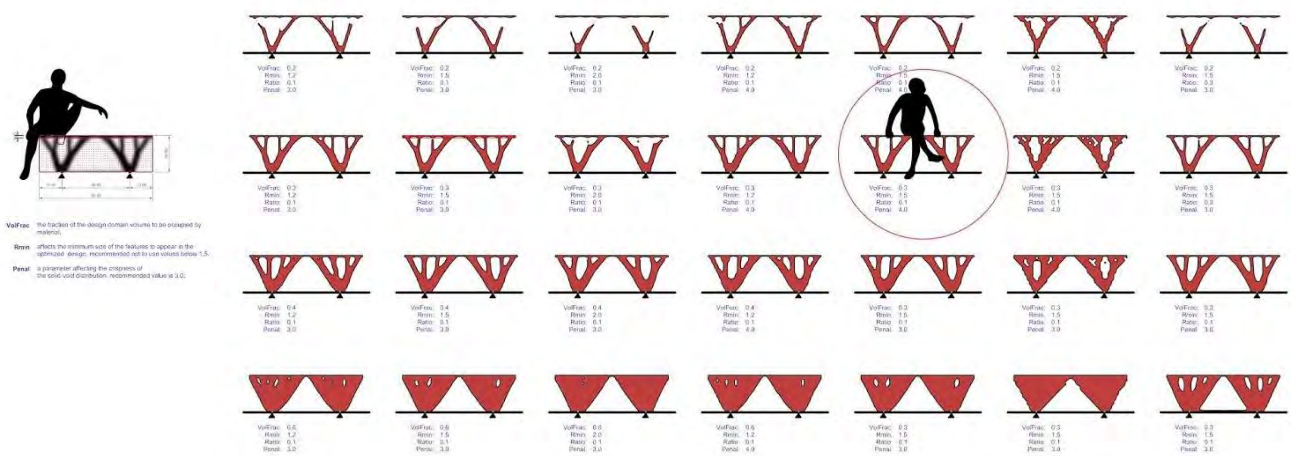

Fig. 2 A matrix of comparative studies (optimization results and values).

compared to existing shapes and common material properties. The beam was further modeled using two types of design spaces: the design space is the volume where the material density may be varied and through the process of optimization material may be removed; the non-design space is volume that is given constant density to be included in the calculations. However, it is excluded from optimization. In this way we have specified areas where material removal is undesirable, such as a deck, a seat, or a support ledge. A non-design 1” thick plate was assigned at the top.

In order to differentiate the performance of the optimized design a series of comparative studies were generated, Fig. 2. The following configuration inputs were variably adjusted: *VolFrac* – the fraction of the design volume to be occupied by material; *Rmin*- affects the minimum size of the features to appear in the optimized design; *Penal* – a parameter affecting the crispness of the solid-void distribution; *Ratio* – a parameter controlling the prioritization with respect to tension and compression.

Fig. 3 Rendering of optimized topology chosen for fabrication

The initial optimization objective was to minimize the deformation energy while achieving a 30%reduction of volume. In consecutive iterations, the varying constraints of input produce a matrix of topologies that contain both thick and thin parts, many of which would be difficult to fabricate. That difficulty can be alleviated by controlling the minimum size constraint, *Rmin*, and by varying the *VolFrac* and *Penal* values. The final topology was chosen to reflect the flow of forces where, in the middle, a void is left by the formation of an arch, and increasing stress around the bases cause transverse webs to form, Fig. 3.

Numerical comparison

Two digital models were created using the finite element analysis software Abaqus CAE to compute the ultimate strength and quantify the efficiency of the optimized shape. “Case A” depicts the optimized shape created using TopOpt, and “Case B” depicts a standard rectangular beam shape with the same overall dimensions, support conditions, and material properties

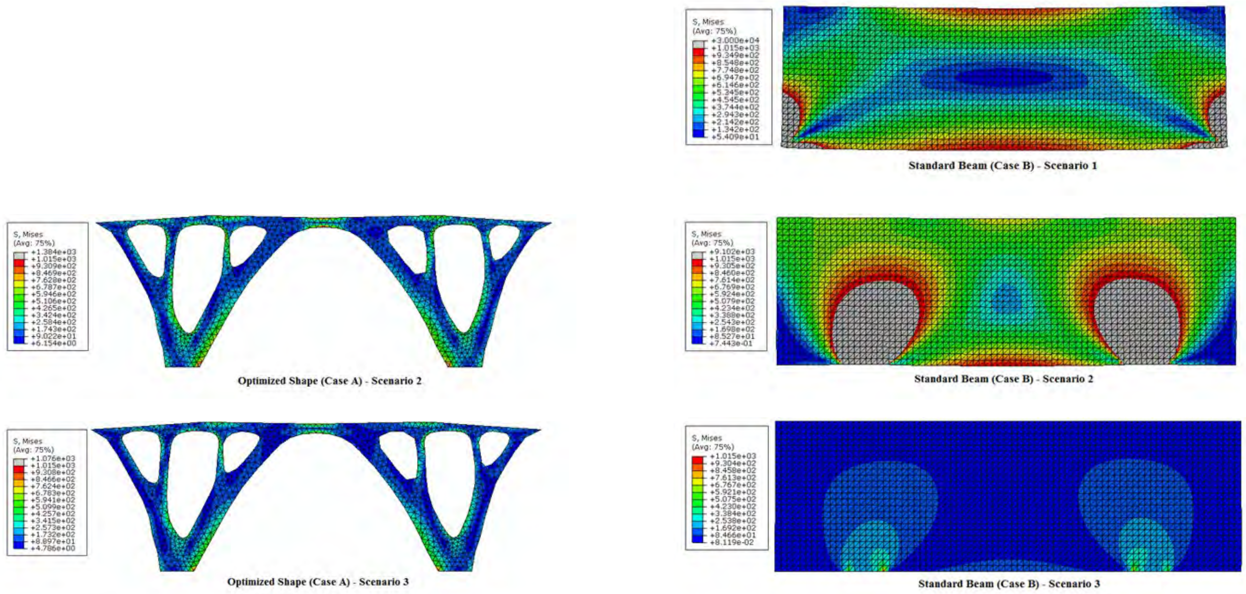

Fig. 4 Von Mises stress contours are shown in the figures for Case A and B for all 3 scenarios.

as the optimized shape. Volumes of Case A and Case B were automatically calculated with AutoCAD and found to be 0.037m^3 (2280 in^3) and 0.131m^3 (8000 in^3) respectively.

Both Case A and B had simply supported boundary conditions with a pin (horizontal and vertical translation fixed, allowing rotation) support at one end and a roller (vertical deflection fixed) support at the other end. Out-of-plane deformation was restricted in the 2D models created. A vertical uniform load was applied to the top face in each case and gradually increased until the maximum compressive or tensile stress was reached. Automated meshing with 3-noded linear plane stress triangles were used to create the mesh of both Case A and B. Element size was gradually decreased until approximately 16.5mm (0.65 in.) when results were no longer sensitive to the element size.

Each model was assigned material properties supplied by the UHPC manufacturer. As discussed above, the maximum compressive strength and maximum tensile strength for our particular material are approximately 130MPa (18,850psi) and 7MPa (1,015psi) respectively. The unit weight is 24.5kN/m^3 (156pcf), which compares to normal strength, normal weight concrete at 23.6kN/m^3 (150pcf). To minimize computational effort, the material was assumed to have linear-elastic behavior up to failure in both compression and tension.

Three scenarios were considered for the construction of the numerical models. In scenario 1, the supports of Case B are placed at the end of the beam creating a span of 127cm (50in.). In scenario 2, the supports of Case B are identical to that of Case A. Both scenario 1 and 2 consider only a flexural failure occurring at the center of each model, where the bending moment will be highest, while scenario 3 considers the possibility of failure elsewhere in each model.

Von Mises stress contours are shown in the figures for Case A and B for all 3 scenarios, Fig. 4. Loaded stresses at each point in a body have a different value depending on location and direction. As a consequence, each finite point in a body has multiple stress components depending on the orientation of the point. Von Mises theory, also referred to as *the maximum distortion energy theory*[19], is one of the most common methods to combine stress components to predict failure of a body. In summary, the standard rectangular shape beam is stronger than the optimized shape; however, the standard beam is also significantly heavier with a weight of 3213N (722lb) compared to the optimized weight of 916N (206lb). The results for each scenario are provided in Table 1, where "Efficiency" is the ratio of the total applied load (the product of the uniform load and the beam length) and the weight of the shape. Due to the simplicity of the geometry and material properties, the Case B numerical result for scenario 1 was easily validated with an analytical calculation, which was found to be within 2%.

Table 1: Comparison of the strength and efficiency of the two cases and loading scenarios.

	Optimized (Case A) total weight 206 lbs		***Standard (Case B) total weight 722 lbs***	
Scenario	***Max load*** *kN/m(lbf/in)*	***Efficiency***	***Max load*** *kN/m(lbf/in)*	***Efficiency***
1	N/A	N/A	23.6 (135)	9.35
2	4.73 (27.0)	6.56	96.3 (550)	38.1
3	3.68 (21.0)	5.10	10.5 (60.0)	4.15

Cases 1 and 2 are assuming that flexural failure will occur at midspan of each section; however, due to the chosen length to depth ratio, flexural failure is unlikely. Therefore, case 3 is most reasonable to occur. The optimized shape is 22.9% more efficient that the standard shape.

Production of optimized forms and casting

The form for the chosen design is manufactured from polystyrene blocks which will be used as molds for casting concrete. The forms were cut on a CNC-router and assembled in a compressive frame. The form was sealed with primer and petroleum jelly, making it water- and air-tight. The concrete was mixed according to manufacturer's ratios and mixing procedures. The concrete was cast and de-molded after 7 days and moisture-cured for 3 additional weeks, Fig. 5

Fig. 5 Image of CNC-milled polystyrene casting form

Conclusions

We have observed significant weight and strength difference between the standard and the optimized shapes. The optimized shape is 28.5% lighter and 35% weaker. However, the overall efficiency, as represented by a strength to weight ratio, is significantly in favor of the optimized shape. The optimized shape is 22.9% more efficient.

The following preliminary conclusions were made. Topology optimization:

- May lead to the development of new structural shapes for fiber-reinforced concrete
- May lead to significant reduction in material use.
- May achieve comparable to standard shapes strength, however there is a relation between the allowable strength to the increased ability to experiment with formal topology
- Allows for direct correlation between aesthetic characteristics and structural performance

Another observation was that the existing commercially available software can be used in optimizing structural members.

In addition to the application of the optimization routine on a simply supported beam, the team plans to test the approach on larger structural beams. We are preparing a case study that compares conventional precast AASHTO

Fig. 6 Photograph of cast beam. Overall dimensions: 50" (length) x 10" (width) x 16" (depth); weight: 206 lbs

beam to the potential gains in structural economy of an optimized beam. By illustrating the expressive potential of structurally optimized precast members we hope to be able to introduce a strictly architectural agenda in structural design. A current call for proposals to the National Science Foundation specifically invites participation from architects in the area of topology optimization. This introductory work and its dissemination are an important step in securing funding and furthering the line of inquiry.

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ISA: Precedent Studies in Arch Structures III

Kristopher Palagi
Louisiana State University, School of Architecture

Abstract

Engaging structures as impetus for architectural design, this paper examines the implementation of an approach to precedent analysis -- the ISA -- within an architectural structures course. As a means to graft the knowledge digested into familiar design languages, this pedagogy frames the precedent work in three perspectives: First, an understanding of the designers' intent through assigned readings, essays, and in-class discussions; Second, computational modeling of structural components utilizing Revit's *Adaptive Families*; and finally, a comparative analysis of the impact of formal variations on the structural efficacy through diagramming load-path and lateral resistance. Selected for their passion regarding structural logic, the semester spans a wide breadth of structural considerations through three paramount engineers; Eugene Viollet-le-Duc, Eladio Dieste, and Peter Rice. Aiming to develop a strong relationship between structural logic and architectural design decisions, the ISA approach weaves an understanding of the designers Intent (I) through the readings, Skills learning (S) within Autodesk Revit, and Analysis (A) documented in diagrams.

In Transition

This paper presents an architectural structures III course developed for a "one-time" transitional moment within an architectural curriculum. This course was charged with segueing an understanding of structural logic back into architectural design thinking for a group of fourth and fifth-year B.Arch and 2nd year M.Arch students who recently completed two semesters of structures coursework instructed by faculty in the Construction Management department. Questioning how structures coursework can best influence students' design decisions in their studio work, the selection of precedent analysis and more specifically the methods one uses to understand the design decisions of past work, became the foundation for this pedagogy.

Following two semesters of structures instruction where isolated elements remained abstract in their calculations -- unrelated to the design decisions -- this course aimed to draw a direct connection between structural concepts and the experience of architecture. The study of architectural precedent was selected as framework for this course for its ability to address the holistic impact of structural design on completed work. To accomplish this, a series of buildings were selected for the explicit and integral nature of structural concepts to their design. This pedagogy proposes that once structural logic has been tied to the experience, a bridge is built for the students to freely move structural intent into the familiar territory of architectural design decisions.

This paper presents the sequence of assignments, work product, and selective answers from the students' evaluation to critique three key perspectives: firstly, engaging structural logic as a design catalyst; secondly, developing proficiency in modeling and the design exploration of structures through greater computational skills development; and thirdly, the ability to investigate and communicate an understanding of complex structures through analytical diagrams.

ISA: Three Perspectives on Precedents

Engaging structures as impetus for architectural design, this paper examines the implementation of an approach to precedent analysis -- the ISA -- within an architectural structures course. This pedagogy frames the precedent work in three perspectives: First, an understanding of the designers' intent (I) through assigned readings, essays, and in-class discussions; Second, computational modeling of structural (S) components utilizing Revit's *Adaptive Families*; and finally, a comparative analysis (A) of the impact of formal variations on the structural efficacy through diagramming loadpath and lateral resistance. Each of these rely on familiar methods of communication to assist the transition of the newly acquired structural concepts into later design decisions by the students.

*Understanding the Designers **Intent (I)***

More than just assigning chapters, the selected readings expose the students to passionate, responsive, and most importantly the inquisitive reasoning for challenging structural standards in construction. The goal of selecting these three specific readings from -- Viollet-le-Duc, Eladio Dieste, and Peter Rice -- is to give the students precedent for making arguments for "why structure can, and in some cases should, take the lead in design investigations".

Student Evaluations:

The readings were perhaps my favorite part of the course assignments. As opposed to the vast majority of readings I have received so far in architecture school, the assigned writings were refreshingly succinct, clear, and demonstrative of solid ideas and understanding from the authors. - Anonymous M.Arch 2020

The readings assigned first helped to frame the specific principles being explored in each project, while class discussions then emphasized key aspects of the architects' and engineers' goals. - Anonymous M.Arch 2020

*Building Computational **Skills (S)***

The computational modeling of each building element within Revit's *Adaptive Family* components demands the students 'construct' a digital model for each building element of the precedent projects. Unlike Rhino, 3dMax, Blender, or Maya, the *Generic Model Adaptive* components in Revit demand the creation of a catalog of individually modeled digital files. These files act much like a hardware store stocked with unique and variable building materials. The students complete the course having developed a collection of various details, structural members, and approaches to long-spans that form a constellation of structural assemblies. The students walk away with the confidence to utilize this catalog of components in their future design work.

Student Evaluations:

By utilizing Revit and building in adaptive components, we had the opportunity to experience first-hand how modifying one element may come to affect another in the overall system, and so on. Having the ability to recreate these components and assemblies, piece-by-piece, and create a library of families with which to pull from in the future really helped to understand how each of the parts came together to work as a unified whole in each related system. - Anonymous M.Arch 2020

The digital modeling was quite challenging with my having had virtually no revit experience. The value of adaptive components in the world of box plug-and-play architecture became quickly apparent. - Anonymous M.Arch 2020

The ability to explore structural principles through 3D modelling forced me to understand individual components, assembly methods, and finally, how the assemblies distribute forces and resist lateral stresses and loads... I felt I was learning from multiple fronts—both structural understanding and new, useful and relevant modeling skills in Revit. The ability to put components together correctly displays a higher understanding of building principles than simple reiteration, verbally or written, of the same principles. - Anonymous M.Arch 2020

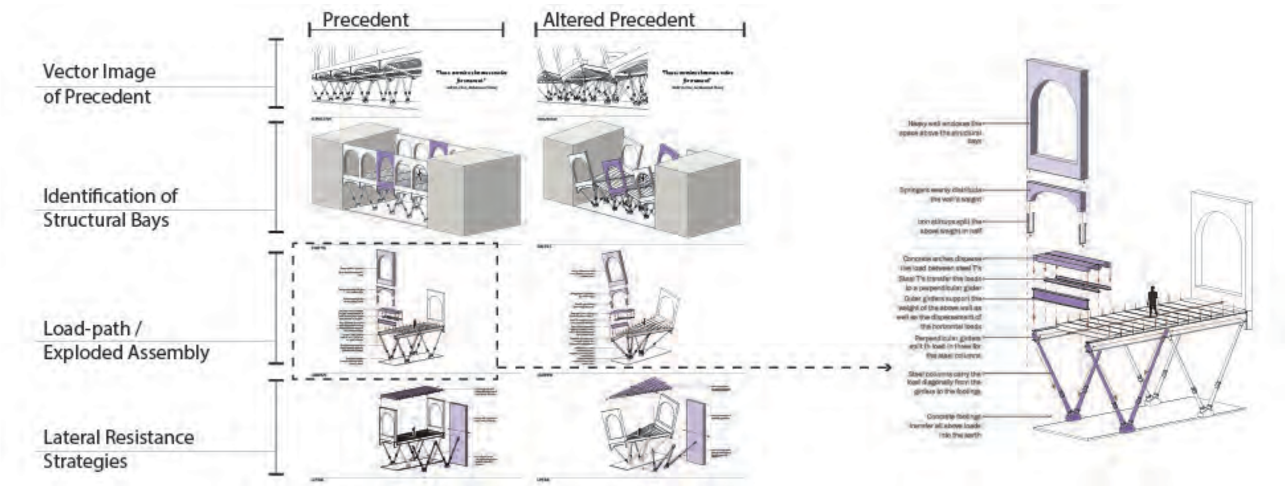

fig. 01 Viollet-le-Duc: C. Crane B.Arch 2020

Analysis** through Diagramming **(A)

Once the components are modeled and the precedent projects 'assembled' in Revit, the students ability to quickly export vector-based, isometric drawings shifts the course towards the diagramming of structural concepts. The use of isometric drawings to diagram load-paths, lateral forces, and assembly relationships strengthen the analytical communication skills the students have acquired in their design studios. In addition to analyzing the precedent, the students are asked to utilize the adaptive nature of the components to stretch, twist, and antagonize the precedents' structural logic. Once adjusted and diagramed again, the class is able to discuss where the structural forces may have been altered. This additional step moves the assignment into design decisions by the student and closer to integration into studio work.

Student Evaluations:
The diagramming of forces was easily the point of the process where I learned the most. I found the learning was equally dependent on the the explanations given in the lectures as well as on my first attempts at diagramming on my own. The diagramming of forces gave me a firmer grasp on the designers' thinking, not only in what they did, but the specific reasons and how they came to those solutions. - Anonymous M.Arch 2020

Being able to show how these forces were affected graphically rather than numerically is extremely useful for explaining compound assemblies to someone who may not quite have the grasp on the physics at work in the proposed building. The analysis of such complex structures requires a basic knowledge of forces that had been buried by two semesters of mine dulling math. - Anonymous B.Arch 2020

The methodology implemented for this class is great and encourage students to expand their way of thinking, interpret, and make diagrams that will be accessible to people that have (may) not be familiar with the project before. - Anonymous B.Arch 2020

Sequencing Concepts and Computational Skills

The course is separated into 3 phases; An introduction into the computer applications, a series of precedent studies, and ending with an independent analysis. The initial three weeks of the course were dedicated to exposing the students to fundamental Revit skills. Although phase one was seeded with a pre-semester dissemination of video tutorials and a reading on Systems Thinking by Donella Meadows, all of the class time was spent introducing benefits of the Watchmaker[i] modeling logic inherent in Revit's *Generic Model Adaptive Components*.

Phase two of the course, spanning 7 weeks, was separated into three near equal parts. Selected for their passion for structural logic, the semester spans a wide breadth of ideas through three paramount structural designers; Eugene Viollet-le-Duc, Eladio Dieste, and Peter Rice. Their selection facilitated discussions on the role of materials, labor, structural form and cultural identity in the design of structural assemblies. The elegance of the ISA process is in the sequencing of the precedents paired with the growing skills demanded of them in Revit's *Generic Model Adaptive* components. Although listed chronologically, this is merely coincidental. Each Engineer and subsequent projects were selected and ordered to develop a linear relationship between an increased complexity of structural concepts and a greater demand of computational modeling skills.

Starting slowly, two weeks were scheduled to investigate a single project by Viollet-le-Duc -- the unbuilt Marketplace. Picking up the pace, the next two weeks addressed complex structural form with two projects by Eladio Dieste; the Church of Cristo Obrero and the Salto Municipal Bus Terminal. Maintaining the momentum, three weeks were dedicated to investigating three projects by Peter Rice; the tensile curtain wall system at Les Serres & Cité des Sciences et de l'Industrie, the gerberettes of Centre Georges Pompidou, and culminating with the complexity of Padre Pio Pilgrimage Church in San Giovanni Rotondo.

Initially, the final phase of the course was scheduled for the student to take this newly acquired skill set to document and assess their current studio project. A mid-semester assessment of the pace of the course demanded this proposed work product be replaced with the development of an annotated catalog of the students work.

Targeted ISA Lessons

Viollet-le-Duc

Drawing from selected chapters of The Architectural Theory of Viollet-Le-Duc: Reading and Commentary (1990), I found the students initially skeptical of a 19th century text's relevance in a contemporary advanced structures course. By throwing the students directly into Chapter 5, Handling Materials, students found they could relate to Viollet-le-Duc's clear respect and interest for materials. Class discussions broached Viollet-le-Duc legacy, specifically regarding his impact on countless architects, and urban planners, who espouse how they too have found inspiration from his words. In Chapter 6, Planning Rationally, Viollet-le-Duc's drive for "Structural Honesty" and "The Ills of Irrational Design" establishes a clear language for the students to question the precedent projects to come.

Sample Student Writing Assignment:
Chapter 5 states, "Materials should be employed in a manor constant with the formulation of a structure. Their proper use contributes to the clarity of structural expression; their misuse, on the other hand, diminishes the effectiveness of a design." This is a rather important note to take away as aspiring architects. Understanding the viable construct-ability of our own designs is a rather powerful tool. When you understand the beautiful, intricate work put into these structures it becomes repulsive to cover it with a facade as many designers do today.
- xx B.Arch '20

It is logical to build and design based on the capabilities of the material, be it the way iron can be molded or the compressive qualities of stone. These principles can be observed as carrying through the future to Louis Kahn's impassioned speech articulating the proper use of material. Le Duc and Kahn both knew that one must not only honor the material, but also in a way that showcases the capabilities of that particular material. - xx M.Arch 2020

The Marketplace, although unrealized, initiates the courses precedent studies. Viollet-le-Duc's disparate, exterior perspective drawing, building section, and written description highlight not a cohesive finished design, but instead stresses key structural ideas. First, the angled columns are discussed for three structural concepts; They are knuckled to decrease their slenderness ratio and in-turn increasing their resistance to bending while sloped; The angles of the columns are equal and opposite with a loadbearing girder above resisting the tension caused by the outward thrust; and, the un-equally loaded columns demands a single foundation to maintain uniform settlement for each pair. In addition to the column system, Viollet-le-Duc's exploration of iron in the floor diaphragm's framing exhibits the beginning of today's composite construction -- steel decking with concrete. The students document the inverted structural "T" which maximizes the extreme tensile fibers while establishing bearing for the solid stone blocks acting in compression.

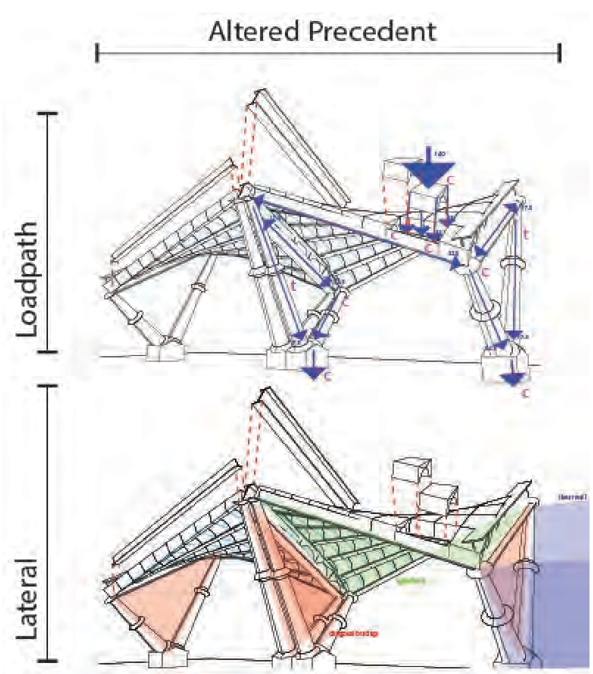

Fig. 02 Viollet-le-Duc: A. Hussain M.Arch 2020

The Marketplaces' structural assembly -- column, girder, beams, joist, and flooring – set the stage for the oldest of the precedent projects selected to demonstrate the potential future use of the individual components created in Revit, but more importantly, act as an accessible introduction to the design potential of parametric qualities of the *Generic Model Adaptive* components. Within Revit's Family types, the *Generic Model* was utilized familiar sweep and revolve commands to model detail connection elements like column caps and bases. More complex parametric variables are introduced with the *Generic Models Adaptive* families when modeling the column and beam members. *Generic Model Pattern Based* exposed the students to the divide surface command and the nesting ability of surface patterns.

Eladio Dieste

The English Summary from Eladio Dieste La Estructura Ceramica (1987) moves the course away from Viollet-le-Duc's fixation on the identity of individual structural elements and towards labor and structural form. By elevating the act of construction -- both the sequence of, and those responsible for -- Eladio Dieste demonstrates the fruitfulness of a cohesiveness approach to material, technique, and humanity in his theory of Cosmic Economy. Eladio Dieste's self-consciousness regarding his lack of formal architectural education, highlights his reliance on the understanding of fundamental yet nearly inconceivable structural logic. Dieste's concern for the "tyranny of the drawing board" and his contempt for modern architectural practice's fixation on the quantifiable plan drawings, directly opposes the students' architectural education. In his essay, "Art, the People, and Technocracy," students are exposed to alternate priorities, such as the roll of labor and embodied knowledge with a field of craftmanship that are the catalyst for his work.

Sample Student Writing Assignment:

Dieste is convinced that construction of buildings has the possibility to be animated and meaningful. The production and composition of the materials of a building should not merely be a skeleton in which the façade is tacked on later; rather the structure itself should show and actually be the eloquence of the architecture. He states, "For architecture to be truly constructed, *the materials must be used with profound respect for their essence and possibilities." In other words, the architecture should not be defined by decorative designs; the materiality and structural makeup of the building should express it. He further reiterates this point when he states, "Coherence between the form and the constructed reality is also very significant (193)." Form should be informed by structure. - xx M.Arch '20*

In Eladio Dieste 1943-1996, the architect and engineer addresses the importance of responsible and rational thinking of an architect in selecting building and construction methods. He states, "A sound and sensible architecture requires the rational and economic use of construction materials." Being from Uruguay, a developing country, the realities of domestic economy, technology, and industry must be intrinsic considerations in the design of architecture. Put simply, if the means are not feasible, the method is wrong. - xx M.Arch '20

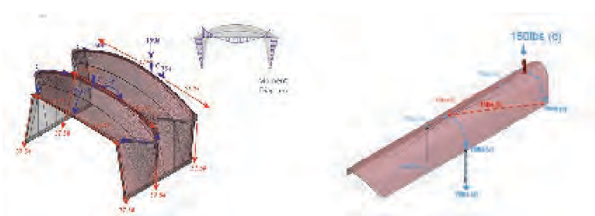

fig. 03 Dieste: B. Bailey M.Arch 2020

Moving beyond the nested assembly in Viollet-le-Duc's Market, the two projects by Eladio Dieste were selected for their clear demonstration of the integral strength of well-conceived structural forms. Discussions of Thomas Jefferson's single wythe serpentine walls at Monticello, ground an initial understanding of the complex shear and moment strength created in Dieste's undulating wall and roof connections in the Church of Cristo Obrero. Further investigation into Dieste's gaussian vaults demonstrate a sophisticated manipulation of simple catenary forces. The second precedent, the Salto Municipal Bus Terminal, like several other of Diestes cantilevered vaults makes use of a nearly imperceivably double wythe assembly. Although balanced with an immense span, the students become keenly aware of the lack of required lateral resistance in the later example.

When modeling the structural form of Dieste's Church of Cristo Obrero, nesting and offsetting *Control Points* on *Reference Lines* created complex forms that segue directly into Revit *Project* wall and roof types. The addition of instance parameters on the offset dimensions of the *Reference Lines* establishes a parametric logic for the sine-wave form of the church's wall and roof. When challenged by the Salto Municipal Bus Terminal, the students set width to span ratios for vaults, along with symmetrical expansion of cantilevers. By nesting *Reference Splines* into *Divided Surfaces*, the complex tensile system of structural rebar would respond to parametric variations within the arch and cantilevers.

Peter Rice

Within the first pages of An Engineer Imagines, Peter Rice's excitement for the expression of structure is palpable as he drops the reader into the design process for one of his most recognized works, Centre George Pompidou. Rice's work, specifically the trusses' at Les Serres, the gerberettes at the Pompidou, and the stone arches at Padre Pio, are the culmination of both Viollet-le-Duc's concern for materials and integrity and Dieste's elevation of the act of construction and structural form. Exposure to Peter Rice passion for elevating the expression of structure, moves the ideas represented in earlier precedents into contemporary and relatable architectural projects.

Sample Student Writing Assignment:

Rice's mentality is shown when he says, "We had built the Sydney Opera House after all, I was the living proof, and now we had to deliver." It is the subtle determination in this quote that shows how much focus Rice puts into his work, and how through this focus he brings to life the true value of the projects he works on.   His determination is also shown in his consideration for the use of cast steel. - xx M.Arch 2020

The journey through the conception and construction of the Pompidou by Peter Rice in An Engineer Imagines reveals a strong adherence to its design intent, through the team's decision making process, choice of materials, choice of forms,

and all the hardships in between. This emphasis on an expressive joint reflected their original theoretical wish for the building to be culturally friendly to all people, open and classless.
- xx M.Arch 2020

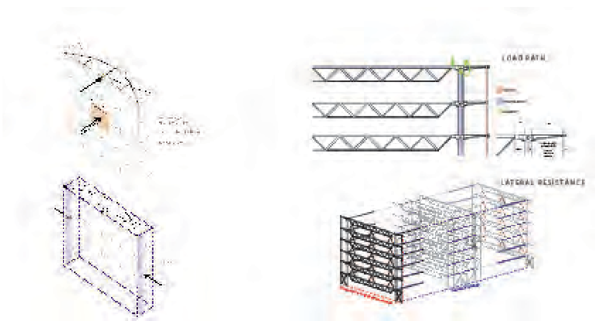

fig. Peter Rice: B.Smith M.Arch 2020

The three final precedent projects were selected to move the structural ideas discussed into contemporary construction. Beginning with the trusses designed for the glass facades at Les Serres & Cité des Sciences et de l'Industrie, the students are exposed to a common structural concept, that of an open web steel truss, refined to respond to a more complex, multi-axis loading. Through the diagramming of the mirrored tensile chord members within the trusses, the students identify how the newly formed offset axis of these tensile members eliminates the need for out-of-plane bracing -- forces highlighted by an expressive photo of Peter hanging from an unsupported 'bottom' chord. Following, the Centre Georges Pompidou demands the students to decipher a network of complex relationships. The pin-connections used throughout the structural scaffolding of the Pompidou, demand that the individual structural members be recognized and modeled for their tensile or compressive forces. Having completed the reading, the students have insight into the design decisions motivating the use of back spanning gerberettes -- maximizing clear spans while minimizing truss depth. A holistic assessment of lateral forces focuses the students on the unique vertical x-bracing connections between trusses on the short North and South facades.

The course ends with an investigation into Padre Pio Pilgrimage Church. Although Peter Rice passed before this project was completed (he is noted as the conceptual designer) this building brings a culmination of the lessons touched upon in the semester. A floating Roof-Diaphragm, angled 'V' metal riser connections, multiple non-uniform loading on catenary stone arches set in a lateral resisting radial all culminate in terrifying foundations responding to the immense thrust.

No additional modeling skills are required for this final series of projects. Rather the complex logic of structural relationships in each demand that the students develop additional 'parameters' in their *Generic Model Adaptive* components. In each, these variables are nested from one file into the next, computationally constructing the structural logic of the precedent work.

Constructive Criticism + Conclusion

Although this course was developed for a unique moment of curricular change, it's success and a current opportunity for redevelopment of our structures sequence, leads to speculation on how this ISA approach may resurface in the development of future courses. Reflecting on the student work and evaluations, I feel a few changes are necessary to the pace of the course and greater clarity brought to the introduction of the computational skillsets.

Student Evaluations:
I understand the 'pros' of using Revit for this course, however, it was overwhelming to learn a new software so quickly, while also facing the deadlines for each project to be completed. - Anonymous

I think the adaptive model portion wasn't quite as useful and should be replaced with something more focused on structure. - Anonymous

The course began a little haptic; however, the corrective actions taken to steer the course in the right direction about halfway *through the semester proved to enhance the course work and experience overall. Although many seemed to complain about the heavy Revit Emphasis -- I found it to be an incredibly beneficial experience and found the skillset that was built through these exercises really was the best way to understand the complexities of the structures. - Anonymous*

I think with a more stringent set of expectations of what is expected out of Revit could help push students to utilize the resources that the instructor is offering. Also, the projects that were created in class were all extremely complex If one of the projects was less complex and explored amore common understanding the foothold needed for the course could have been strengthened. - Anonymous

With a 77% response rate of this 30-student course, the student evaluations identified two areas of concern. First, a collection of students made note of the difficulty of learning Revit in tandem with the course content. For context, early within our curriculum, we have a course dedicated to learning basic computational programs (Adobe suite, Rhino…). Although a few students felt they should have a separate course to be 'taught' these skills, I believe the imbedding of tutorials within the course curriculum is beneficial. If instructed again, I would dedicate more energy in the first three weeks to developing the students' fundamental skills in Revit and Illustrator to facilitate the learning outcomes of the later work. A second critique, questions the selection of Revit over a structural analysis program. With my professional practice, teaching experience, and considering the average student's work product from this course, I have found that Revit's *Generic Model Adaptive* components can act as a unique lynchpin between understanding the structural logic of assemblies and facilitating creative design exploration and communication.

When considering the three goals of the ISA pedagogy, the first, engaging structural logic as a design catalyst, the student essays effectively demonstrate a clear appreciation for the role that various structural ideas played in the precedent projects. Achieving the second goal of developing proficiency in the computational modeling and design exploration of structures, proved to be the most challenging. The student work product parallels the evaluations with approximately a third of the class never becoming facile with the program. With regards to the final goal, success in the development of the students' ability to investigate and communicate an understanding of complex structures is explicit in the students' graphic work submitted and reflections in the course evaluations. The ability to communicate clearly, through familiar graphic diagraming strategies, set a stage of for in-class discussions of complex course material.

Considering these outcomes -- with the aforementioned adjustments -- I feel the ISA approach to precedent analysis is an effective bridge between structure course content and a nascent architecture designer's studio work.

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[i] A fable of two equally skilled watchmakers. The first works on a single watch diligently from beginning to end. The second, develops sub-systems, so unlike the first, does not have to restart when disrupted. The quality remains but efficiency increases.

Microclimates at the Sixth Facade

Abby Reed, David Fannon
School of Architecture, Northeastern University

Abstract

Elevating buildings above grade is an increasingly-common design approach to address risks of costal and riverine flooding. While elevating buildings improves resistance to flood waters and potentially debris damage, other implications are less well-understood, including the influence of unique thermal and moisture conditions in the space between the ground and the underside of the elevated building—the so-called sixth facade. Unlike conventional basements, crawlspaces, or slabs-on-grade that respond to soil moisture through the installation of a vapor barrier, exposed, elevated floors contend with unique hygrothermal conditions, linked-to but distinct-from both the soil and the ambient air.

Uncontrolled moisture has significant energy consequences, can foster mold and fungi growth, and contributes to deterioration of building materials through rot and corrosion. To better understand conditions at the sixth facade, this study compares the conditions of the sixth facade to those of the interior and exterior ambient air of the same elevated building during the condensation-risk period of a year. Temperature and relative humidity were recorded inside, under, and adjacent-to the building at sub-hourly intervals for eleven months, to enable calculations of condensation risk. While extensive prior literature considers condensation in wall and roof assemblies and vented versus unvented crawlspaces; little data or guidance is available about the frequency of condensation risk on the underside of elevated buildings. The growing awareness and effort to improve building resilience at the residential scale demands a greater understanding of conditions at the sixth façade to guide design.

Background

Risks of water in Buildings

Water has long been understood as the enemy of building durability. Since wood is hygroscopic, the moisture content of the wood increases with relative humidity; even when not directly exposed to precipitation or ground water. Wood moisture content must remain below 19% to prevent rot, and below 16% to prevent mold.[1] The fiber saturation point of wood is between 27% and 30% for most species, and if wood remains above this threshold for a prolonged period decay occurs.[2] Excessive moisture can also affect the structural integrity of wood-framed buildings.[3] Moisture, oxygen and temperature, along with an adequate food source, are the main factors for mold and fungi growth in buildings, and since the presence of spores can never be adequately controlled, the moisture conditions in which they thrive must be managed. Water condensing on surfaces creates conditions conducive to mold growth, and if water diffuses into the grain of cellular materials like wood it can support fungal growth.[4] Molds and fungi can have consequences on the health and well-being of building inhabitants, and the integrity of building materials. Practically speaking, the occurrence of these biological activities and material decay are best controlled by controlling moisture and temperature through building systems to avoid moisture accumulation.

Vapor Drive and Condensation

Water vapor generally moves from the warmer to the colder side of building assemblies, from the wetter to drier; and from higher air pressure to low; as a result, vapor diffusion depends on the combined differences in temperature, humidity, and pressure usually described as vapor pressure. Moisture can condense within assemblies if the hygrothermal conditions reach saturation and dew-point temperature, so vapor diffusion is a greater problem in colder climates, where significant vapor drives can be coupled with large temperature gradients. The design of vapor retarders to restrict the diffusion of water vapor in assemblies depend on seasonal temperature shifts and the heating and cooling of a building. Thus climate, plus the location and type of vapor retarder affects the amount of moisture accumulation and mold growth.

Vertical Wall Assemblies

There has been significant research in recent years focusing on the effect of moisture on the building envelope of wood framed buildings, particularly on the effect of moisture within vertical walls. Many empirical studies compare humidity, temperature and moisture transfer measured in various wall assemblies under real world conditions.[5] For greater control of variance, some experiments test the hygro-thermal performance of wall assemblies in controlled laboratory environments,[6] while others seek a compromise by designing and constructing test-bed buildings with specific component and assembly performance that operate under ambient conditions.[7] These studies describe the effects of materials and assemblies on heat and vapor transfer, with data including temperature and relative humidity at different points in the wall, under various indoor and outdoor conditions.[8] While this prior work describes the effect of moisture on the building envelope and defines research methods, vertical walls and horizontal floors are subject to significantly different exterior conditions and internal flows.

Crawlspace Conditions

Fewer studies have considered conditions in elevated crawl spaces, focusing on the management of moisture, ventilation requirements, ground moisture evaporation, and the use of ground cover in crawlspaces.[9] One study compared conditions (air change, relative humidity, temperature, pressure variation) of a mechanically ventilated to a naturally ventilated crawl space in Finland.[10] A subsequent experiment focused on the effect of ground moisture evaporation on the moisture of a crawlspace 0.9 meter in height and 1 meter below ground level.[11] In this experiment, Kurnitski found that a crawlspace with relative humidity levels over 80-85% for “several weeks or months” can result in mold growth.[12] Similar periods of elevated moisture have been found to occur in crawl spaces when ground moisture evaporation raises the relative humidity of the space.[13]

Adding ground cover in the crawlspace, coupled with a low air change rate or natural ventilation, has proven effective in controlling the moisture of crawlspaces. Ground covers prevent evaporation from the ground, as the studies show a clear correlation between relative humidity of ground surface and moisture evaporation rate. Higher ventilation rates may lower relative humidity which can in turn prompt greater evaporation rates. Ventilation may also reduce air temperature and thus potentially increase relative humidity. Seasonal and daily weather changes significantly affect the moisture conditions of crawlspaces. Dry, winter air removes absolute moisture from the crawlspace; however, colder ventilation air decreases the temperature of the crawlspace and increases the relative humidity. Summer air is warmer and more humid than the crawlspace air, so ventilation increases temperature and decreases the relative humidity of the crawlspace. The studies did not find high relative humidity levels in summer, and only short condensation peaks were detected.[14] Together these results emphasize the need to characterize conditions under elevated buildings seasonally.

Elevated Floor Assemblies

Given that it is not exposed to precipitation, condensation is an important source of moisture at the sixth facade. In older buildings without floor insulation, the floor framing generally remains above the dew point temperature of the crawl space, preventing condensation.[15] Adding insulation can reduce surface temperatures below dew point, resulting in condensation on the insulation and exposed floor framing. Cantilever floors with a similar exposure to exterior conditions address the problem by sealing exposed joists with a foam barrier.[16]

As ground moisture evaporation is a primary moisture source under the building, many authors recommend the use of polyethylene sheeting as a vapor barrier between the ground and crawlspace.[17] Additional steps for reducing moisture in crawlspaces include effective site drainage and providing a minimum of 8-inches vertical clearance.[18] These recommendations have been proven for crawlspaces, but not for an open, sixth-façade condition.

Building regulations in flood zones require elevating buildings above average flood levels. The FEMA Advisory Base Flood Elevation guidelines require new homes built in post-Katrina New Orleans to be elevated a minimum of five feet above grade on raised pier or raft slab foundations but note that flood waters may reach higher levels. FEMA further requires the use of moisture resistant materials such as fiber cement protection board over insulation, and a 2-inch foil-faced polyisocyanurate to act as vapor control layer. To address concerns of moisture accumulation in floors with these new insulation requirements, the guidelines require insulation to be on the exterior and be removable to assist in drying if vapor/water enters cavity.[19]

The organization Project Home Again (PHA), replaces homes that were badly damaged or destroyed from Katrina and developed a system of building assemblies to prevent flooding and moisture damage. PHA Phase 1 houses are elevated at 3-feet above grade on a block foundation. The 3-foot space is vented and surrounded by latticework to allow flood waters to pass underneath. Floor framing is insulated with 2-inches of high-density spray foam underneath CDX subflooring. Spray foam has a low vapor permeability, keeps the subfloor warm to minimize condensation, it can also dry quickly in the event of moisture intrusion.[20] In some cases, as with the PHA homes, enclosed or partially-enclosed crawlspaces are permitted in flood zones, if they include flood openings not more than one foot above grade to allow water ingress. Ventilation openings do not generally satisfy these flood requirements.[21] Because the FEMA regulations focus on the threat of flooding, they do not address the less-dramatic effects of ongoing moisture damage, although they may create these conditions.

Method

The test building for this study is a wood-framed residential building on the Tug Hill Plateau in north-western New York, climate Region 5A. The building measures approximately 24’ x 36’. The structure is elevated on wood piers above the ground, which slopes slightly such that grade level is approximately two feet below the finished floor at the south end, and approximately three feet at the north end. The walls and floor are insulated with friction-fit fiberglass batts between studs and joists. The first floor is finished with vinyl tile adhered to an OSB base on a plywood subfloor. The floor insulation is protected with an asphalt impregnated particle board attached between (not below) the joists, which does not provide a continuous air- or vapor seal. The soil under the building is uncovered, the spaces between the piers are open to the air, and surrounding site is a grass lawn.

Data were collected using Onset Hobo datalogging sensors. Type MX2301 temperature and relative humidity sensors were placed centrally in the first and second floors. Type MX2302 sensors (which have the sensors in an external probe to facilitate placement in awkward locations) were installed in the attic and at the sixth façade, in both cases in the center of the building and the vertical midpoint of the space. Both the MX2302 and MX 2301 have an accuracy of +/- 0.2ºC and +/- 2.5% relative humidity and can download data via Bluetooth once installed. To measure ambient exterior conditions, an Onset U23-002 housed in a light-colored solar radiation shield was mounted five feet above the ground on a pole north of the house above low grass. This sensor has an accuracy of +/- 0.21ºC. Additionally, Onset UA-002-64 pendant dataloggers with an accuracy of +/- 0.53ºC, were placed under the eaves on the north, south, east and west facades of the house to record radiation and air temperature for each orientation. Figure 1 diagrams the locations and placement of the sensors.

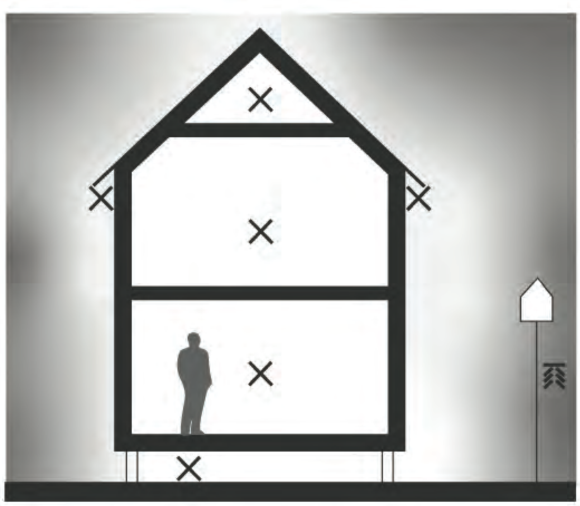

Fig. 1. Sensor placement diagram, section cut east/west.

The study was conducted over winter, the period with highest condensation risk, recording data from August 5, 2017 through June 27, 2018. The sensors logged temperature and relative humidity at 15-minute intervals. At the end of the study period, data values were read out and the sensors left in place for further study.

Results

Industry standards suggest risk of condensation on surfaces whenever relative humidity of the air exceeds 80%.[22] Of course, whether or not condensation will occur on any *particular* surface depends on the temperatures of the surface, and the presence of water vapor (by infiltration or diffusion), all tied to specific assemblies as well as environmental conditions. However, the 80% RH benchmark was used as the threshold for this analysis, because it is based on measurements of surrounding air temperature and humidity, rather than the temperatures and moisture content of possible condensing surfaces in the floor assembly.

Over the study period, ambient relative humidity consistently enters and remains in the condensation risk zone, as shown in Figure 2. However, the trend line for the outdoor data stays within the risk zone for almost the entire year, with less variance in the hourly data between the months of December and February corresponding with the lowest air temperatures.

At the sixth façade, there is a clear trend of an increasing relative humidity for the below-building air during the winter months; between December and March the conditions at the sixth façade remain in the risk zone and then decrease in the warmer months. When compared to the sixth façade, the first-floor interior conditions maintain a low relative humidity. The temperature mirrors the sixth façade and outdoor temperatures as the house remains unconditioned throughout the year, aside from several weekends when it is inhabited, these weekends can be seen in the spikes in November.

Discussion

A risk index was developed to identify times when the relative humidity of the sixth facade was greater than 80% and the relative humidity of the outdoors was less than 80%, indicating times of unusually high moisture below the building while excluding times that might have overall high RH, for example when it rains. Parameters were set by the accuracy of the sensors (+/- 2.5% RH) with a conditional statement: if the difference of the sixth facade and 80% was greater than the absolute value of 2.5, and the difference of the outdoors and 80% was less than the absolute value of 2.5. Data that fit between these parameters was compared with the difference of the relative humidity of the sixth façade and 80% relative humidity divided by the difference of 80% relative humidity and the relative humidity of the outdoors, as shown in the Risk Index Equation. During 520 out of 7,824 hours (6.6% or 22 out of 326 days) the relative humidity of the sixth façade was higher than that of the outdoors. The risk index ratio described below quantifies these hours of condensation risk.

Figure 3 depicts the trend lines in comparison to the risk index and condensation risk zone. The index peaks at the times when the trend of the sixth façade is greater than that of the outdoor relative humidity.

Risk Index Equation

$r_s = Sixth\ Facade\ Relative\ Humidity$

$r_o = Outdoor\ Relative\ Humidity$

$If\ r_s > 80\ and\ r_o < 80,$

$and\ if\ r_s - 80 > |2.5|\ and\ 80 - r_o > |2.5|\ ,$

$$then\ Risk_{\ condensation} = \frac{(r_s - 80)}{(80 - r_o)}$$

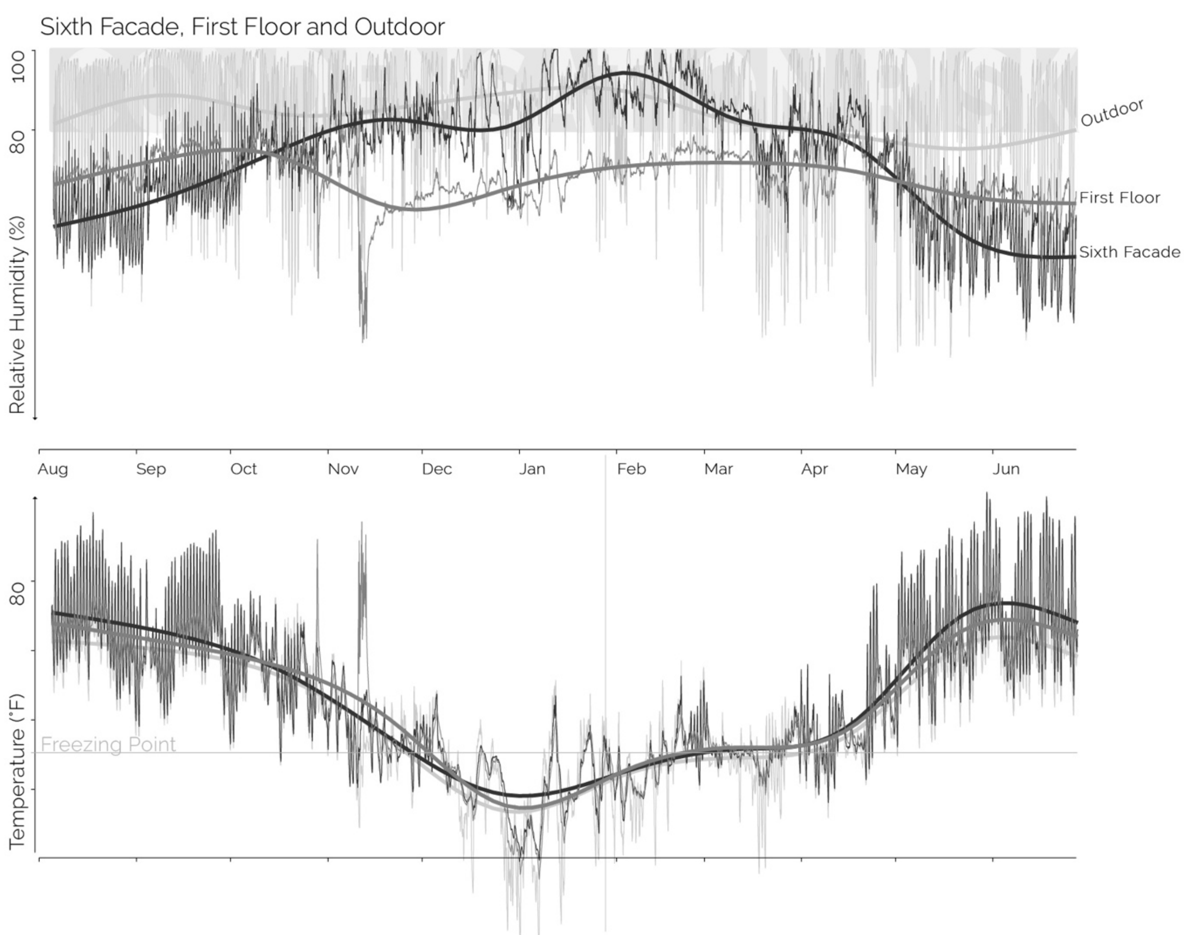

Fig. 2. Annual hourly of Relative Humidity and Temperature

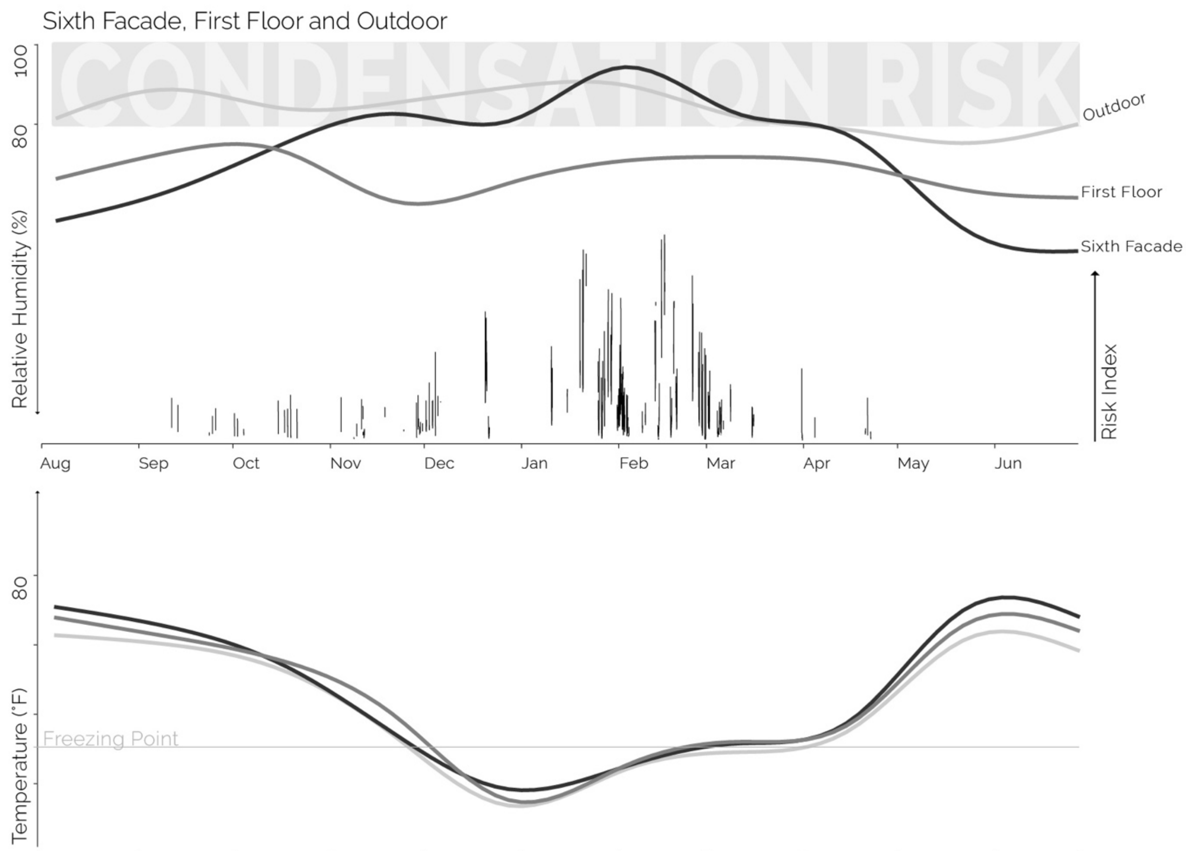

Fig. 3. Annual trends versus calculated risk index.

Conclusions

While limited to measurements of temperature and humidity of air, this data helps provide a better understanding of the microclimates that occur at the sixth façade. Understanding that buildings experience (and indeed create) multiple surrounding conditions, rather than a singular “exterior” supports further study of the response of various building assemblies to their specific environments. The condensation risk index clearly illustrates winter as the risk season even though RH is low. This risk is particularly evident when the house is heated (although this may also reverse the vapor drive) and on the edges of winter, when the temperature is near but not quite below freezing. This can be seen in the spikes between the end of January and early March.

Since the test building was unoccupied for most of the year, future work includes an analysis of occupied buildings to determine the condensation risk and moisture accumulation in various locations of floor assemblies separating occupied (heated) space with the environments below the sixth façade measured here. This would necessarily incorporate measurements of the specific assemblies, and their materials’ conductivity, permeability, and airtightness relative to the vapor drive and exterior conditions.

Although well-documented for walls, the effects of building-ground radiant exchange and solar radiation on vapor drive at the sixth façade are not well studied. Similarly, the influence of the dimension between grade to the underside of the floor and the effect on ground moisture evaporation represent areas for additional work. Finally, while not the focus of this study, the experimental design included collecting data in the attic, which exhibited even greater extremes of relative humidity than those on the sixth façade. Comparing this data to the second floor and outdoor condition may lead to similar conclusions.

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Comprehensive BIM Integration for Architectural Education Using Computational Design Visual Programming Environments

Roger Schroeder and William Dean
SUNY Alfred State College of Technology

Abstract

It is well established that Building Information Modeling (BIM) has had a significant impact on the way Architects and their firms view and approach design projects, and, to a larger extent, how this evolution is influencing and advancing workflow in the Architecture, Engineering and Construction (AEC) industry as a whole. What is not as clear is how the academy is responding to these changes, and the challenges associated with integrating the complexities of a fast-emerging technology into the architectural curriculum. Recent developments in visual programming environments that function as integrated components of the BIM software point to new ways to interact with the emerging and evolving BIM paradigm now common to most educators. Presenting this material comprehensively across the program curriculum is difficult since the expertise to develop course-specific computational content may not yet exist.

This idea of exploring computational visual programming across the curriculum can be envisioned as a tool for reimagining aspects of the process of design education and learning methodologies. Core evolving features of using this technology are the ability to include new collaborators, create real-time collaboration across web interfaces, provide design participants interactive design tools, compress design development cycles, and create more efficient designs that enhance beauty and functionality.

This examination explores a methodology of applying computational frameworks into coursework throughout the curriculum. It is proposed that building learning components in a modular form will allow both educators and students improved accessibility to the concepts. Underpinning this modular approach is the availability of using node based parametric modeling tools to extend BIM software, notably Dynamo for Revit, and the nodes being developed for it by the design community.

Course materials are envisioned around a pre-constructed BIM model (or one developed for the course) and will use guide documents and step-by-step video instructional support to simplify inclusion into the course. Conceived to be one class period in length with the exercise completed outside of class, a few examples will be explored and developed for this initial survey. Instructors would use the material directly or as boilerplate for customizing it to varying instructional situations. Specifically this learning framework uses visual programming experiences applied to parametric elements (glazing, wall type, room shape etc.) to achieve insight into specific course concepts. For example, in a course section on life safety codes, egress distances can be explored using parametric tools that calculate distance

dynamically as rooms and exit doors are moved during design development of a mockup model. Students will work from a model and then add code and components allowing for conformance reporting. In another example for energy analysis, a parametric louver system might be adjusted in real time in simulations to optimize orientation.

Analysis will also include a deeper exploration of the BIM component, and exploiting it using advanced expression of embedded data using visual code and computational concepts. In addition to looking inward at BIM components, possibly more impactful will be looking outward to model sharing across the browser using WebGL (web graphic software) and code for web and other new functionality now part of standard browser features. Both learning experiences prepare us for the future of integrating AI and machine learning into design tasks.

These individual experience “modules” embedded throughout the curriculum have the ability to connect information to design, allow interactivity and facilitate collaboration with potentially new outcomes. This might create new ways of sustaining creativity and interest in this evolving aspect of design education that might otherwise appear as a “dry” subject.

The Relevance of Visual Programming Throughout the Curriculum

Just as the BIM paradigm has become fundamental in architectural education and shifted thinking on many aspects of design education, it is likely that computational design and visual programming will have similar profession-wide effects.

It is not surprising that many AEC conferences feature presentations by leading firms illustrating the use of visual programming and computational design as a strategic component of the design process. These presentations, by the nature of their sophistication and complexity, are also uniquely interesting. Typically, they describe the coordination between a team of experienced users as a significant element of successful implementation. It is natural with this level of inherent complexity that computational design and visual programming are treated as specialized technologies and presented in stand-alone advanced courses.

To address the idea that this is a complex “high level” concept reserved for advanced courses, the initial program development focuses on learning experience modules that have the potential for being most impactful and accessibility. A design or analysis task that would be difficult to accomplish any other way or with great difficulty has the potential demonstrate usefulness and encourage engagement especially if it can be demonstrated to be implemented with relatively ease.

The best known computational design visual programming environment (CDVPE) for architectural use is Grasshopper, first released in 2007 as a tool for McNeel Associate’s Rhino modeling software. Rhino was quickly adopted by students and architects interested in developing complex but very accurate NURBS defined geometries and Grasshopper allowed for detailed component development on these surfaces. This positioned both the software and the resulting architectural forms at the advanced level in terms of perception. Knowing the history of the development of these tools helps us understand how it is positioned and perceived today.

It is useful to start with an examination about the breadth of the utility of Grasshopper specifically because of the expansive plugins and application this software is used for. A list of plugins to accomplish tasks (some are just in early stages of development while others are mature products) include:

- Daylight and Energy Simulation (Ladybug Tools)
- Structural Analysis (Karamba 3D)
- Acoustic Analysis (Pachyderm)
- Behavioral Space Planning (Space Syntax)
- Evolutionary Problem Solving (Galapagos)
- Form Finding (Kangaroo)

Since the tools that augment the visual programming software extend its utility to many aspects of architectural design and learning, it is an opportunity to look for ways integrate them throughout established courses.

Already, computational design techniques are being applied in industry to achieve objectives that are also taught in architectural course, but without the advantages of these techniques. And while CDVPE's are not currently fundamental to the process it may be informative, creating an important foundation for the evolution of these techniques and better preparing students for the technological changes happening in practice.

Still, having applicable technologies (task specific nodes in the case of CDVPE) is only one element of making it a useful and meaningful educationally. For lessons to work in a proposed modular fashion, they must be both manageable in scope (fit in the time allotted) and be able to expand on the concept in a way that advances thinking. Building these modules successfully will require effort, coordination and desire by all stakeholders. Fortunately we have many examples of computational tools that are creating academic interest because of their usefulness.

For example, for environmental design courses (i.e., Environmental Controls 1&2) "Some of the world's leading architectural practices have developed teams with a special focus on sustainability have implemented the use of building simulation, parametric design techniques and customized computational tools."[1] (Emanuele Naboni 2013).

In courses that focus on building codes and compliance (i.e., Municipal Codes and Regulations) research is being done on automated techniques using visual programming to check BIM models for code compliance.[2] (Preidela and Borrmanna 2015)

Space planning components of studio work could anticipate exploring the mapping of space utilization in the BIM model by using data sets of occupant behavior integrated into a visual representation with Dynamo.[3] (McGinley and Fong 2015)

Delivering Visual Programming Learning Objectives Throughout the Curriculum With Insertions Into Existing Courses

We are already familiar with the fragmented (but improving) application of BIM being applied throughout design education curriculum in the last decade. The BIM model can provide the framework on which to build visual computational concepts. The idea of bridging curricula is not new. "For AEC education to set the pace for industry, the siloing of curricula must be broken down through integration of the disciplines, similarly to what is seen in the industry."[4] (Becerik-Gerber, et al. 2011)

Making curriculum space for the inclusion of new ideas and technologies presents unique challenges. Adding courses seems a cumbersome and fragmented way to introduce ideas that are basic and comprehensive. Our work with developing modular learning components for

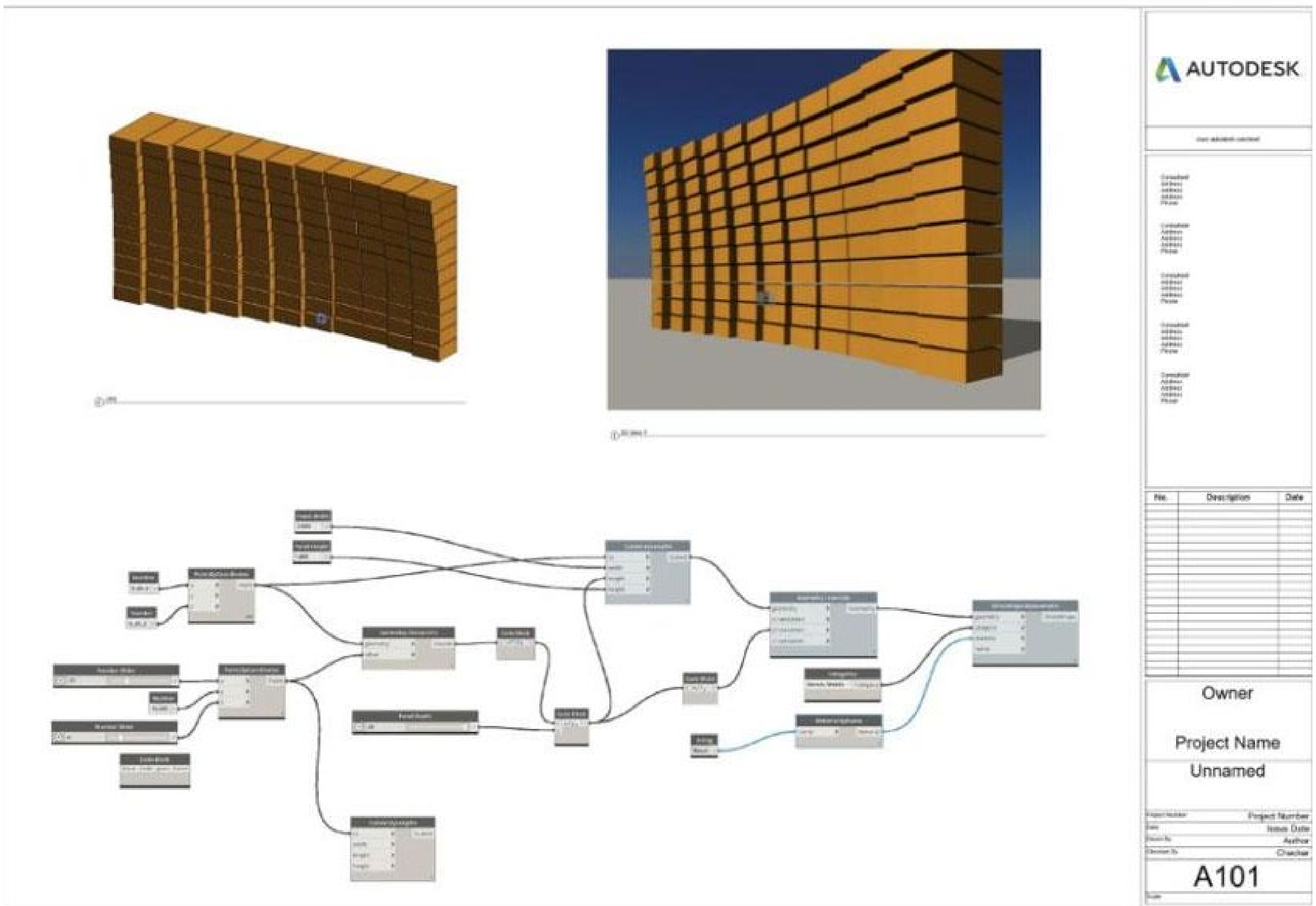

Fig. 1 Attractor Point to Control Panel Depth.

both BIM and Visual programming course work at SUNY Alfred State indicates a potential methodology.

CDVPE Concept Accessibility

Before considering the introduction of computational design concepts to a pre-existing curriculum at the undergraduate level, it is important to gain insight on how early in the sequence students can grasp the concepts well enough to create meaningful learning experiences.

To help us answer this question, in the spring of 2017 faculty introduced a computational design exercise using Dynamo into the Computer Visualization course, an introduction to BIM. This first-year, second-semester course is the first experience students have with BIM software. This project is structured around creating an array of “facade” panels and varying panel depth computationally according to the distance from the panel to a point in space (attractor point). The position of the attractor point is controlled in 2D space using adjustable slider inputs (Fig.1). Students performed as well with this task as other modeling tasks assigned in the course with 72 out of 76 completing the task. This module is now a permanent component of the syllabus.

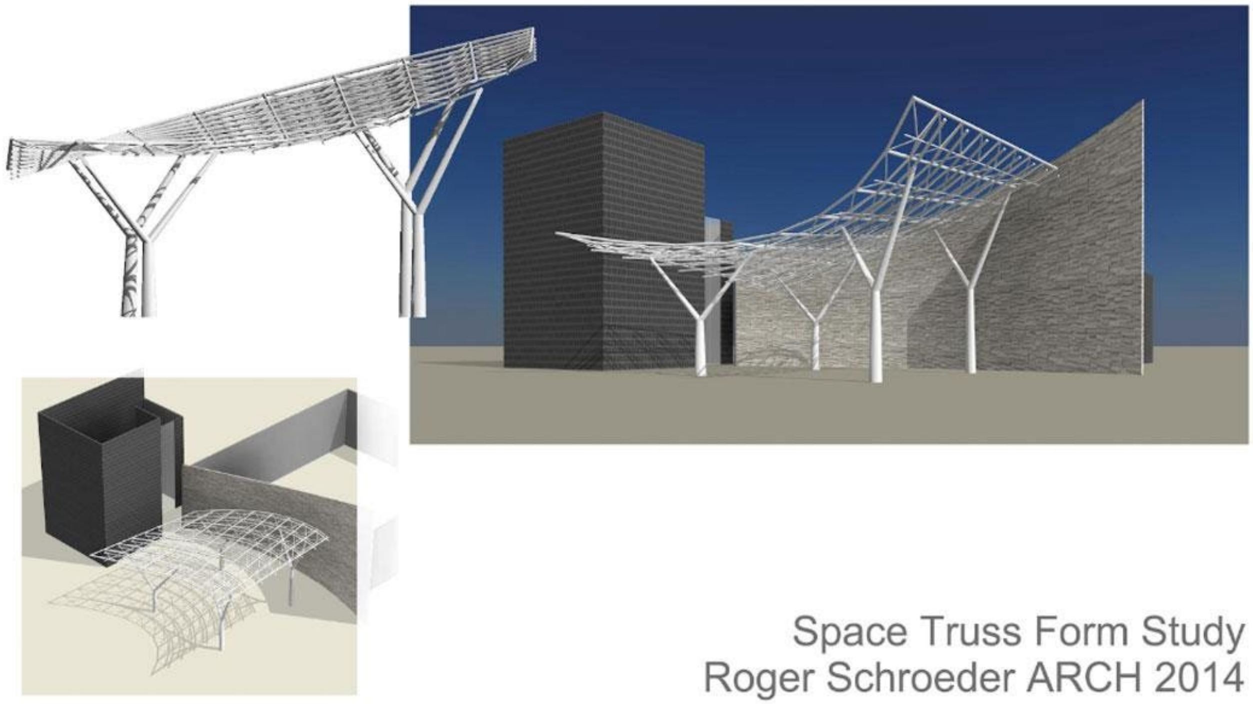

Fig. 2 First Year Space Frame Truss Project for ARCH 2014 Computer Visualization.

The fifth-year Advanced Structural Concepts course contained many CDVPE components in project assignments, and a survey of students (response 13 out of 24) at the end of the semester indicated that students felt that CDVPE material could be introduced by at least the third-year with 60% indicating an introduction even earlier in the second-year.

Software accessibility has also improved with the availability of CDVPE software to students and faculty. Visual programming environments were until recently more complicated to access and had the potential for added student expense. In the case of using Rhino and Grasshopper there was a cost and the need to learn a new software. Within the last few years Autodesk Revit has simplified the task with the inclusion of their CDVPE in the taskbar. This allows quick access by anyone using Revit. Outside developers that have produced nodes for Grasshopper are now making similar if not identical ones for Dynamo, likely in part to the significance of being on the Revit platform.

A Basis for Considering the Integration of Computational Design and Visual Programming into the Architectural Curriculum

The intention of an across-the-program insertion of visual programming, computational design and data driven design use is not to “train” specific solutions, but to create the idea of these tools becoming “natural” in use and application, not unlike sketching is used to inform the creative process.

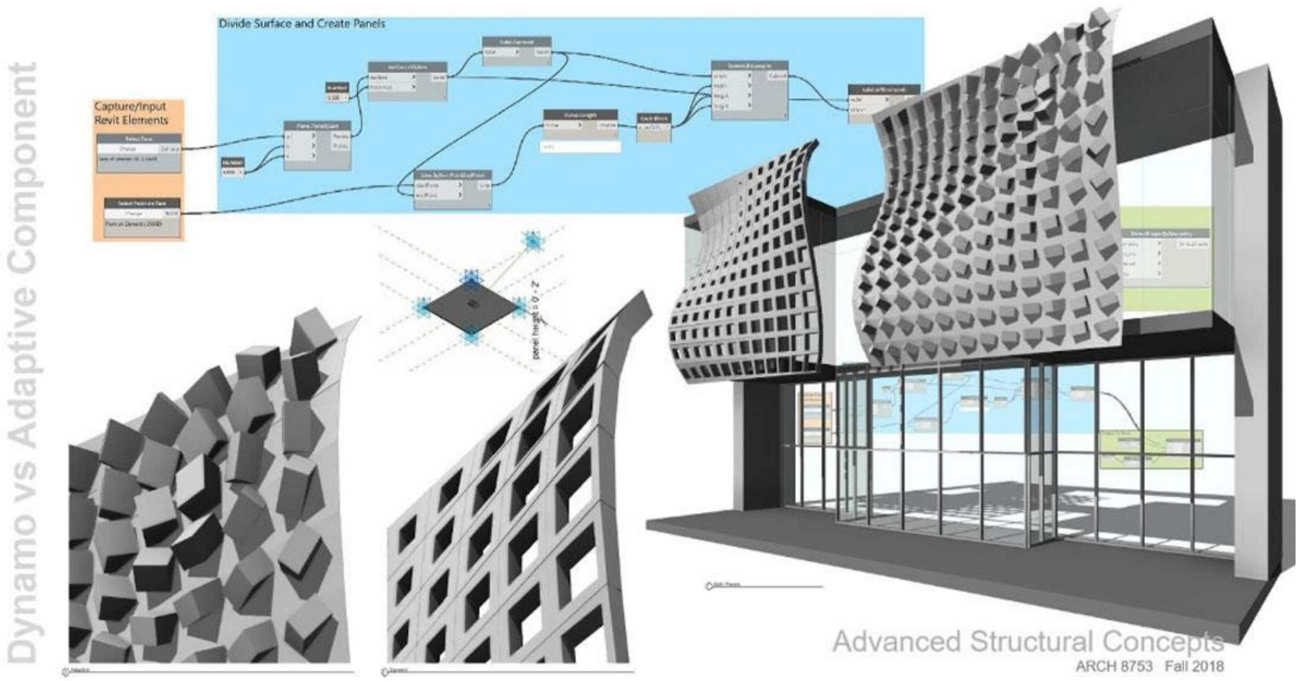

Fig. 3 Project to Contrast Adaptive Components to Dynamo Elements.

Just as BIM is now a commonly accepted component of architectural education programs, visual programming and computational design might then be considered the second-generation evolution of this platform. More concise CDVPE may be considered an augmentation to BIM process techniques.

Fragmentation of technologies resulting from the need to fit into course structure may be an impediment to advancing integrated learning of CDVPE. Just as with early BIM introduction, "Previous studies suggested that offering stand-alone BIM courses without any follow-ups in other courses do not support student long-term learning because students rarely find an opportunity to reuse BIM skills in different courses"[5] (Hu, M. 2018). The intentional injection of CDVPE modules into coursework is intended to address this concern.

Visual Programming vs Parametric BIM Components

The earliest advantages of visual programming were the ability to parametrize, subdivide and apply panels and other components to complex surfaces. Many BIM modelers today address this with features incorporating similar functionality. Pattern based surface division with adaptive component instances is a popular way to create complex geometry in Revit (Fig.2).

It might be argued that many of these types of higher-level tools obviate the need for visual programming knowledge.

While the evolving feature set of BIM software functionality can be viewed as a natural response to improving products in response to customers/industry demands, many BIM features are first developed in a CDVPE. Both the academy and profession are challenged to consider whether to wait for the new feature to be added to software or view CDVPE as an opportunity to innovate and use it as a driver for innovation in both toolset creation and design innovation.

Revit also anticipates this use of visual programming as an "innovation tool" with the development of a Dynamo Script Player. This plugin allows anyone the ability to create scripts that help automate common tasks, for example, calculating room occupancy capacities or automating rebar placement in concrete. This use of visual programming to develop workflow task automation makes learning it a practical as well as creative tool.

Still, there will exist a question about whether CDVPE will lose importance with increasingly sophisticated BIM functionality. To address this question, a project module has been created that solves a parametric problem using both adaptive BIM components and the CDVPE (Dynamo). This allows students to see both methods and the advantages and disadvantages of the alternate techniques (Fig.3).

Inserting Complex Ideas and Techniques in Introductory Courses as Modules

An advantage of exploring ideas in a digital software environment is the ability to easily describe ideas and process across the computer screen. The faculty took advantage of the fact that most concepts can be explained and demonstrated in the BIM screen interface in development of the Computer Visualization course (ARCH 2014). In the spring of 2017 video instructions for each project were created to enhance instruction. Students expressed almost unanimous preference to watching video instruction as an alternative to direct instruction. Reasons stated by students included the ability to individually pace the activity and review problem elements of the process (i.e., rewind the video). This experience is reinforced by a Harris Poll sponsored by Pearson "Beyond Millennials: The Next Generation of Learners" with 59% reporting YouTube as the #1 preferred learning method with 47% spending 3 or more hours on YouTube[6] (Harris Poll 2018).

The general positive response to this type of instruction set the stage for development of visual programming projects/experiences in the Advanced Structural Concepts course (ARCH 8753). In that course students were able to execute complex visual programming tasks without step-by-step classroom instruction. Using the knowledge gained from that experience, the authors are encouraged to attempt to create trial stand-alone visual programming modules that can be made available as components of existing courses. The intention of the module is that instructors need only the conceptual knowledge of the learning objective and no expert (just a working) knowledge of the technical visual programming process. This knowledge can be gained by pre-working the module.

Surveying Student Experience for Understanding

At the conclusion of the Advanced Structural Concepts course, the faculty surveyed students specifically about the visual programming component of the curriculum. This first survey is preparation for developing the ongoing survey instrument for gathering data.

The response rate for the survey was 13 out of 24 students. The survey was presented as a link to a Google form after course grading was completed to remove bias over grading and evaluation concerns. Students were encouraged with a follow up email to respond. In the future the bias concern may be outweighed by the need to improve the response rate. Surveys may be a course

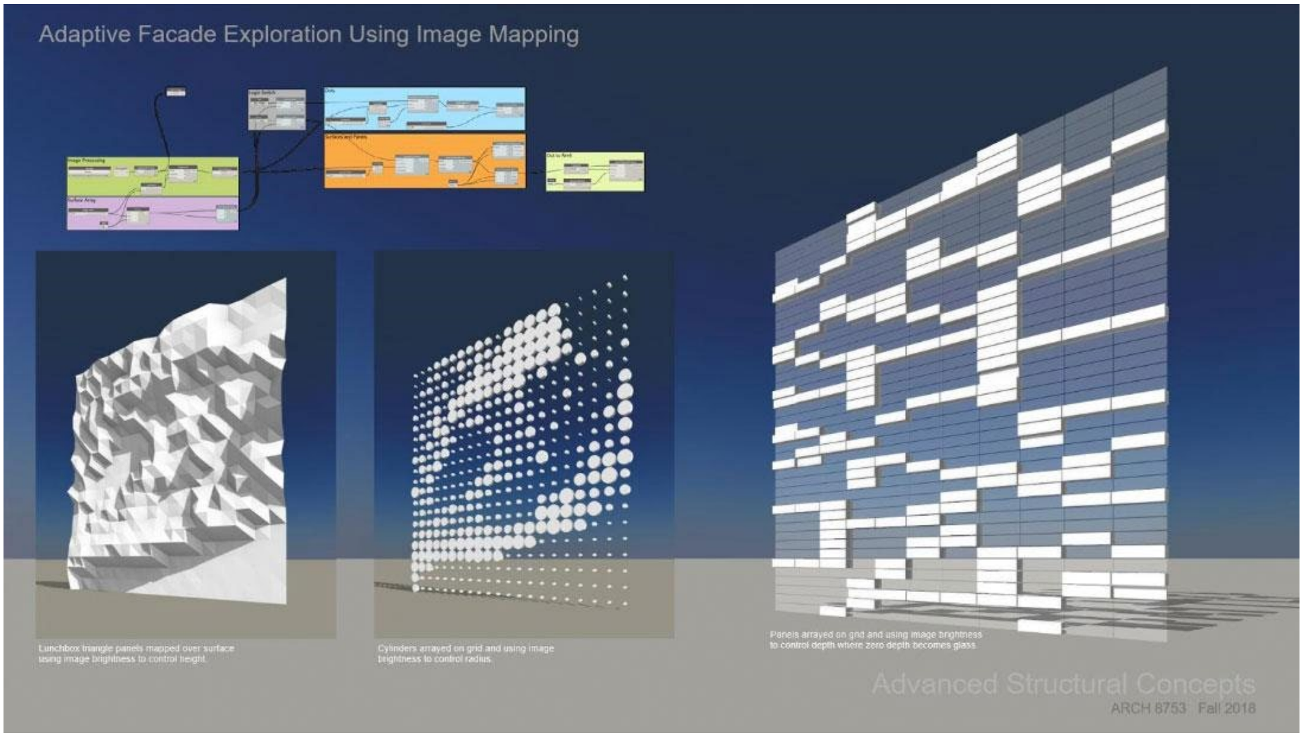

Fig. 4 Adaptive Facade Using Image Mapping.

requirement next semester with users remaining anonymous ensuring a larger survey cohort.

Noteworthy in this first survey was that 76% responded that visual programming will allow them to be more creative designers. The consensus on the difficulty of learning visual programming when compared to other architectural skills was reported to be the same or just slightly higher than other skills.

Important going forward is the development of methods for validating any findings and conclusions with survey and testing instruments.

Formulating Visual Programming Modules

Inserting visual programming components into current course curriculum begins by looking at the existing courses, pre-existing visual programming conceptual projects then finding reasonable first fits. Visual programming content development for the Advanced Structural Concepts course provided good initial candidates for project modules.

Module: Relating Random Data to Form (Facade)

An introductory module was developed to relate data to an architectural form that involves using a photographic image to alter one characteristic of a facade. Specifically in this exercise, students link an image to an array and use that array as the basis for a facade surface. Data is extracted from the image at array points and numerical values are assigned according to image density at that location. The data is adjusted to a useful range and then used to drive facade component parameters to create variations in surface topography, opening diameter, and

Fig. 5 Conceptual Tower Form Using Dynamo.

panel depth in a series of digital mockups. Finally, for the final digital mockup, a threshold is set and Boolean logic is used to substitute solid for glazed components (Fig.4).

The abstraction of data allows students to see data in freeform ways by removing conceptual barriers to both creating and using data.

This project can likely be introduced as early as the first or second design studio with very little dependence on the BIM modeler and a focus on the visual programming interface.

Module: Data as Form (Tower)

High-rise form development using visual programming, while cliché, is also a useful instructional technique. In this module the building floor plate is defined by 4 points joined into a surface using NURBS curves and manipulated by rotating, translating and offsetting the initial surface. Students see how complexity can come from relatively simple math. In this project the sine function is used to create building curvature (Fig.5). Variation is created using slider inputs to vary parameters for height, twist, and curvature, etc. Example applications of this project as a module might be a component of an urban planning design studio or building massing project.

Module: Form from Mesh (T-Splines)

T-Splines can be thought of as the three-dimensional equivalent of a two-dimensional NURBS curve. In this module, students create a form and divide it into a panelized form, and apply T-Spline forms with variable inputs for shape values of radius and fillet, etc. (Fig.6).

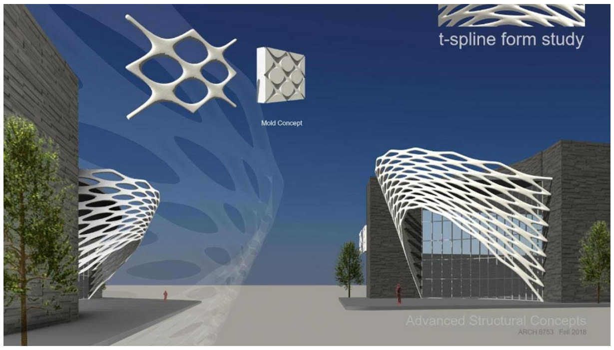

Fig. 7 T-Spline Form Study Project.

It is interesting to note that T-Spline geometry was a component of one of Autodesk's products (Inventor) and is now "exposed" in Dynamo as an experimental function with approximately 150 nodes.

T-Spline geometry is new and evolving but evident in some of Zaha Hadid Architects projects [7] (Schwerdtfeger, E. 2018). Because the resulting forms are organic and interesting, a module could be part of a first- or second-year design fundamentals studio in the program.

Module: Visual Programming and Making

Translating complex forms into buildable components is one of the most powerful applications of CDVPE. In order to build complex forms, one typically needs to be able to manipulate from a position in three-dimensional space to a two-dimensional plane for cutting sheet goods or creating construction drawings. This module takes a curvilinear form and panelizes it before rotating the panels onto a fabrication plane (Fig.7). Students get both the basic ideas of translating geometry and an understanding of flatness as it relates to panelization. When panels are oriented to a plane, the out-of-plane shape of the panel becomes apparent. The techniques

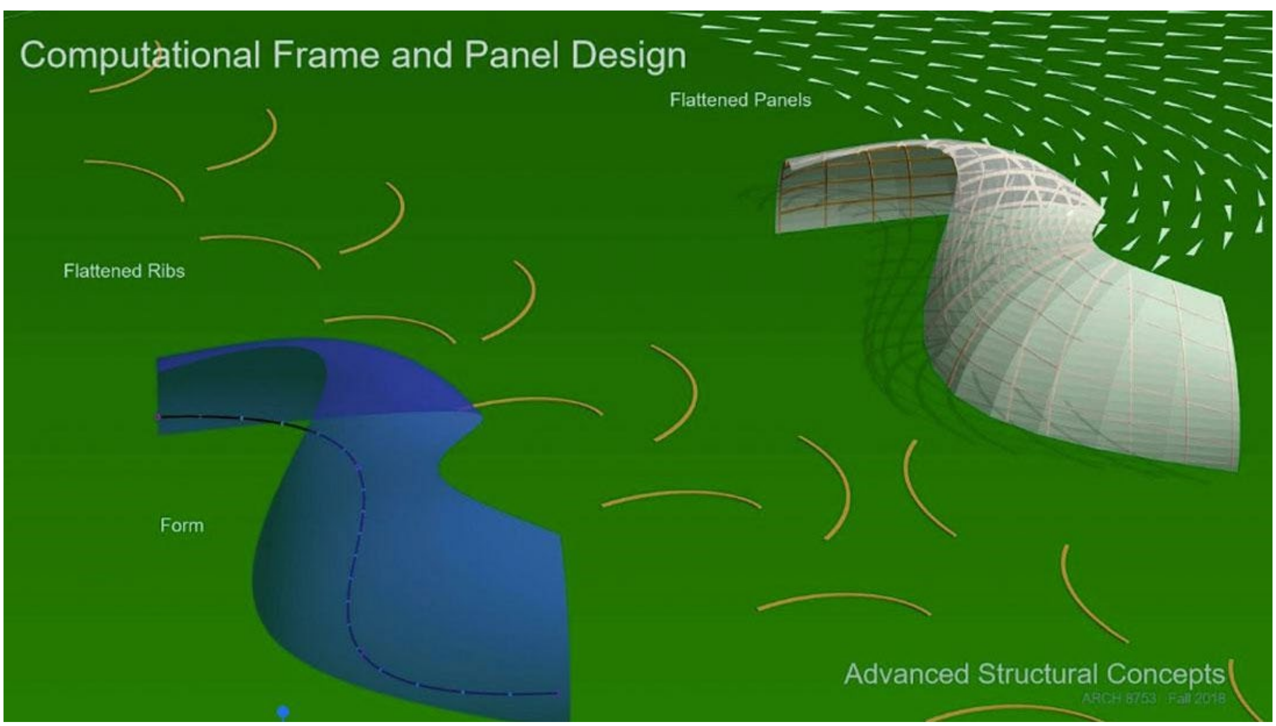

Fig. 6 Project to Design and Flatten Components.

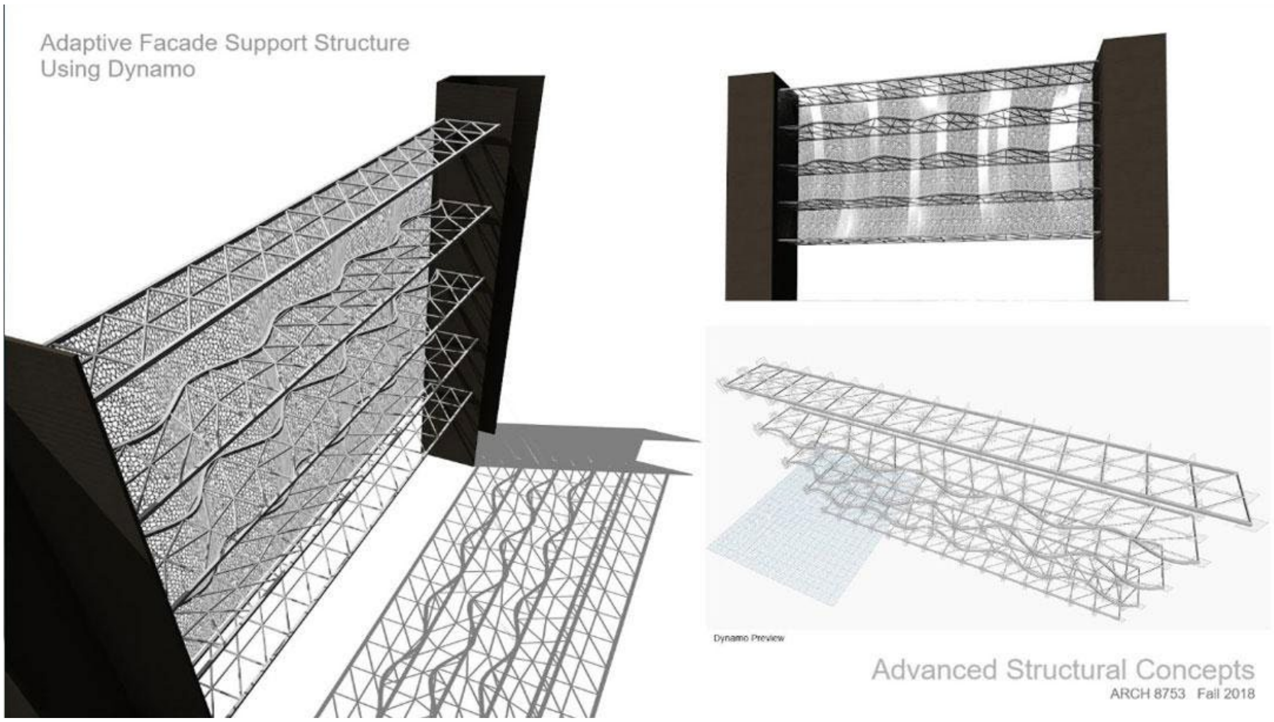

Fig. 8 Computational Truss

developed in this module would be a good fit for studio work involving physical model making and fabrication

Module: Complex Structural Elements

In a previous project, students constructed a wave facade and were then directed to develop structural trusses to adapt to the facade form. Top and bottom truss flanges are identified by intersecting surfaces to find the contour. Flanges are then formed by extruding a profile along the contours. Web bracing is developed by creating a frame in the surface and finally completing the web with the extrusion of a cylindrical profile on web brace elements (Fig.8).

This module could be part of the truss component of a structure's class.

Frame on Form

Visual programming is used to define a form to which an adaptive structural family (BIM component) such as structural ribs can be applied. Inspired by the forms of architect Santiago Calatrava [8] (Calatrava, S. 2014) (World Trade Center Transportation Hub), the visual programming element allows all the shape parameters to be adjustable including the number of ribs (Fig.9). Ribs can be constructed of a variety of structural materials allowing this to work in structures courses or studios which explore materials and their application and expression.

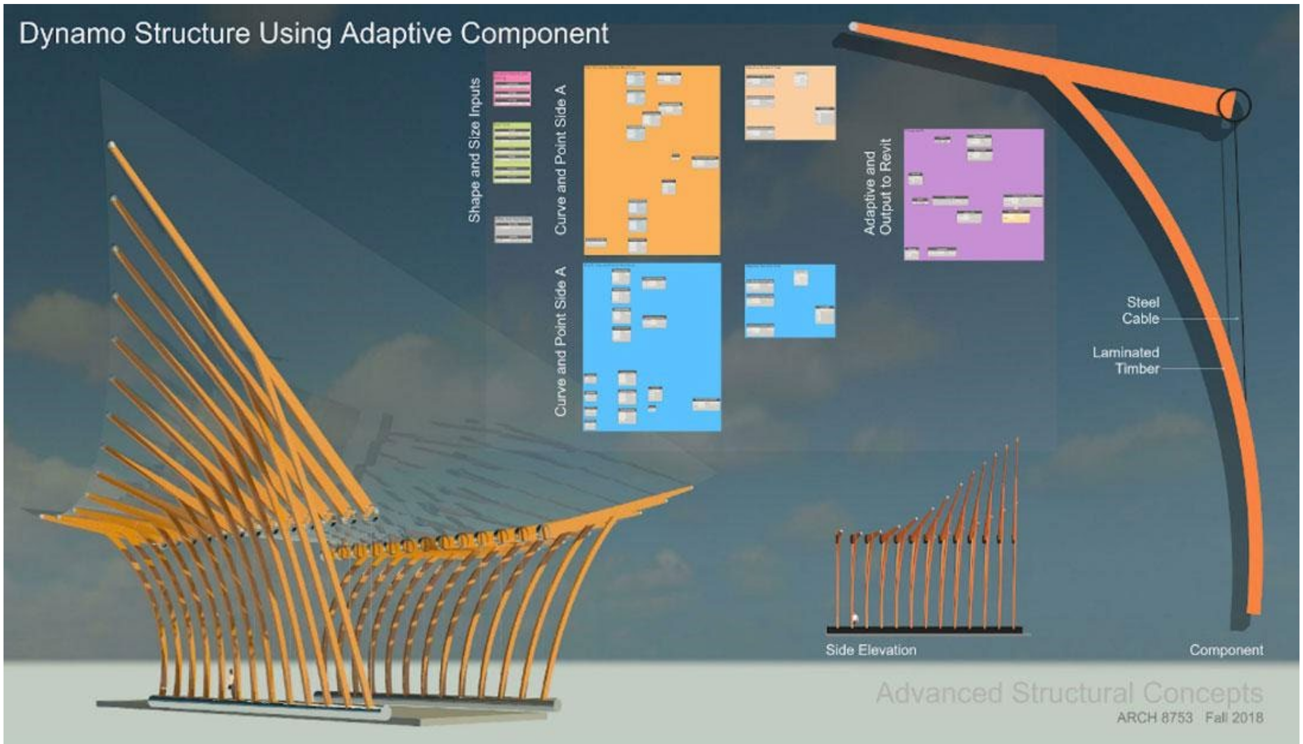

Fig. 9 Adaptive Component Applied to Computational Form

Future Modules: Automated Reiterative / Optimization Modeling (In Development)

Once BIM models are set up parametrically with accessible parameters, they can be uploaded into software that can automate reiterative modeling. Autodesk offered a web version that would allow uploading Dynamo files and provide variable input values (according to user setting) to run the model and save the output (Fig10). Users could review the output for those achieving desired criteria, and because it was web based, it could share the outputs remotely with collaborators. Discontinued in January of 2019, the company is working on an alternative version (Refinery) that is in development with a preview version available. Other companies have similar tools in various stages of development.

Sharing Modules Throughout the Web

Dynamo's visual programming environment can be uploaded to the web, and the ability to share across the web interface opens up opportunities for collaboration. It is unclear where the development of this web product is moving, but as it takes new forms it shows promise as an experimentation tool for collaboration in the classroom (Fig.11).

Methods for Sharing Modules Throughout Courses

Most colleges and universities use course management software that provides a platform for content delivery. Blackboard (software tradename) is used by SUNY Alfred State and is effective for delivering high definition (1920x1080) quality instructional video through high-speed internet connections. The format also allows for multiple instructors, important for responsive technical

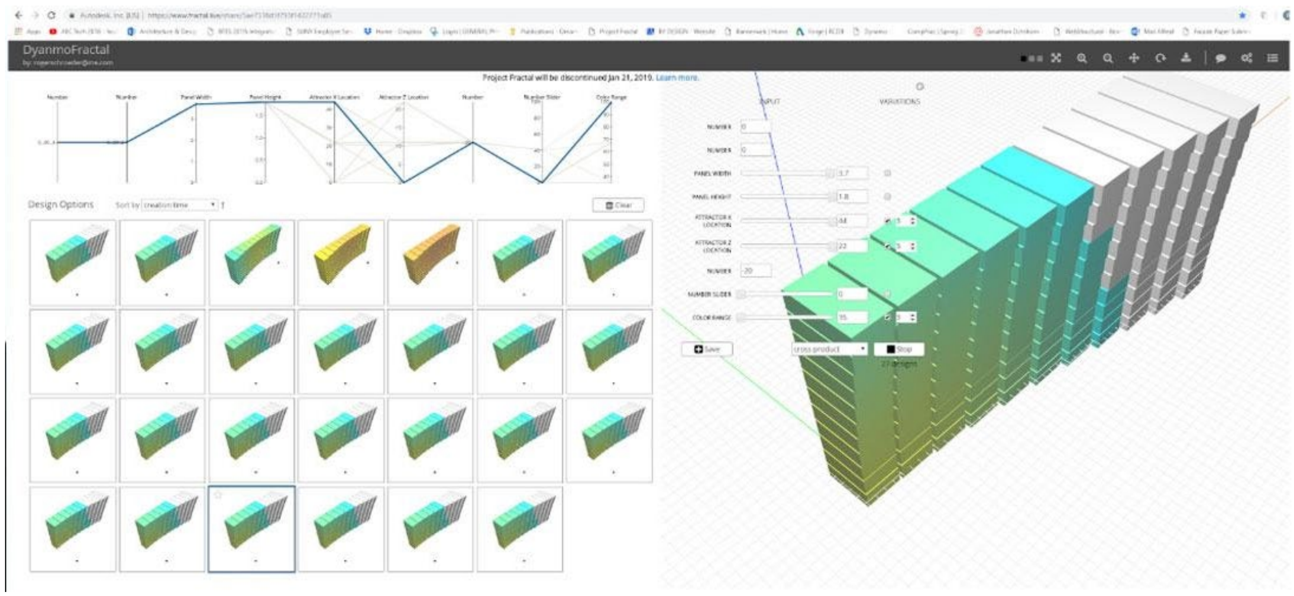

Fig. 10 Autodesk Fractal Live

support for primary course instructors unfamiliar with specifics of visual programming software. The faculty have set up a development "dummy course" to host modules in development.

Developing an Implementation Plan

The concept of introducing shared content between courses might need to be envisioned as part of a larger college experience based on familiar concepts like a lecture series where participation is expected school wide. The depth of an initial trial might involve three courses in a single semester with the related modules built to be a two-hour online tutorial/project. Course faculty would participate in crafting or modifying content and determining scheduling and grading assessments that are consistent with the specific course requirements. Modules would be developed and faculty would be trained on the techniques prior to the semester implementation. Surveys would be added to existing course evaluation tools to provide specific assessment data.

Discussion

All of the projects presented for the initial development of the modules were given to fifth-year Bachelor of Architecture students with no visual programming experience. These students were mature and motivated to complete projects. Students many times expressed frustration with Dynamo issues creating time-consuming functional problems when running. This will be an important consideration going forward when planning for implementation with students in early parts of the undergraduate program.

Faculty interest and enthusiasm to adopt new elements into establish courses will determine the effectiveness of the investigation of these modules.

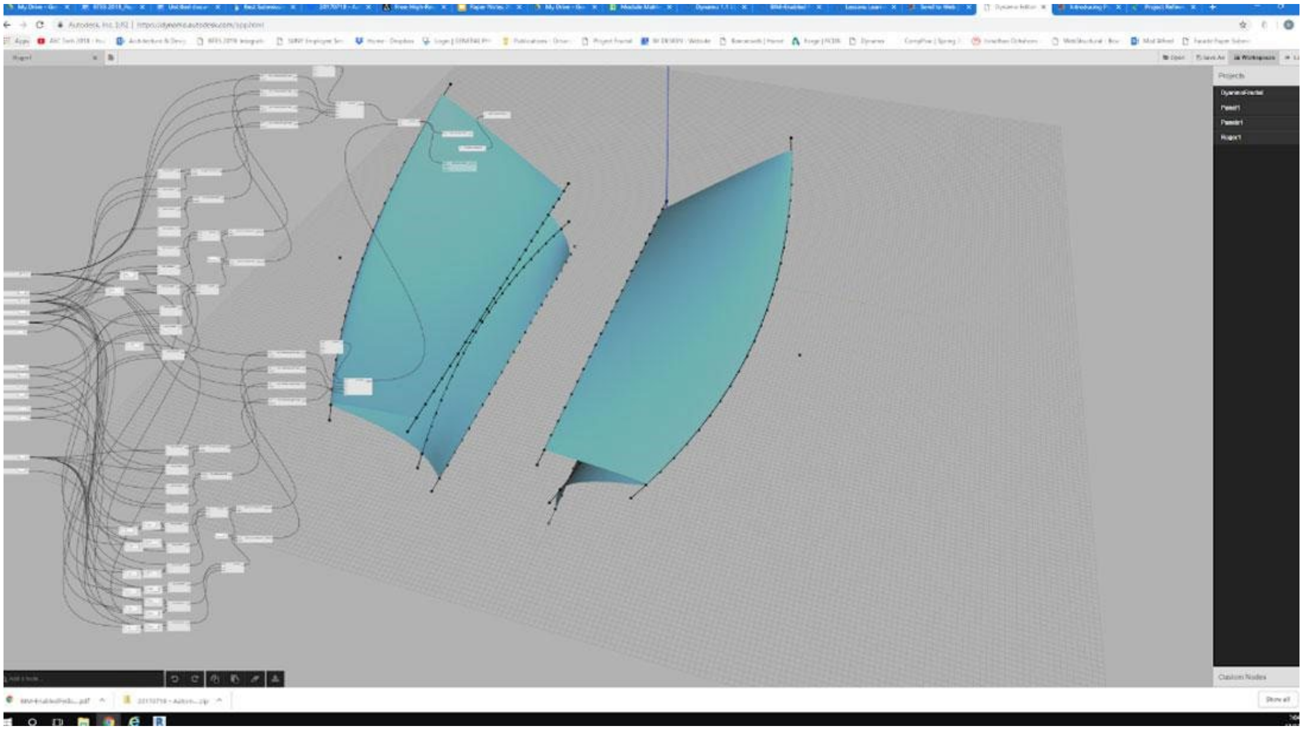

Fig. 11 Dynamo Editor (web based interactive interface)

Conclusions

While Computational Design and Visual Programming Environments appear now to be an advanced curriculum content that may be become accessible to undergraduates with well-developed projects and exercises throughout modules introduced into the curriculum.

Initial success with visual programming at the first-year level indicates that early introduction of these concepts may be effective in other courses encouraging the next steps in initial trials.

Further experience with fourth year students in using CDVPE's demonstrates the possible introduction of these tools earlier in the program and into a variety of courses.

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Situated Learning Through Robotics Processes

Shahin Vassigh, Jorge Tubella, Hadi Alhaffar, Julian Ramirez and Sara Pezeshk

Florida International University

Abstract

Technological advances in robotics, digital fabrication, and sensor technologies are changing the landscape of innovation, design, and production. However, integration of these technologies in architecture programs is a challenging task. It requires extensive knowledge of the robotic arm operations, complex computer applications, and developing interdisciplinary skills for producing the end of arm tooling, which makes architectural experimentation and production possible. The following paper describes an informal approach to an interdisciplinary collaboration experiment for initiating operations of a new robotics lab. Leveraging the inaugural event of the lab, students and faculty were invited to design, construct, and participate in exhibiting four projects at the event. The paper explains each project, how student and faculty interacted and learned advanced fabrication techniques, and how their experience contributed to the overall establishment of the lab.

Introduction

Technological advances in robotics, digital fabrication, and sensor technologies are changing the landscape of innovation, design, and production. Intelligent machines are not only replicating human's physical capacity but are increasingly enhancing and augmenting humans in a wide range of endeavors and businesses in manufacturing, construction, and engineering among others. These technologies are no longer the province of large corporations and institutions but are becoming prevalent in small businesses and firms (Manyika et al. n.d.). It is expected that they will become ubiquitous - a competitive necessity for large and small organizations across the economy.

These advances are also reshaping the Architecture profession. Automated building design with advanced software, mass customization of building components with robotics, and large-scale 3D printing of buildings are growing at a steady rate (Kolodner n.d.). According to the World Economic Forum (WEF), robotic construction and production will be strong drivers of employment in architecture and construction. They foresee that manufacturing will transform into a highly sophisticated sector where high-skilled people, such as architects, will be in strong demand (WEF, 2016). It is also expected much of the routine activities of architects will be automated in the near future (Davis, 2015). Therefore, advancing technological capability of architects is becoming a critical aspect of the profession, research, and education.

While technical and specialized skills of architects will continue to be important, because of the interdisciplinary nature of advanced technologies, collaborative skills are becoming increasingly critical as well. Building an understanding across different disciplines as well as the ability to work with others creatively will be a key element that will differentiate the new workforce (Partnership for 21ST Century Learning, 2015).

With these technologies and their associated skillsets as the hallmark of future jobs, architecture schools are moving to incorporate robotics technologies into their curriculum and create interdisciplinary educational opportunities for students. Many schools are investing in robotic arms and the required infrastructure (Brell-Çokcan and Braumann 2013). However, other than a handful of universities with extensive resources, integration of robotic arms into architectural curriculum is challenging and faces several challenges which goes beyond securing funds for the purchase of equipment.

The first challenge is getting started which is often a long process. This requires a custom-built environment with adequate physical infrastructure, knowledge of hardware components, understanding the operating system, and calibration of the arm and tools. The second challenge is having the right tools. Robotic arms are extremely versatile and can carry numerous tasks, however a key barrier is in devising the appropriate end of the arm attachment or “end-effector”. Producing end-effectors which makes architectural experimentation and production possible entails knowledge of computer applications, mechanical systems, and integration of sensors and in some cases small robotics. Many of the available end-effectors in the market are produced for repeatable industrial applications, have limited use for architectural production, and are cost prohibitive. Therefore, architecture students often need to design and fabricate their own.

Finally, the absence of a support structure for integration of these technologies to the curriculum, and facilitating interdisciplinary collaboration is another barrier. Many architecture students are not aware of the utilities of the robotic arms and lack the required programing skills which makes them disinterested. Because these skills are not often taught in the architecture curriculum, reaching out to other disciplines for collaboration is critical. Providing incentives for collaboration with other disciplines, developing team-based projects, and opportunities for students to integrate new skills into their coursework are all a part of building students’ motivation, capability, and their use of these technologies.

This paper describes an approach to engage students with the newly established Robotics and Digital Manufacturing Lab (RDF) at Florida International University. The approach involved an interdisciplinary experiment for developing several projects for the inauguration ceremony of lab. The authors (faculty and graduate students) of this paper were the inaugural team in reasonable for organizing several student teams who exhibited their projects at the event.

Inaugurating the RDF

Upon agreement on the event, the inaugural team proposed several projects to highlight different technologies and tools that the lab offers. Once the projects were announced to architecture students, they were placed into groups based on their interest in the projects and each graduate student of the inaugural team became responsible for mentoring one of the groups.

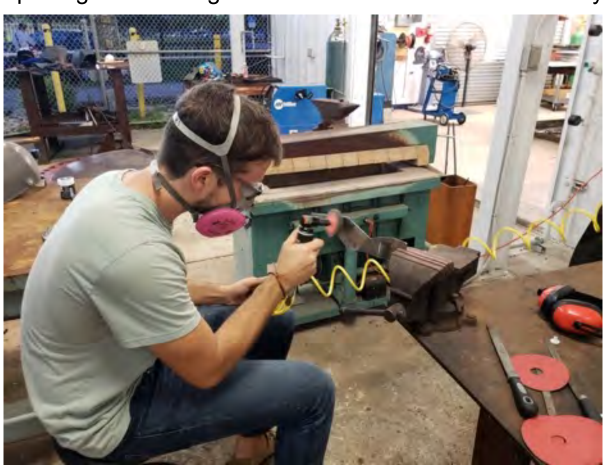
To begin, each group conducted a charrette on how to approach the project and understand the required technical expertise to complete the project. Then, the mentors of each team reached out to students and faculty from computer science, art, engineering, and music to join the teams. Brining faculty and students from other disciplines onboard was not a difficult task as they realized the event’s high visibility.

Mentors served several roles in the project. They led the project by identifying problems, providing feedback, and facilitating communication among different disciplinary perspectives to resolve issues. They helped students to learn from each other, build their technological skills, and understand how to navigate in interdisciplinary environment. Each project engaged a specific aspect of robotic processes for showcasing the end-effector design and development, convergence of digital and physical simulations for artifact creation, and incorporation of external data to control a system of actuators. These projects are described by the mentors of each team in the following sections.

Inaugural Scissor

This project commenced the event by a novel approach to cutting the inaugural ribbon with a scissor controlled by a robotic arm which involved close collaboration with sculpture art students. The project was conducted in three stages: 1) design and fabrication of end-effector, 2) integration of end-effector with the robot, and 3) programming of simulation for robotic movement and scissors actuation.

First stage required creating a frame for mounting the scissors to the robot. The team decided to use a steel frame (because of its strength) for attaching the scissor to the robotic arm and mounting a linear actuator onto the frame safely. The next step was to transfer the linear motion of the pneumatic actuator to radial motion for opening and closing the scissor. This was achieved by



Sculpture department student grinding steel frame

mounting the actuator on separate pivot points and give it enough tolerance to open and close completely. The final step of fabrication was to create a 3D printed attachment for the eyelid of the scissor handle that would be fixed to the linear actuator. The scissor was 3D scanned and the model was imported to Rhino for designing the attachment which was printed from PLA filament.

The second stage involved mounting the end-effector to the robot to check its tolerance for collision. Once the actuator was tested manually it was connected to a two-way pneumatic solenoid controlled by the robot.

The final stage was to program the end-effector for a simulation that demonstrated the range of motion of the robotic arm as the end-effector actuated to open and close the scissor. The simulation moved around the envelope of a geodesic dome (see next section) in a playful manner until it reached the cut point. A final calibration of the simulation was conducted at the day of the event to ensure the end-effector lined correctly with the ribbon for cutting when the President of the University pressed the command to initiate the sequence.

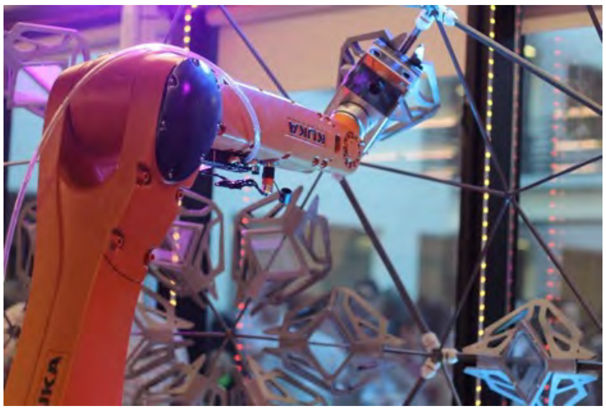
The project was successful and the attendees enjoyed

Scissor end-effector mounted to robot and actuated

the show. However, the most important aspect of the project was the interdisciplinary collaboration and learning teamwork. Working collaboratively students learned about fabrication techniques using steel and understood the mechanical principals needed to properly actuate the end-effector. The development of the end-effector was documented and are currently used to teach workshops for developing them.

Geodesic Envelope

This project was an open-ended exploration of robotic assembly to demonstrate the KUKA KR10's reachability, flexibility, and accuracy. Our team developed a geodesic steel dome and envelope components to be placed on the structural frame of the dome during the event. We



Placement envelope components on Geodesic Dome

designed the project around the vacuum gripper which was one of the lab's first purchased and integrated end-effectors. The project was conducted in three stages: 1) development and testing of a vacuum gripper pick and place script, 2) design of a robotic arm assembly, and 3) design and fabrication of the dome and its envelope components.

To design a sequential motion of the arm we developed a pick and place script using Grasshopper 3D, which is a visual programming software. The team created a 3D model of the physical environment surrounding the robot (work cell) to avoid any possible collisions. Once that was accomplished, the script was tested with the robotic arm controller. In our first test, the gripper was damaged because of minor discrepancies in the heights of the physical environment and the digital model. Small adjustments to the 3D model were then applied to reconcile to the digital and physical environments and the simulation became successful.

The second stage involved developing a form which showcased the robotic arm's capabilities. This was achieved by mapping the maximum reach of the robotic arm's work envelope. The envelope has a deformed spherical shape that represents the full extent of the arm's movement in all directions. This realization led the

Geodesic Dome with KUKA KR10 in Action

team to design a geodesic dome fabricated from steel. This structure provided the right shape to showcase the accuracy of the pick and place simulation and it could be fabricated easier with modular construction.

The envelope components were milled from wood and used magnets to attach to the steel frame. The physical placement of the components by the arm inside the dome was challenging as the physical locations did not match the virtual environment. In fact, even small movement in the dome caused discrepancies and deflections on the sides of the dome. Our team's deliberation on how to solve the problem led to designing a new end-effector which could calibrate the joints coordinates in the virtual 3D model accurately. Once the coordinates were updated, the simulation succeeded.

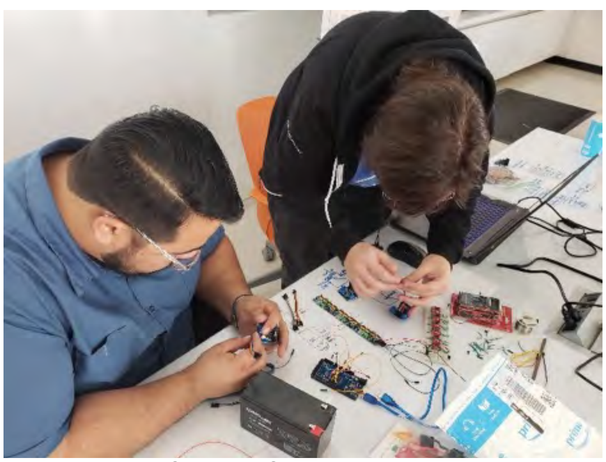
This project was a learning experience in how to use a vacuum gripper that required establishing a workflow for using an extremely accurate tool (robotic arm) and reconciling it with analog fabrication. This workflow was documented and is used by other students at the lab.

Arduino Drum Installation

The ribbon cutting ceremony was accompanied by a drum roll that was played by four automated drums. The premise for the project was to play several algorithmic musical pieces written for percussion instruments at a speed and complexity which humans could not play. To create the system, several activities occurred simultaneously.

One of the activities was the fabrication of the mounting system for the mechanized drum stick connection to the drum set. To save time and effort, our team used an existing system to produce the mount. Another activity required prototyping and programming of the drums which was controlled by an Arduino micro controller. To achieve this, the team had to resolve several issues. First was the actuator movement, as it only moved in one direction and then needed to be reset. The team's solution was to use a computer chip that controlled the power input for the motor to actuate back and forth.

Another problem was controlling multiple actuators simultaneously because the Arduino is a single task controller. After some research, we were able to use a digital library that allowed the Arduino to multitask. Developing communication between the Arduino and the musical composition program was also a problem. We overcame this by using a digital output from the program



Architecture and Computer Science students working together for actuator prototyping

which was interpreted by the Arduino to control each drumstick independently based on the note it was assigned to play. The drum set was then stress-tested and became ready for playing music pieces that were composed by the team to highlight the drum set's capability.

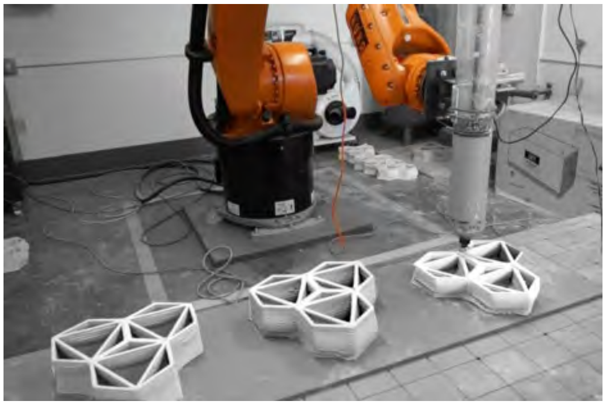
As this project involved different skills form each discipline, communication between the team members became the main driver of learning. The lessons learned through our interactions were valuable for the members of the team and will be shared through workshops and future collaborative project.

Inauguration attendee viewing the robotic drum installation

Ceramic Wall

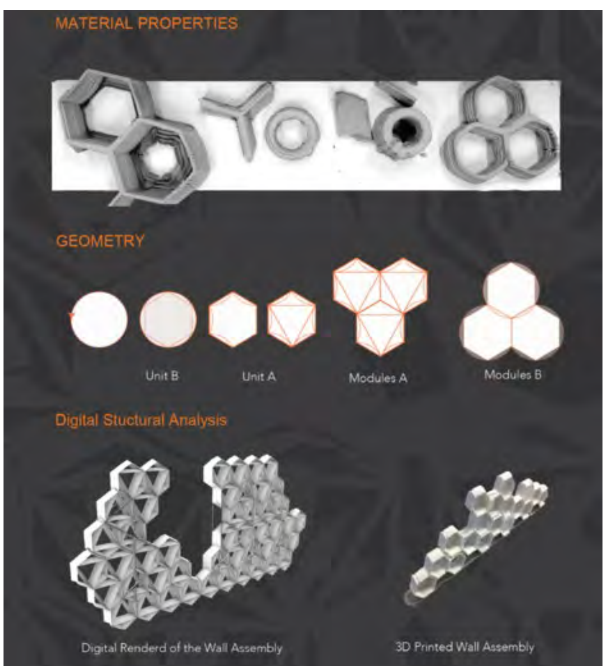
In this project, we investigated and tested clay printing techniques using the robot's manufacturing logic. The result was a wall assembly composed of non-uniform ceramic modules. The project's aim was to explore new possibilities for a traditional material using digital craftsmanship. The design of the modules required the team to understand the material properties of clay and develop an algorithm using Grasshopper 3D software. Clay consistency and plasticity, the speed of the robot, and extrusion rate were the main criteria for designing the algorithm.

The team optimized the printing process by manipulating three variables: different clay mixtures, feedback from the robot's execution of the script, and extrusion rate from the clay extruder mounted on the robotic arm. Once the team found the appropriate balance between these variables, the modules were printed and were ready to be fired at the Art Department's kiln. This process required guidance by students with expertise in ceramics. The modules were then connected and assembled to a small wall system.



Digital translation from KUKA-PRC algorithm

The overall process combined traditional and digital fabrication techniques. The ceramic students contributed knowledge of clay properties and firing techniques, while learning about the robotic arm's capabilities. Architecture students became exposed to the ceramic art and many variables involved in the fabrication of a computational design.



Ceramic modular wall assembly

Both disciplines gained crucial problem-solving skills, which took place over the course of the project in continuous conversation about the traditional and digital processes and best strategies to integrate them.

Situated Learning

Reflecting back on how the team of students came together, interacted and worked at the lab, what worked and what failed, can be explained through the lens of situated learning theory. This theory which was first introduced by Lave and Wenger, views that learning occurs when people are placed into authentic real-world context and interact with others (Lave and Wenger, 1991). Situated learning theory emphasizes the role of social learning and how specific patterns of experience are tied to specific contexts and places. In situated learning, cognition is through the "dialectic between persons acting and the settings in which their activity is constituted" (Korthagen, 2010, p.102 and Lave & Kvale, 1995, p. 219).

McLellan introduces a model of situated learning built on several components. She considers that stories, reflection, cognitive apprenticeship, coaching, collaboration, articulation of learning, and technology are key elements in making meaning and constructing an understanding of our experiences (McLellan,1996, p.7). Using McLellan's model, we can reflect on our experience of the inaugural event as embracement of all of these components.

The celebration of the lab through exhibition of student work was the "story" that created a meaningful structure for remembering what was learned; "reflection" happened in social interaction and conversations among the team leading to problem solving; "cognitive apprenticeship" and "coaching" were a part of the support scaffolding created by the mentors as they participated and provided guidance on the side; “collaboration” which led to sharing knowledge across disciplines; “articulation of learning” occurred in confronting ineffective strategies and team’s arguments on the best way to move forward and; “technology” which was at the core of experimentation.

Project Schedule

The following table shows the progress of the projects over the course of the month prior to the inaugural event.

TASK NAME	DISCIPLINES	WK 1	WK 2	WK 3	WK 4	WK 5
Inauguration Scissors						
Schematic Design	Arc	■				
Template Fabrication	Arc	■	■			
Mechanical System Design	Arc + Arts		■	■		Event
Mount Fabrication	Arc + Arts			■		
Testing of System	Arc + Arts			■	■	
Programming of End	Arc				■	
KR10 Envelope						
Gripper Pick and Place Script	Arc	■				
Design of Geodesic Dome	Arc		■			
Fabrication of Steel Dome	Arc		■	■		Event
Envelope Components Fab.	Arc + Arts			■		
Design End Effector	Arc			■		
New Pick and Place Script	Arc				■	
Drum Bot						
Planning of System	Arc + CS	■				
Fabrication of Parts	Arc		■	■		
Prototyping Logic +	CS + Music		■	■		
Programming	Arc + CS		■	■		Event
Musical Composition	Music		■	■		
Testing	Arc + CS +			■	■	
Assembly + Final Calibration	Arc + CS				■	
3D Printing Ceramic						
Design Development	Arc	■				
Material Testing	Arc	■				
Programming Script	Arc	■	■			Event
Execution	Arc		■	■	■	
Material Enhancement	Arc + Arts			■	■	
Fabrication	Arc				■	

Key Arc: Architecture CS: Computer Science M: Music

Conclusion

Using the event as a catalyst, we were able to address some of the challenges for establishing the knowledge base required to operate the lab. Each project showcased at the event was designed to engage a specific aspect of the robotic processes for developing end-effectors, convergence of digital and physical simulations, and incorporation of external data to control a system of actuators.

By leveraging the physical space of the lab, creating a mentoring structure, and facilitating interdisciplinary collaboration we were able to provide an informal setting for situated learning. Participating students in the Inaugural Scissor project learned how to develop end-effectors, the Geodesic Envelope team learned how to use the arm for pick and place assembly, the Arduino Drum Installation team learned about sensor actuation using microcontrollers, and the Ceramic Extrusion students learned about the 3D printing capability of the arm. Mentors of each team became a knowledge source for students by offering multiple workshops in the following months and participating students in these projects became vested in the success of the lab.

With advanced fabrication technologies moving at a fast speed it is critical to equip our students with the ability and competence to use and implement these technologies successfully. Training students with advanced technological skills and ability to work across disciplines will provide them with a competitive advantage and flexibility in the future job markets.

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Big Glue!

Testing the Scalability of Adhesives in Architecture and Design

Emily White and Erik Sapper
California Polytechnic State University, San Luis Obispo

Abstract

This paper documents the questions, methods and outcomes of "Big Glue," a research collaboration among students and faculty from Cal Poly, San Luis Obispo's chemistry and architecture departments that explores the potentials of structural adhesives in architecture and design. The project asks how adhesives can be more broadly used as work increases in size from the scale of models to full-scale construction.

Our focus is on aluminum structures. We looked at existing adhesive use in construction and in the automotive industry, where adhesives are increasingly used on aluminum and aluminum composites to reduce weight and consequently increase fuel efficiencies. We see potential overlaps between automotive and architectural applications of adhesives in sheet metal structural skins.

We began at a small scale to get acquainted with adhesives and to test using bonded joints in applications that would typically be welded or mechanically fastened. Our team formulated custom adhesives based on parameters we defined as specific to architecture and construction, then tested this lab formulation and other adhesives on glued joints at three scales—extra small, small and medium—in the form of test coupons, a "ravioli" structure, and furniture.

Working at the scale of furniture allowed us to test material interactions on load bearing seams that are structurally analogous to larger scale architectural applications. Using adhesives instead of welds or mechanical fasteners allowed us to work more fluidly between scale models, digital simulations, and final products. This research lays the groundwork for scaling up to large and extra-large projects.

Keywords: Materials & Construction Techniques, Design/Build

Adhesives Applications

There is precedent in engineering and chemistry for using adhesives in large-scale sheet metal assemblies such as aircraft, car bodies and other structural skins, especially at the original equipment manufacturer (OEM) stage of development. Recent advances in adhesive and bonding technology are being promoted by the increased use of thermoplastic and thermoset composites in aircraft fuselages, automotive components and spacecraft. These composite assemblies are often chemically bonded together before the incorporation of mechanical fasteners as a means of introducing safety redundancy into the product. Car, truck, plane and rail bodies that substitute adhesive bonding for welding and fastening are lighter, stiffer and more durable.

Adhesives have been used in the aerospace industry for interior and airframe applications that require strong composite-to-composite bonds and composite-to-metal bonds with high mechanical strength and chemical resistance. This allows for the structure to require fewer or no fasteners, and consequently a lower adherent thickness. Furthermore, adhesives are used in specialized applications such as shims and surfacing films for lightning protection. Adhesives also have been employed for repairs where the structural integrity of key aircraft components is critical.

Automotive applications of adhesives are similar to the demands of the aerospace industry, requiring high mechanical strength and allowing for the bonding of two dissimilar substrates. With the increased use of composite materials in automotive parts, the need for automotive adhesives has grown. Not only are adhesives practical for joining two dissimilar parts but can lead to lower weight by eliminating the need for mechanical fasteners.

In buildings, adhesives are widely used in concrete, wood and metal construction and in applying finishes (carpet, tile, etc.) In building envelopes, adhesives appear in plywood, cross laminated timber, structural insulated panels (SIPs) and Insulating Concrete Forms (ICFs). Structural silicone sealants are used to secure glass in curtain wall systems and steel façade systems also rely on adhesives.[1] Finally, fiber reinforced composite building components and composite building systems are emerging areas where adhesives are essential.

Composite systems in architecture, like in the automotive industry, can reduce waste in design. Bill Kreysler frames an argument for a more streamlined process of design and construction in his article “Waste and Tolerance in Design and Construction” as follows:

> Building materials developed during the industrial revolution, when energy was cheap and raw materials seemingly abundant, are not suited for our world today. Buildings made with these off-the-shelf products waste energy and natural resources and take enormous amounts of time to assemble....New materials must be found, design methodologies must evolve, and most importantly, these materials and designs must integrate into the workflow from the ‘drawing board’ to project completion.

Beyond their impact on waste, adhesives have potential to streamline project workflow because the representation of glued joints is the same at model and full scale, and their construction is more straightforward. Use of adhesives has clear structural advantages as well. Substituting adhesives for mechanical fasteners eliminates corrosion risk and catastrophic failure. Adhesives eliminate stress concentrators around drill holes and the fastener/body interface. And they create stiffer and more continuous bonds.

Greg Lynn describes the situation in “Chemical Architecture” as follows:

> There is a sea change going on in the world of construction: the shift from assemblage to fusion. In material terms this translates into a shift from mechanical to chemical attachments. More simply, things are built without bolts, screws, nails, or pegs; instead, they are glued.[3]

While our project’s scope is glued sheet goods, not composites per se, we see parallels with composite materials in our shared interest in using adhesives to reduce waste and streamline project workflows. We also see aesthetic advantages to using adhesives, particularly in joint design and its impact on the legibility of building massing.

There are differences in the parameters for glue selection between automotive and architectural adhesives applications. Architectural applications are subject to similar environmental forces as cars, but unlike automotive applications, construction occurs in the field rather than on the assembly line. A primary factor in selecting adhesives for architectural use is their suitability for application in variable (e.g. minimally controlled) conditions. This means selecting a glue that can be applied to minimally prepared metals and that can cure at a range of normal room temperatures, without any special processing (UV, moisture, extreme pressure.). A secondary factor is strength. There is more latitude in architectural applications than in automotive, for example, where impact resistance is a major consideration. For us, this means prioritizing field-application parameters over maximum strength.

Adhesive Formulation and Testing

Based on the parameters of suitability for field-application and reasonable strength, we formulated a custom adhesive and tested its shear and peel strength at a small scale.

We limited our study to epoxy adhesives. Although acrylic adhesives can be more amenable to being applied in field conditions because they require a less pristine surface for a good bond to form, epoxies are generally stronger. Structural bonding using epoxy-based adhesives is a mature technology in aerospace and automotive industries, where adhesives are used to join structural components and skins without fasteners, or in areas where anticipated stress on the material necessitates adhesive as well as mechanical fastening of components.

We used two commercial, over-the-counter adhesives: Gorilla Weld Steel Bond Epoxy and JB Weld KwikWeld Steel Reinforced Epoxy. The Gorilla Weld Steel Bond Epoxy product consists of a methyl methacrylate and methacrylic acid-based resin, crosslinked with a methyl methacrylate based hardener containing talc and fumed silica as inorganic fillers. Presumably, the inorganic fillers are supplying mechanical toughness and enhanced ability to mechanical interlock the adhesive with a substrate material. JB Weld KwikWeld is a bisphenol-A based epoxy resin containing carbon black as an inorganic filler meant to provide mechanical toughness and improved mechanical interlocking with the substrate.

A third material was a lab formulated epoxy adhesive consisting of a stoichiometric amount of EPON 1001-CX-75 and EPIKURE 3115-X-70. EPON 1001-CX-75 is an epoxide resin in a 25% solvent mixture of methyl isobutyl ketone and xylene. EPON resins are typically used in industrial maintenance coatings where chemical resistance, corrosion resistance, and low or no color is desired. EPIKURE 3115-X-70 is a high molecular weight reactive polyamide crosslinker delivered in xylene as a solvent. EPIKURE cross-linking resins are chosen for their water resistance, chemical resistance, and corrosion resistance.

The over-the-counter glues were chosen for their commercial availability and use as a general adhesive for multiple applications which may include smaller scale applications and provide insight and inspiration into the scalability of adhesives. The lab formulation was used in a “neat” fashion, without the addition of additives, in order to assess the baseline performance of the polymer adhesive, and was chosen based on its prevalence in the industrial coatings sector.
All three adhesives systems studied here are prevalent in industry applications and are cost effective. Different fillers and solvents are used in each, and some structural resin features are unknown due to trade secret protections, but the class of materials presented here nonetheless represents a “builders basic toolkit” of polymeric adhesives.

Fig. 1. Big Glue lab-formulated epoxy

For each glue, we tested lap shear strength. The tests were performed following ASTM D1002.[4]

For most of the adhesives, the maximum load of the adhesives increased with more areal coverage of the lap joints, allowing for a weaker adhesive to compensate through a larger covered surface area, increased interfacial adhesion between bonded parts, and more bulk adhesive to contribute to carrying a structural load. However, the JB Weld showed the opposite trend, likely due to the curing mechanism or application of the JB Weld, allowing for a void to form and create a weak point that allowed for fracture of the adhesive resulting in cohesive failure within the bulk body of the adhesive. Maximum load of the Gorilla Weld reached 16000 N (approximately the bite force of a 5 meter long saltwater crocodile), which should be more than sufficient for the architectural applications described.

We also compared lap shear strength to peel strength for one pair of 1/8” thick aluminum samples. The shear strength was much greater than that of the thinner test coupons (13,000 N) and the peel strength was 850 N.

Adhesive		
Lap Joint Overlap (inches)		
Shear Strength (ASTM D1002, N)		
Gorilla Weld		
1	*2*	*3*
1,500	10,000	16,000
JB Weld		
1	*2*	*3*
7,200	7,500	6,000
Lab Formulation		
1	*2*	*3*
1,700	3,250	3,750

Lap Joint Overlap (inches)		
Shear Strength (ASTM D1002, PSI)		
Gorilla Weld		
1	*2*	*3*
112	375	400
JB Weld		
1	*2*	*3*
538	281	150
Lab Formulation		
1	*2*	*3*
127	122	94

Fig. 2. Adhesive Shear Strength Tests, first round results in Newtons and PSI

Considering one of our parameters was reasonable strength (compared to a welded joint, but not needing to withstand crash impact, for example), our lab formulation performed fine. Although it wasn't the strongest glue, the lab formulation had other advantages. Working with bulk material allows for lower costs compared to commercially available adhesives. It also provides a baseline to compare to and adjust the formulation to the desired properties (scalability, mechanical strength, environmental resistance).

Joint Types for Bigger Tests

While the adhesives tests were being conducted, students evaluated joint types and potential forces they would be subject to in the context of furniture. We reviewed many metal furniture precedents to identify joint types that could be reinterpreted with adhesive bonds. Most of the precedents were welded. Two precedents of note are Oskar Zieta's hydro-formed metal Plopp Stool and Joris Laarman's Asimov chair.[5,6,7] Both of these are made with sheet metal and neither relies on straight folds for its shape, as is typical for most of the other sheet metal furniture we reviewed.

We developed some sample joints for our next scale of adhesives testing according to three areas of interest- a curved lap joint subject to shear and peel forces, a perimeter lap joint subject to peel forces only, and a mixed material joint between wood and steel rod.

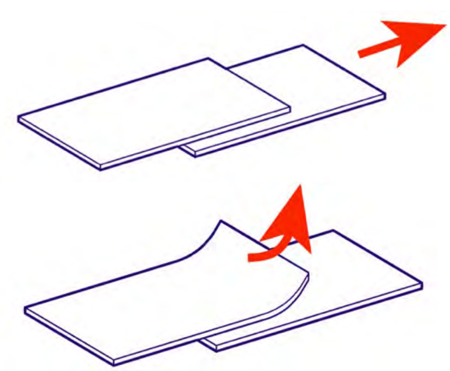

Fig. 3. Shear force (top), peel force (bottom)

Case Studies: Student Projects

Each student developed a piece of furniture to test the field application and strength of adhesive joints with various glues. Each of the three case studies and its successes and failures is described below.

Case Study #1: Ravioli

The Ravioli are made from "inflated" sheet metal. Two sheets are laminated along the perimeter and a hydro-forming process forces the sheets to warp apart. Oskar Zieta / Prozessdesign's FiDu technique is a precedent. FiDu, however, uses welds rather than glue. Within the context of this project, a test of outward pressure on metal sheet seemed like a useful intermediate step between test coupons and full-scale furniture.

Fig. 4. Ravioli (Diagram author: Bennett Mueller)

Initial Ravioli tests provided feedback about surface preparation. While the test coupons for the first round of shear strength tests were prepared in lab conditions per ASTM D1002, The Ravioli was produced in a considerably less controlled studio environment. The surface was lightly abraded and de-greased, but conditions were more similar to what one might encounter in the field on a construction site. The hydro-forming was done using a conventional pressure washer connected via hose to a nozzle embedded in the perimeter of the Ravioli. Some of the first Raviolis exhibited super localized cohesive failure at points along their perimeters. The Ravioli, when inflating, are only as strong as their weakest point - a leak will cause the hydro-forming process to fail.

Epoxy provided a major obstacle to the tests, resulting in a number of failures. Because Ravioli need glue spread over a large area, epoxy's viscosity and set time were both problematic. Using a polyurethane adhesive that reacts with a few drops of water fixed this issue. The thin polyurethane easily spread across the entire surface of one sheet while water was put on the other sheet. The two were then sandwiched together, the water started the glue curing, and the foaming polyurethane filled any potential gaps.

The force required for plastic deformation of the metal needed to be less than the adhesive strength. To assist with this, clamps were used to push the edges of the Ravioli towards each other as the pressurized water entered and pushed the centers of each sheet apart. Thin (30 ga.) galvanized steel gave the best results. After inflation, the Ravioli was filled with expanding foam and the edges were sealed with epoxy.

Fig. 5. Ravioli during hydro-forming (photo credit: Bennett Mueller)

Future hydro-forming would require better adhesion and glue that had stronger peel strength. It is likely that polyurethane or acrylic adhesive would continue to perform better than epoxy, even with additives to decrease viscosity or lengthen set time.

Case Study #2: Funky Legs

The second student, Mariana Puig, was interested in mixed material glued joints. Her furniture is made from 12 bent steel legs attached to three wooden planks, and has both metal-to-metal connections and metal-to-wood connections.

Fig. 6. Funky Legs (photo credit: Bennett Mueller)

To make the legs, she built a jig with three cut pieces of rebar around which to bend heated steel rod. She welded each steel leg into a closed loop before powder coating them. The decision to weld rather than glue the legs was made based on an intuitive assessment of joint geometry- because the legs are ¼” diameter rod there isn't much surface area for adhesion. We thought a weld would have a better chance for success. Glue was reserved for wood-to-metal connections. The wood elements have 12 grooves cut to receive the legs.

After analyzing the joints and doing some tests, we concluded that although the glue was theoretically strong enough to keep the wood and the metal together, the shape of the joint would support a welded connection better than a glued one. Again, joint geometry was not ideal for an adhesive bond. For any future mixed material connections, better joint design would be needed to support strong adhesive bonds.

Case Study #3: Three Egg Whites, Soft Peaks

The third project was a chair designed as non-concentric truncated cone that overlaps at one seam. This shape provided good testing conditions for our glue, as the joint was subject to both peel and shear stress. The truncated cone would be rolled into shape from a single sheet of 1/8” thick aluminum. This design minimized the appearance of all artifacts of the fabrication process as a way of highlighting the seam. Three Egg Whites, Soft Peaks operates somewhere between chair, chaise lounge, and dog bed exhibiting characteristics of all three.

There were several rounds of iteration at the study scale and subsequently as full-scale prototypes to test the angle of the tilt and sizing of the chair. Initial studies had trouble translating to the full-scale and would tip over on its own weight. The center of gravity would shift depending on the position of the occupant. The wide base was necessary to accommodate for a wide variety of positions. In addition to the use of epoxy, other fabrication constraints included the size of the waterjet CNC mill and the rollable thickness of aluminum in a hand-powered plate rolling machine. The most difficult part of the fabrication process was the rolling of the aluminum sheet metal. At ⅛” thick, we were pushing the limits of the hand-powered plate rolling machine we had available. In addition, we had to manually adjust for a continuous change in radius along the entire truncated cone. The glued joint, therefore, needed to withstand stresses internal to the aluminum and its tendency to spring back to a flat shape.

Fig. 7. Three Egg Whites, Soft Peaks after rolling and before gluing (Photo credit: John Lin)

The resulting truncated cone was epoxied along the overlapping seam, clamped, and left to cure for 12 hours. The application of epoxy to the overlapping seam was a success. After 12 hours, the epoxy, while not at full strength, was strong enough for the clamps to be removed. It would take another 12 hours for the epoxy to fully cure. In this instance, epoxy was a good way to join material due to its ability to remain hidden and stay true to the design (as opposed to mechanical fastening) and its relatively easy field application process (as opposed to TIG welding aluminum).

The chair was painted after the glue cured, and it has stood up well to normal use. There hasn’t been any explicit strength testing on the glued joint.

Fig. 8. Three Egg Whites, Soft Peaks (photo credit: Bennett Mueller)

Conclusions

Initial testing of the lab-made epoxy has shown promising results, providing sufficient mechanical strength for furniture. Our adhesive performed well in case study #3 and we feel confident about undertaking larger work with adhesives.

The failures of the epoxy in case study #1 were related to properties other than its strength, and in case study #2, the joint design was insufficiently resolved. Future work with adhesives and sheet metal will be limited to lap joints and metal will be formed by rolling or bending. The hydro-forming process described here was an interesting detour, and gave opportunity to collect material feedback about another type of adhesive (urethane) that we did not include in our project at the outset.

Performance of the lab-made epoxy could be improved by the addition of adhesion-promoting additives such as inert inorganic fillers, carbon nanotubes, carbon black, or ceramic nanoparticles, all of which have imparted adhesion improvements in similar studies, where the filled, over-the-counter adhesives show generally greater adhesion compared to the neat formulation.

Some potential challenges in using adhesives in construction remain, including their costs, questions about their effect on the life-cycle of otherwise recyclable materials, and their toxicity. More information on these characteristics of adhesives can be collected from further review of their use in other industries. In addition, more data about adhesives environmental performance is needed. Test standards exist to measure effects of humidity, temperature and UV radiation on adhesives joints. Moving forward, members of our team will further refine the parameters for field-applied, structural glues and continue to test at increased scale. Future adhesives selection parameters will include the two described in this project- suitability of application in the field and reasonable strength- and include two additional parameters- cost and impact on material life-cycles.

Student Researchers:

Ethan Kim
John Lin
Bennett Mueller
Mariana Puig Guijarro

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Structures for Relief & Resiliency: Enhancing Creative Applications of Technical Acumen through Constrained Conditions

Rob Whitehead, AIA, LEED AP
Iowa State University

Pairing Building Technology with Humanitarian Design Efforts

Every year, tens of millions of people worldwide are displaced or otherwise harmed by natural disasters, warfare, and economic / social inequities—an even larger number suffer from oppressive conditions that also require humanitarian assistance. Relief operations rely heavily upon the availability and usefulness of places, objects, and experiential operations used to help them provide provisions for food, water, and shelter.

And yet, despite nearly a century of historical precedents and technology-centric design philosophies aimed at addressing humanitarian issues through design, integrated design solutions still remain largely marginalized or omitted from these practices. In fact, the operational manuals developed by the most predominant relief agencies and non-governmental organizations (NGOs), have included very little, if any, information about the *actual* design dimensions, materials, or deployment strategies.[1] These efforts are incomplete without design.

These unfortunate omissions suggest an important opportunity to engage real-world humanitarian design efforts with practical efforts and educational activities. This paper will argue that the constrained conditions related to disaster relief and resiliency are, in fact, ideal topics for building technology educators and students—and that integrating these efforts into course activities is highly beneficial to student learning. Technical acumen is an inherent part of all phases of work particularly because of the expectations of elevated material utilization, a synergistic connection between products and production, and a necessary portability / deploy-ability of the designs. The work has inherent evaluative standards for performance assessment as well—both functionally and technically—that go beyond a judgement of ‘right or wrong’ solutions.

Unfortunately, the multi-faceted nature of disaster relief and resiliency problems often excludes this work from traditional architecture design studios and/or building technology courses. Or worse, sometimes these complex topics are marginalized into a search for “better” shelters for the sake of pedagogical simplicity. Effectively conveying these learning objectives requires changes in traditional building technology activities, participants, and assessment criteria.

This paper will discuss three exemplary projects that were designed and prototyped by interdisciplinary teams of senior and graduate Architecture, Landscape Architecture, and Interior Design students in the *Structures in Service: Design for Relief and Resiliency* design studio at Iowa State University’s Department of Architecture. The projects include: A portable storage container that doubles as an elevated beam/slab floor system for relief tents, a shell that uses a modified ferro-cemento solution to enclose a well-water system while integrating physical spaces for social activities, and a “brick” made from recycled tires that is retro-fit into existing masonry houses in Mexico to increase resiliency to seismic forces.

The work was completed in a design studio which included an explicit emphasis in building technology principles of design and production, and the haptic-learning opportunities of design-build activities. The groups researched real-world ongoing relief and rebuilding efforts that would benefit from a critical integration of structural and materials design principles—including the design of objects or operations. The "build back better" ethical framework and categories of care adopted by the relief organization suggest a more thorough assessment of use and re-use, so full-scale prototypes were constructed and tested as part of the design process (Figure 1).

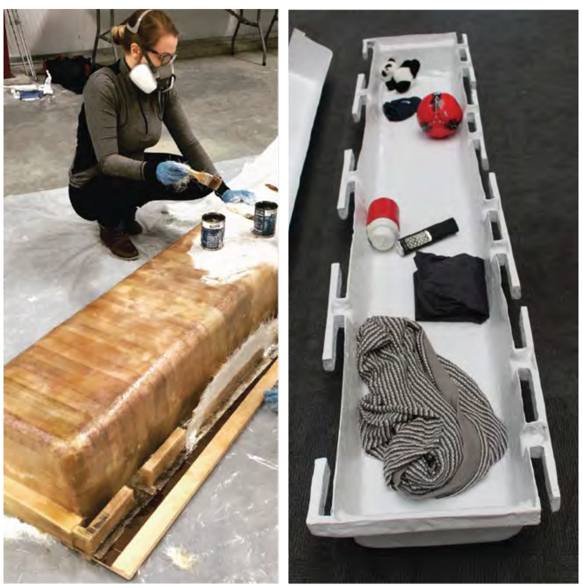

Fig. 1. Constructing fiberglass bin for Store Floor design, 2017

The Role of Design-Based Research

The first step in developing this coursework was to create a learning environment in which students assume the role of design-researcher. Researchers play an important role in supporting real-world humanitarian efforts. Relief and recovery efforts are so complex and multi-faceted, that organizations such as the United Nations (UNHCR & UNISDR), and various NGOs rely, to an extent, on an open-source approach to accepting research from outside sources. By policy, before operations are implemented in the field, these practices are initially researched, tested, and evaluated—eventually becoming position papers or policies.[2] In support of these efforts, researchers produce topic-specific position papers based on their expertise and pursuing funding to help develop and test their work. This process can be translated to design efforts.

Designing for disaster relief, recovery, or resiliency is another form of applied research. As such it requires a foundational hypothesis, an ideology that guides the work, a design methodology that incorporates the particular tools and materials proposed for the design and production, and an evaluative process of prototyping including deployment and use.

In the initial stage of design-research, students study various design philosophies and ethical practice models for humanitarian design. This design research is commonly situated within the broader questions of modern design; specifically the question of how technological innovations can be leveraged to assist in humanitarian efforts through the design and production of constructed environments.

Foundational Design Philosophies

In the 1938 book *Nine Chains to the Moon*, Buckminster Fuller (1895-1983) outlined a philosophy of industrialization that concluded with the belief that humankind could actively evolve by transforming our patterns of "making" to create more possible efficiencies by harnessing our available technology. He coined the term "*ephemeralization"* to describe a philosophy of design and systems operation that sought to do "more and more with less and less."[3] Fuller would evaluate the proportional weight of an object because he believed a lightweight structure reflected an efficient combination of materials and forms.

The applications for this philosophy weren't limited to disaster relief or rebuilding efforts but were an important part of this type of work. The performance objectives for objects and spaces utilized for humanitarian relief—lightweight, efficient, portable, innovative, etc.—all aligned well with this ideology. His eventual development of geodesic domes and a joint system that allowed for rapid deployment were widely implemented in operations for relief agencies and military operations.

The German engineer, builder, and Pritzker Prize winning designer Frei Otto (1925-2015) spent a great deal of his career developing designs for humanitarian purposes. Like Fuller, Otto believed that the inherent efficiency of innovative materials and lightweight structural forms could help solve difficult problems in disaster relief or rebuilding scenarios. He described his philosophy as search for a broader view about the purpose of design—something that went beyond "buildings." Otto's particular focus was the development of, as he described, "Structures with a minimum of material and time related to economy and energy."[4] Specifically, he believed that designing with tensile structures (tents, membranes, and pneumatics) would provide the ability to create highly portable and rapidly deployable structures (Figure 2).

Relief tents are now ubiquitous, but Otto saw the potential for tensile structures to solve greater problems than simply shelter. For the last decades of his career, Otto developed and engineered a myriad of tension-membraned objects including: floating cities for food production, suspended water cisterns in remote areas, and rapidly deployed pneumatic dams for flood prevention. Surprisingly, despite the thoroughness of his engineering work, few of these proposals were ever widely implemented.

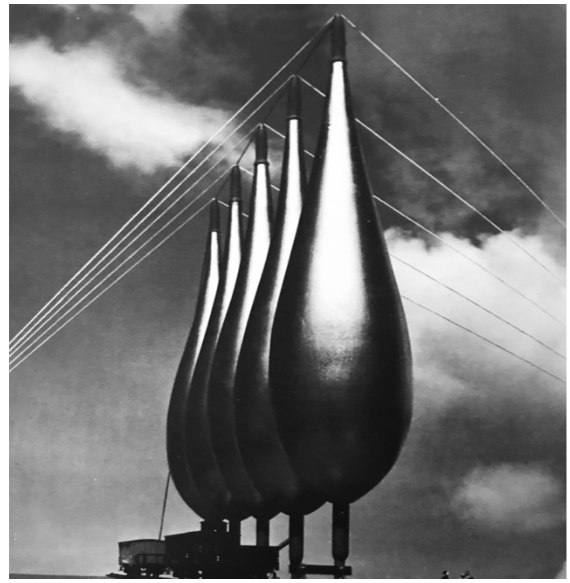

Fig. 2. Water cistern "bladder" design proposal, Frei Otto, 1956.

Victor Papanek (1927-1998) was contemporary of Fuller and Otto, who focused on post WWII-era industrial design objects created for humanitarian efforts. In *Design for the Real World*, he argued for a social-consciousness design ethic that including users/participants in the design process—particularly groups that had been traditionally marginalized.[5] Papanek saw design as a tool for social good and political change and spent a great deal of his career working in developing countries. He had less faith than Fuller and Otto on the role of contemporary technological innovations (called them tools for "techno-ideological paymasters"). He often looked at vernacular methods, or "local solutions to local problems" instead. His design philosophies and probing ethical questions established him as a predominant voice in humanitarian design efforts in the 1960-70s.

Conspicuous Absence of Design

Despite the compelling proposals put forth by Fuller, Otto, Papanek, and others, the larger focus of designers in the 1950-70s was the design for spaces that could survive or mitigate the impact of atomic war, not the broader humanitarian crises of food and water shortages or refugees.[6] During this same era, influential bureaucracies of humanitarian care emerged and evolved (e.g., United Nations, U.S. Federal Emergency Management Agency (FEMA) etc.) and their adopted design philosophies shifted as well.

Instead of embracing a human-centric design focus for innovative technical solutions, most agencies and organizations opted for consistency and uniformity. This is understandable as it relates to policies of care, but it was detrimental to the integration of specific design efforts. One type of design solution shouldn't be "universal" or interchangeable with all others. The functional failures of the standard UNHCR relief tents and FEMA trailers are evidence of the consequences.[7]

During this era, the balance of design-based research and development for objects and spaces used for humanitarian efforts (shelters, food, water, infrastructure, etc.) shifted towards military industries and private and/or non-profit researchers. The practice of technology transfer between entrepreneurial designers, researchers and the military thrived, particularly as global defense budget funding increased rapidly in the 1980s. Unfortunately, many of these innovations weren't widely applied to relief activities because military interventions in international relief efforts are often met with skepticism and distrust by communities in need. Frankly, relief agencies didn't have the same type of access to funding for research and development as they channeled their money towards operations.

This gulf between design-research and humanitarian relief operations has only increased over the last several decades. Its absence has even become codified. For example, the operation and training manuals developed and adopted by a large consortium of renowned NGOs, including *The Sphere Project* and the *Good Enough Guide* don't include *any* design drawings or diagrams.[8] These manuals discuss operational guidelines for managing water, shelter, food, healthcare, and education in great detail—all aspects of daily life that have predominantly shaped the design of our physical environments—yet the associated design considerations remain absent from policies of care.

Not including explicit design content is understandable to a certain extent. These NGOs don't produce design solutions themselves and don't have funding for research and development. They rely on technology transfer from military applications, and / or the ingenuity of researchers and developers to create available products through an entrepreneurial system or a shared open-source research program.

This entrepreneurial system of research and development has negative consequences on the types of design environments integrated into the field operations. Specifically, because the development and production is market-based, it is inherently biased towards the most affordable and widely available solutions. UNHCR tents aren't used because they are the possible best relief shelter, but they meet the margins of the lowest-acceptable denominator of the agencies cost-benefit analysis (Figure 3).

Fig. 3. UNHCR Tents provide marginal qualities of shelter

By failing to integrate design considerations into their operations, the spaces and products are treated as either interchangeable or inconsequential. This is a difficult lesson for students to learn; particularly when they realize that the "quality" of their design won't solve the larger problems. This lamentation can be shifted towards other opportunities by accepting the entrepreneurial model of design development and finding other entities that support, fund, and implement good design work.

Defining the Problem by Embracing Constraints

Design work can be implemented into relief and resiliency efforts without relying on operational manuals. Professional volunteer organizations (e.g., Engineers without Borders), privately funded philanthropic foundations (e.g., Rockefeller Foundation), non-profit architectural design consortiums (e.g., the former Architecture for Humanity), and design-oriented governmental organizations all make significant contributions to world-wide problems and each participates in creating (or funding) design. Instead of relying upon one entity for funding, development, research, and implementation students discover that a broader network is needed.

Learning how to develop a design proposal that appeals to a larger group is challenging. Student work left unchecked tends to either aim too broadly (e.g., "our goal is to end world hunger") or to believe that an empathetic approach to design (like Architecture for Humanity's motto "Design Like You Give a Damn") is sufficient. Constraints are useful.

Students are asked to see their work not as an independent inquiry, but as an extension of an ongoing "conversation" and/or design efforts related to food, water, education, health-care, power, and even economic and social issues. They identify real-world efforts in research, practice, or field operations where additional design attention could improve the resiliency of environments, or improve reconstruction, or assist in relief efforts. Teams are encouraged to add others to their design team including other instructors, researchers, fabricators, or corporate sponsors.

The most difficult portion of establishing a scope of work is being both realistic and aspirational about the desired impact of the proposal.

Evaluation Challenges and Incremental Improvement

How should performance or impact be measured? Giving someone a safe and secure water source who previously didn't have easy access to one is certainly an improvement. But this "have or have not" method of evaluation doesn't distinguish the relative value of a solution compared to other options. What makes a particular design "better" than others?

Groups who do this work in real-world practice tend to favor a performance-based design ideology—one that seeks incremental improvements (e.g., a well that pumps water faster, or a tent material that is more durable, etc.). The viewpoint is so predominant that the United Nations International Strategy for Disaster Reduction (UNISDR) thematically named a resolution for their rebuilding policy, "Build Back Better" to reinforce the idea of steady improvements in recovery and reconstruction.[8]

This engineering-based approach emphasizes the practical manifestation of a solution (e.g., "building a well") over the broader inquiry (e.g., "what are the larger issues related to water safety, security, and community space?"). Tim Brown of IDEO distinguishes this by classifying the problem being solved as either a "noun or a verb;" by focusing on a noun (e.g., "water well") the work is locked into a mindset or incremental betterment. But when the problem is treated as a verb (e.g. "water collecting") it can be seen in "…all of its wicked complexity."[9] Because academic course-work has the freedom of initial design inquiry, students are encouraged to see the problems as "verbs."

Prototyping: Structures, Materials, and Operations

Most of the course activities are based on real-world examples of research, design methods, and evaluation standards, so it may be implied that the work produced is intended to be implemented immediately into field operations. It isn't. One might assume that doing so would help one to see if the solution "works" or not, but this could be more harmful than beneficial. Student aren't field-operators, they are researchers. Designers are not trained for field work, academic calendars are too constricted, and short-term engagements with communities are proven be more harmful than beneficial. Communities in need aren't lab subjects.

But like any research question, the work *must* be assessed. It is important to develop other ways to test the work and improve it. One approach is to embed a performance-based criteria in the work (e.g., an outdoor classroom shelter that can be folded and unfolded when needed)—either that process works or it doesn't. Technical acumen is an inherent part of all phases of the work particularly because of the expectations of elevated material utilization, a synergistic connection between products and production, and a necessary portability / deploy-ability of the designs.

The relative success of the work can be assessed, at least from a technical perspective, by emphasizing the importance of integrating and refining structural and material performance standards. This degree of assessment also requires more work than just drawings.

In order to demonstrate the critical lessons of material utilization, fabrication limits, portability, affordability, and integration with operations, each group is required to build a *full-scale prototype*. Building prototypes has two critical pedagogical benefits: it immediately engages students with haptic-learning methods of "making and breaking" and it allows them to see the limits of how contemporary design and production tools can be leveraged in support of these efforts. Students seek out external funding sources to under-write the expenses and find partners with local fabricators for more difficult construction proposals (Figure 4).

The final prototypes are all intended to be portable—as they would be in real-world scenarios. Therefore they are constructed in one location and installed temporarily in other locations for reviews and exhibitions. This process embeds the lessons of material efficiency (Fuller's valuation of "lighter" structures), challenges them to develop deployment strategies, and reveals the difficulty of creating buildings and objects that must "perform" a function.

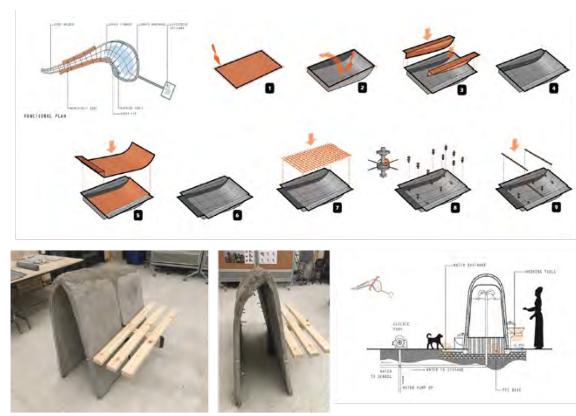

Fig. 4. Digital tools used to translate complicated forms into an accurate construction manual for prototyping the Waterwall proposal, 2018.

Project Examples: Design for Relief and Resiliency

The following projects demonstrate the breadth of possible project designs, the value of linking the design-based research to building technology, and the continued learning opportunities revealed through a design-build process. Each project description will include a brief description of the problem being addressed, a description of the proposed solution, the specific structural or material issues addressed, and a summary of the evaluation process.

Like other compelling research projects, the development of the projects weren't intended to end at the course's conclusion. All three of the projects discussed are still in a particular state of continued development, even though the studios finished long ago. Two of the projects are undergoing the initial stages of review for potential patents (Store Floor and Retro-Brick) and the construction process of the third project (Waterwall) is being further developed by the author as part of a sponsored Wells Concrete Construction Research fellowship (Figure 5).

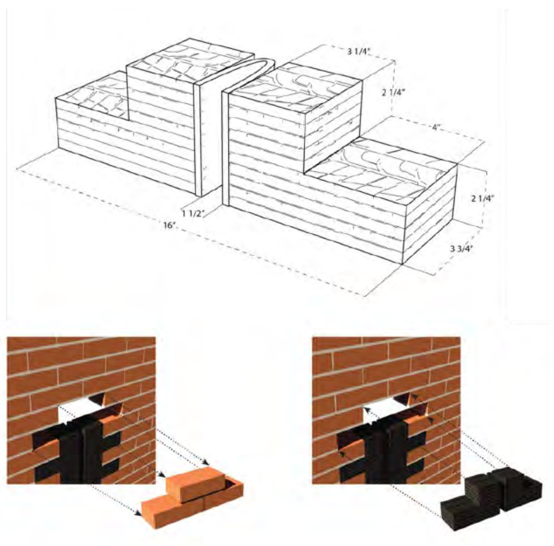

Fig. 5. Drawing submitted for patent review, Retro-Brick proposal, 2018.

Project 1: Store Floor Elevated Slab and Storage

Instead of trying to design a better emergency shelter enclosure than tents, this group designed a system that could improve the quality of life *within* the tents by focusing on the ground/floor. In their research they discovered that nearly 4 million people live in tents worldwide—many for years longer than the intended 6-month lifespan. To remain portable and affordable, tent systems only include the membrane and supports. Although they shelter from the sun, wind, and rain, these tents do not include any floor system—inhabitants rest on the ground. Living on the bare earth causes higher risk for parasitic infection, anemia, diarrhea, lower development rates, suicide and depression, flash flooding risks and hypothermia.

Although most inhabitants rest directly on a membrane spread on the ground, some tents use rubber tiles laid atop wooden pallets. Neither solution can accommodate for a variety of scenarios including rocky, uneven ground, sloped terrain, and/or flash flooding. Functionally, the membranes are also a problem because the tents aren't secure environments so issues of food and water security, and personal safety are at risk. The average refugee spends 16-20 hours a day in this environment so the problems are profound.

Their solution, named Store Floor, was designed to provide a solution for both secure storage and human comfort and health by creating an elevated floor system that doubles as a storage space within the floor itself. It was designed to be a modular system that is adaptable to UNHCR tent sizes that could be easy to assemble by the tent inhabitants. The bins are fabricated out of recycled structural plastic; they rest on a perimeter support frame made of aluminum. Each bin is capped with somewhat flexible plastic lids to safely storage personal belongings and provide a comfortable surface for seating and sleeping.

The floor bins had to solve difficult structural and material problems. For issues of portability and assembly, the floor system needed to be somewhat deep, hollow, lightweight, stiff, yet strong enough to span between the adjustable supports on the perimeter—a paradoxical challenge. To achieve the structural criteria of a spanning system, the cross-sectional geometry of the Store Floor looked at a single-pan formwork used in pouring structural slabs and modified the profile to optimize function. The dimensions were developed in collaboration with a local structural engineer. (Figure 6).

Fig. 6. Store Floor proposal and prototype, 2017.

For testing, the students re-enacted the entire process of receiving, unpacking, and assembling the system. They built two full-length bins by creating a fiberglass shell over a digitally fabricated formwork (a concession of time and expense that different from their actual design). The perimeter frame was built by a local steel fabricator who helped the students design the details that helped it fold, like a bed-frame, and snap into the four adjustable legs. They all stood on the bins at the same time and invited all four reviewers to do the same to demonstrate the strength, stability, and stiffness of their proposal.

Project 2: Waterwall Community Water Station Shell

This group framed their problem—water access, safety, and security—not as an issue related to emergency relief operations, but as a fundamental humanitarian issue. Their design work started at the conclusion of a meeting they attended for the Engineers Without Borders student group. The group described a well they had just recently completed in Ullo, Ghana and shared photos of the project. The well was useful, but the photos showing how it was being used were disappointing. Despite a great deal of engineering "design work" there was only a pump handle sticking up from the ground—no accommodations for any of the myriad functional and social interactions that occur at such important community locations. They imagined a scenario of how the project could changed if they would have worked as design collaborators with the Engineers Without Borders.

They immediately set constraints to limit their "what-if" options: They'd include a cistern into their proposal for functional reasons (it reduces time to access water) but the cistern would need to be properly secured so it couldn't be easily vandalized or stolen. They determined that they'd only use the same scope of tools and construction materials that were already used to construct the well. They wanted to create a water station that accommodated a broad range of functions such as: sitting, bike storage, water container storage, dish washing station, and run-off tray for watering livestock. To solve this problem, they decided to use digital design tools to create a double-curved shell enclosure that could enclose the cistern and provide a variety of curved surfaces for the functions (Figure 7).

Fig. 7. Rendering of Waterwall proposal, 2018.

They recognized that the biggest problem with their proposal is complicated nature of the constructed form and the heavy mass of the shell structure. As a solution, they created a modified "ferro-cemento" system for the shell that could be assembled and post-tensioned from several individual pieces. They developed a system for casting the shell pieces on the soil spoils from the well drilling; to achieve the double-curvature of each piece they developed a low-tech three dimensional grid system of measurement and specific fabric “pattern” that would fit in a properly formed hole.

They created a design manual with step-by-step instructions for construction, cut out a variety of membranes derived from their curved form, and built a free-standing six foot long portion of the shell from four separate curved pieces that were cast using the construction system they developed. A bench was integrated into the shell. The additional ongoing work seeks to clarify this process of form-finding and construction, ideally using feedback from local contractors and implementing a natural fiber reinforcing.

Project 3: Retro-Brick: Enhanced Seismic Resistance with Recycled Materials

Six months before the studio began, 228 people were killed in the earthquakes in Mexico City and the surrounding areas. 44 buildings collapsed and 1,800 other were greatly damaged. This group all had personal ties to Mexico and wondered if there was something that could be done. They researched traditional solutions to make buildings more resilient to earthquakes and realized that many of the recommendations (more rebar, stiffer concrete frames) weren’t practical for the economic and construction conditions of housing in Mexico and did little to address existing buildings.

Their goal was to develop a building system that could be retrofit into existing masonry structures in Mexico to make them more absorptive of seismic forces. One of their primary goals was to make this system something that could be installed without special tools or expertise. Ideally it would be easily available and relatively affordable too. The solution was to create an expansion joint system to absorb the seismic energy so they needed a flexible building material. They found their solution in a scrap heap of tires. Mexico collects 40 million tons of scrap tires a year, recycling only 12% of them. Because tire rubber is strong, yet ductile, it is an ideal material to act as a brick with an expansion joint.

They created new “bricks” by laminated layers of recycled tire rubber together. Through a testing process on a full-scale brick wall prototype they built, they realized that a vertical course of bricks alone wouldn’t be absorptive enough so they created two bricks and connected them with a single layer of rubber that would act as an expansion joint between the two bricks. In the process of retro-fitting this new system within an existing wall, they eventually created a Retro-brick that was two courses high with a vertical joint between. Starting at the bottom, they’d remove two bricks and a single brick centered above (running bond) and all mortar and then install and shim in place the new rubber brick. This process of removing and replacing the brick took only 5 minutes (Figure 8).

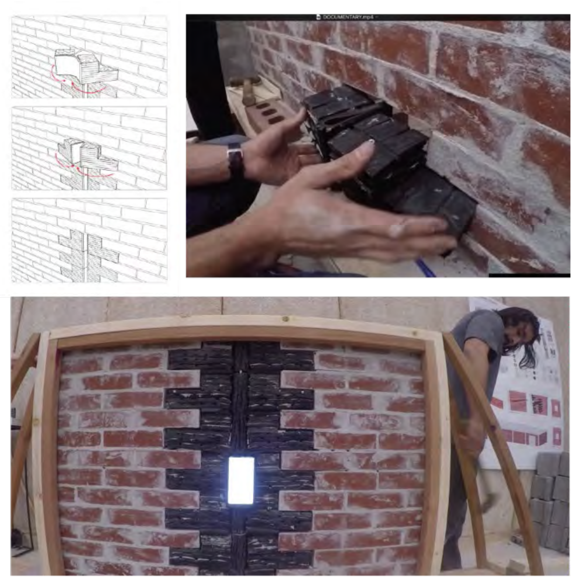

Fig. 8. Testing of Retro-Brick installation and vibration dampening, 2018.

Testing the effectiveness of the application was difficult—seismic evaluation always is—but there isn’t one particular arrangement of existing housing in Mexico so there was no guarantee that this system would be sufficient. They settled on evaluating the design’s seismic performance in relative terms to see if it would it absorb energy in a basic vertical wall applications. Digital simulations weren't effective, so they consulted with a civil engineering researcher to determine an initial physical testing method. They applied a lateral force by hitting one side of their wall with a mallet and measured the dissipation of horizontal forces on the opposite side of the Retro-brick. Using a vibration measuring application on their phones they recorded results which showed a dramatic decrease in the force transfer. The data wasn't accurate enough to run calculations, but as a proof-of-concept test, it succeeded.

Reflection, Critiques, and Lessons Learned

Because these problems are vexing and multi-faceted, it is difficult to assess the overall success of the proposed solutions from a functional and operational point of view. There are many potential solutions that could provide incremental improvements and the studio limits don't allow for proper evaluation and redesign.

This process of how the course was set-up should be subjected to the same critiques that are often leveled at similar work. For example, it is important to reflect on any inherent biases held by the designers and the systems that support this work. This is particularly true because the work was prepared "outside" of the context of where it would be applied. Additionally, the work was completed with very little, if any, contact or collaboration with agencies that do this work—one of the constraints of a semester's time-line.

There is a risk that producing this work would be perceived as an expression of colonialism or that it oversimplifies more complex economic, social, and cultural factors that have contributed to the problems. To an extent this is a fair concern, but it isn't the intent of the course activities. These concerns were intended to be mitigated by anchoring the research topics and potential projects towards on-going efforts, and learning from the work that was already started by others. One way to address this problem is to realize that this work need not be made exclusively for "others" in far-away places. There are design issues related to relief, recovery, and resiliency in shelter, food, water, etc. in many communities—including nearby locations.

Overall the course activities successfully provided a forum for design-based research that effectively addressed various problems found in relief and recovery methods. The focus on critically integrating building technology topics from the initial design thinking, to the haptic-learning methods of development, and through a set of evaluation protocols, provided opportunities for increased learning about topics not normally accessible from studios or technology classes. The student work addressed difficult problems in a way that demonstrated a high level of technical acumen related to structural and material technologies.

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Applying Nature's Solutions to Architectural Problems

Jay Yowell, AIA
Oklahoma State University

Abstract

Nature has inspired architecture for millennia and recent discoveries allow designers to understand the wealth of biological information further. The architectural profession is at a critical point in history with regards to reducing its impact on the environment. To truly minimize a building's impact it needs to interact more holistically with its surroundings. The lessons learned from natural systems can be applied to architecture to lessen its environmental impact, and this is a critical point to ask: Will architects utilize construction technology as well as advanced scientific knowledge to create an architecture that behaves like nature? Imagine a building that can convert carbon dioxide to oxygen and during the process efficiently converting sunlight into energy.

The Architecture + Biomimicry course was set up so students could specifically address this question and explore these possibilities. Research of literature and experts helped the students seek an answer to 'What would nature do?' This knowledge was then applied to an architectural solution that addressed the original challenge they selected. Work culminated in an exhibit and was attended by numerous faculty and students from cross-disciplinary fields (including engineering, interior design and sustainability). Discussions with these professors planted the seed for this course to expand and coordinate with their courses. This will lead to a new interdisciplinary approach to seeing and solving challenges in a new light.

Students will learn to look beyond the forms in nature and understand the principles behind them in order to create effective solutions to environmental issues; for example carbon dioxide emissions. Which will require the construction industry to look beyond itself and look to nature with its array of plentiful, creative appropriate designs. Since buildings account for thirty-nine percent of carbon dioxide emissions in the United States, these designs provide crucial for architects to learn from.

Keywords: Biomimicry, Biomimetic, Design, Carbon Dioxide, Building Envelope

Why Biomimicry and Architecture

Looking beyond architectural design to nature is not a new idea. Architect Petra Gruber states, "Researchers and scholars, who have used biological role models for their work, can be found very early in history."[1] DaVinci, Gaudi and Fuller showed how nature inspired their work. If these innovative historical designers looked to nature for inspiration shouldn't today's architects do the same? Especially with our knowledge of architecture's impact on the environment and advanced knowledge of how nature functions.

There are many terms to describe this process: biomimicry, biomimetic, bioinspired, bionik, and biogenesis. For simplicity, this course and paper used the term Biomimicry, the title of the book by Janine Benyus in 1997. In this, she says that "Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems…" [2]

Today we know more than past generations about nature's principles and also have better understanding of our impact on the environment. Therefore, it is important to teach architecture students to utilize this knowledge and learn how nature solves similar problems we are attempting to solve. Gruber agrees, "The study of the overlapping fields of biology and architecture shows innovative potential for architectural solutions. Approaches that have been taken to transfer nature's principles to architecture have provided successful developments." [3] Furthermore, innovative architect Frei Otto declared, "Not only has biology become indispensable for building but building for biology." [4]

This interest in the connection between building and biology was evident in being invited to present at the American Institute of Architects (AIA) National Convention in 2007. The theme that year was "Growing Beyond Green". This led to more presentations on biomimicry to AIA chapters in Nashville and Denver.

Architects working on small scale projects up to urban scale design projects were seeing the viability of applying biomimetic principles in their projects. In Denver, the architects that taught at the University of Colorado Denver, also saw the importance of teaching students these principles and had them attend this presentation. The feedback from these students influenced the shift to focus on biomimicry and architecture research in the academic setting.

Academic Setting

In 2009, I introduced this biomimicry approach to students in an Urban Design studio. We applied nature's solutions to urban issues. One of the main lessons learned was how differently this type of thinking was from the standard design approaches taken in studios. Typically, the student comes up with a concept for the problem defined in the project description. They often create multiple options and then, with the help of the studio professor, select the best option to develop. After pin ups and critiques, this option is fine-tuned for the final project.

This pattern is repeated project after project and semester after semester. The building type will change as will the approach of how to conceptualize and develop the design. But the framework and mindset remains the same. Taking a biomimetic approach interrupts this process. A detailed description is given later in this paper, but the main interruption is how a student comes to their final project. Instead of coming up with a concept quickly, the biomimicry approach causes the students to spend a long time defining the problem before coming up with a concept. Consulting with scientists is another interruption that students have to adjust to doing.

Biomimetic Building Skins Masters Research

Being able to teach this process is a result of not only teaching it in a previous class, but also from lessons learned by completing my master's in architecture degree. The thesis was to look at how building skins could function similar to tree bark. It was a result of trying to solve two major problems in architecture: energy inefficiency and loss of place. Trees are literally rooted in place and their bark is a reflection of this place while also providing protection, thermoregulation and conduits for food and water. Buildings perform these functions, but we would do well to perform similar to these natural systems.

Trained as an architect, this biomimicry process of design proved a difficult hurdle. To help, the first year was spent consulting with just scientists. Diagramming was a common communication method to help explain architectural skins (Figure 1) and for scientists to explain photosynthesis for example.

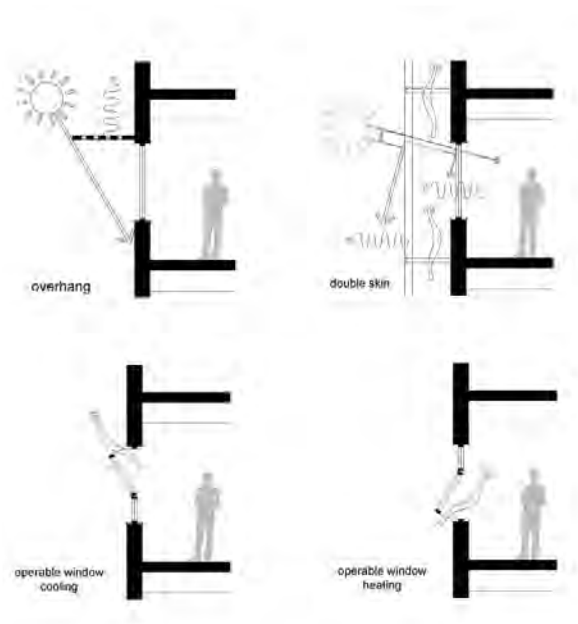

Fig. 1. Diagrams of existing building skin strategies.

The back and forth communication format proved helpful. Diagrammatic explanations eventually led to being able to understand tree bark and its direct comparison to building skins (Figure 2).

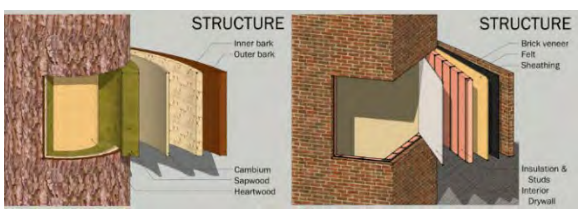

Fig. 2. Diagram of structure of building and tree skin.

Learning from their focused scientific approach and how they analyzed the organisms they studied proved to be a valuable methodology still applied to teaching today. Looking outside of the construction industry also led to being one of seven fellows at the Nature, Art & Habitat Residency (NAHR) program in Taleggio Valley, Italy during the summer of 2016.

Biomimicry and Architecture at Oklahoma State

Expanding upon this experience, a new course was created in the Architecture School at Oklahoma State University (OSU) in the spring of 2018. The focus of the course was to move beyond just form and copying how nature looks. A quote by architect Michael Pawlyn summarized the approach to the class, 'The intention is therefore to transcend the mimicking of natural forms and attempt to understand the principles that lie behind those forms and systems.' [5]

Biomimicry Design Spiral

With this mindset, the overall methodology framework was based upon the Biomimicry Design Spiral (Figure 3). The Biomimicry Institute says that it 'provides a succinct description of the essential elements of a design process that uses nature as a guide for creating solutions.' [6]

It breaks down the process in clear steps and format was used to layout the project assignments and steps to solving the design problems.

Fig. 3. Biomimicry Institute's Design Spiral

First Steps

Showing the students what has been and is currently being done laid the foundation for them to build upon. Specifically, investigating what other universities have a biology and architecture program. These schools included Georgia Tech, Arizona State, Minneapolis College of Art and Design, and the Architectural Association School of Architecture in London.

Additionally, the following literature was recommended to introduce biomimicry and architecture: 'Biomimicry' by Janine M. Benyus, 'Emergent Technologies and Design' by Hensel, Menges & Weinstock, 'On Growth and Form' by D'Arcy Thompson and 'The Gecko's Foot' by Peter Forbes.

Project 1 – Group Presentations

For the first week-long project, the twenty-three students gave group presentations on an innovative architect or engineer working with biomimicry (listed below).

Buckminster Fuller	Haresh Lalvani	Achim Menges
Frei Otto	Neri Oxman	Michael Pawlyn
Jenny Sabin	Doris Kim Sung	Julian Vincent
Michael Weinstock	Jeanette Yen	

Studying what these innovators have built, researched and written about their processes proved invaluable. It allowed them to see how to go deeper than just form when relating design to nature and also pushed them to go further with their ideas while seeing the historical context in what they are proposing for this class. For example, both Fuller and Otto were concerned with lightweight structures and minimal surface areas. Also, the students learned how each approached these concerns with different methods. Fuller explored the strength in geometric patterns of microscopic organisms while Otto studied soap bubbles as a form finding exercise. In these, the students saw that there are multiple ways to approach the same problem.

In addition to looking at historical precedents, students researched current academic work. Achim Menges's investigation of shell structures at the University of Stuttgart and USC's Doris Kim Sung taking inspiration from human skin pores revealed the variety of similar biomimetic research. Pioneers in their respective fields, architect Michael Pawlyn and engineering professor Julian Vincent, showed the students they needed to take their ideas to a more thorough functional level and not be satisfied with simply mimicking shapes.

Project 2 – Distill

With this foundation, the students spent a week and identified current problems with the built environment. Categories created were: building interiors (i.e. indoor air quality), building systems (i.e. wind power), construction, urban design and materials. Each student then selected a single problem to develop based on their specific interest. Problems they researched ranged from lighting, efficiency, and insulation to material improvements (preventing wood rot, self-healing and non-toxic) to adaptable parking, road construction and safer road intersections for bicyclists.

The standard architectural studio approach would be to jump in to creating concepts on how to solve this problem. However, working with the biomimicry design spiral, the students spent two weeks defining the problem by investigating why it was a problem, what essential issues were, and what attempts had been made to solve it.

Project 3 – Translate

With the problem clearly defined, the next step was to translate it to biology. To seek out how nature solves the problem, an important question to ask is, "What would nature do here?" Simply using the original design to answer that question, it would be difficult to research. For example by asking. "How does nature make cycling at night safer?" It is better to biologize it and ask "How does nature enhance visibility in low light?" Seeking answers will lead one to identify the functions of the problem, reframe the questions and translate design parameters. Class presentations were also given to give insight into this process.

For two weeks, the class studied how nature uses feedback loops, how it operates with its diversity and design, symbiosis and nature's patterns. Nature repeats certain forms that conserve resources using the least amount of energy. Understanding how nature utilizes these patterns is invaluable for architects designing energy and resource efficient buildings.

One example presented was the 120 degree pattern. Seen in the honeycomb cells of bees, this pattern lets the bees minimize the amount of wax they use, while providing a strong structure to store honey. Approximately thirty percent less material is used with this pattern when compared to using a 90 degree grid. Scaling, fractals, symmetry, and spirals were other patterns discussed. Effective transportation flows were seen in the pattern of branching. Rivers transport water efficiently, lighting dissipates electricity efficiently, and plants and blood vessels move water and nutrients efficiently all with the pattern of branching. Discovering these repeated patterns in nature's design helped the students make a connection to the next phase.

Project 4 – Discover

After weeks of investigating, asking questions, reading and presenting, the students were ready to design. But it still wasn't time yet; students spent two more weeks discovering natural models. There was some frustration at this point in the semester since it was different than their standard process in a studio. Discovering natural models was the last step before they could begin what they consider 'designing'.

To help and find the strongest examples, it was good to consider the so called champions in nature that specifically solve their problem. These champions are typically found in extreme environments. For example, the desert or the arctic. It was also a beneficial exercise to utilize proper terms for natural systems and use terminology used by researchers being studied. For example, when looking for how design relates to its local environment, architects often use the term 'regionalism'. Scientists, however, use the term 'speciation' to describe the development of species in a region.

Project 5 – Emulate

With the knowledge of these natural strategies, the students could finally begin to seek design solutions to the problems they had clearly defined. For four weeks, they created multiple concepts based on work in projects three and four in addition to the literature, professionals presented on, and the work in other universities.

Final Project - Communicate

The semester culminated in an exhibition of the students' work. Standard final presentations just show the finished design and presentation boards. For this exhibit, however, in addition to their final design, process work and research was also included.

Specific Student Examples

Two student projects below show this process in detail.
Victoria R. – Macro Stomata

The problem Victoria was proposing to solve dealt with light in buildings. The question she asked was "How can we control the quality and quantity of light inside buildings through sustainable materials and structure?" She saw that many glazing and façade designs function like units of separate systems. Which leads to a disconnect of controlling the light on the interior leading to glare, heat gain on one end and no connection to the outdoors on the other end. Both extremes create an uncomfortable interior for users. Environments that have the proper amount and quality of daylight increase occupant productivity and comfort. Controlled, it also helps with the heating and cooling loads on the building.

Victoria began to biologize the issue and explored how it was possible to create a symbiotic relationship between the building's structure and skin. She sought to discover natural models where material functions as the structure and the system.

For the Discovery phase, she focused on two organisms: cactus and the glass sponge (Figure 4). The cacti, because it is designed to survive in the most extreme hot conditions. She found that they embody self-shading and self-harvesting properties that could translate to a building's façade. Chemical and structural compositions were explored in the glass sponge.

Victoria formulated questions to further her knowledge of these two natural systems. How does the structure of cacti allow them to develop variable heights? How do glass sponges filter light so deep below sea level? How does materiality in glass sponges have an effect on how light is processed?

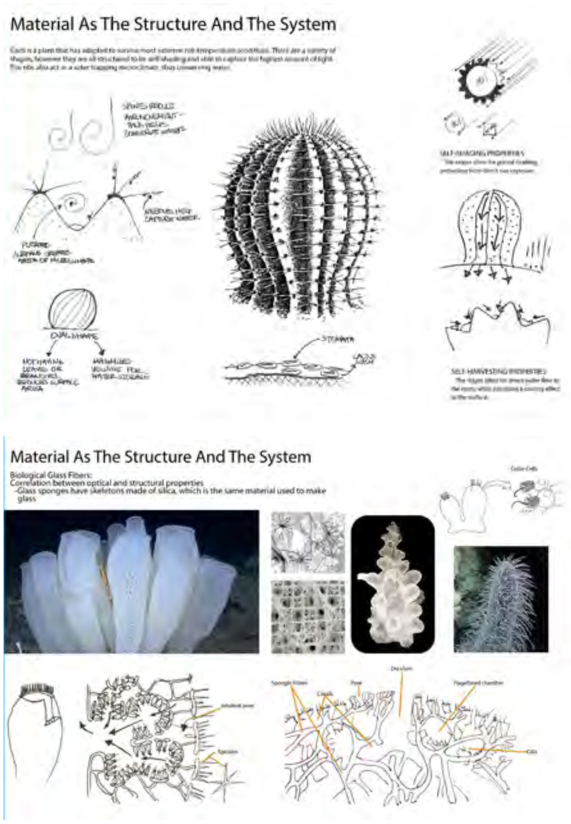

Fig. 4. Victoria's Discovery of Cactus and Glass Sponge

In answering these questions, she focused on cactus for the inspiration organism. She researched numerous cactus pecies and analyzed which best addressed her defined problems. Through further research into literature and scientific work, she concluded that the Saguro Cactus encompassed the two fundamental goals of her project: light control and material as structure.

First, the plant is adaptable and uniform. It is able to survive in this harsh environment up to two hundred years. Second, the Saguro cactus is the largest cactus in the United States, growing up to thirty to forty feet tall. [7]

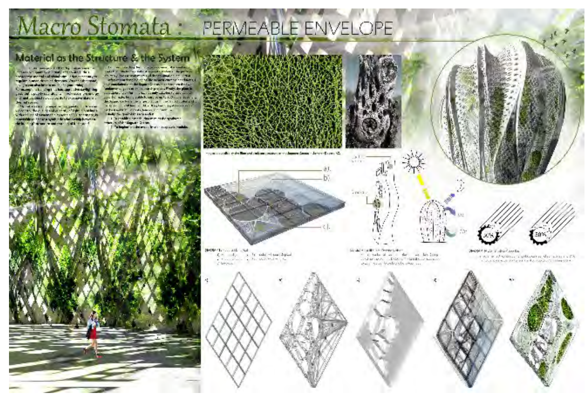

Fig. 5. Macro Stomata Final Board

Creating a building skin based on the fiber and skeleton structure of the Saguaro Cactus was completed for the Emulate phase (Figure 5). She designed a modular living wall composing of structural fibers woven in a structural skin creating a stomatic surface allowing contraction and expansion. Similar to the natural system, this skin can filter carbon dioxide and oxygen through this movement.

In addition to the skin filtering, it was designed to have self-shading properties. In extreme heat, contraction of the surface can restrict sun exposure and in cold temperatures, its expansion allows sun exposure.

Holly S. – Algal Energy

Reducing the urban heat island effect was the problem Holly proposed to solve with her design solution. The materials, dark surfaces and lack of vegetation in urban spaces absorb heat and raise the temperature in these areas. These structures and surfaces also radiate heat when the sun goes down. Energy efficiency is greatly reduced in structures as a result. In her research, she found that some attempts have been made to combat the urban heat island effect by adding vegetation and light colored roofs.

She sought to discover how plants help combat the urban heat island effect. [8] They lower air temperature through evapotranspiration, which is the process where they evaporate water through their leaves. In the Discover Phase, she focused on algae and how it covers a body of water and lowers the water's temperature. As it spreads out on the surface, it speeds up the efficiency of photosynthesis, rapidly spreading out more and making shade for the environment below. Additionally, she found that this algae converts sunlight and carbon dioxide into an oil it uses for energy. Other systems Holly explored were how whales regulate their temperature and into electric eels that are able to produce a sizable amount of electricity.

She focused on algae mainly because of its temperature reducing qualities, but also because of its ability to produce large amounts of energy. Plus, it has been used in a similar manner in buildings. In an article about Arup's Bio Intelligent Quotient building in Hamburg, Mark Hay states, "Producing about five times as much biomass per square foot as soil grown plants, and thriving on carbon dioxide, algae have the potential to grow almost limitlessly and produce oily lipids and gases that can be transformed into relatively clean energy." [9]

To emulate this, she proposed to create a skin with algae that shades the building while the film still allows for evapotranspiration, cooling the air around it. The panels tilt away from the building, following the movement of the sun to maximize photosynthesis and shading. The waste water and carbon dioxide waste from the building can be converted into usable nutrients for the algae.

Fig. 6. Algal Energy Final Board

The panel is comprised of a layer of glass, a framework with algae covered in a water-permeable membrane and has a sieve at the base that lets oil through but not the algae. This excess oil can be used for fuel. These panels can be used in new buildings or retrofitted to older buildings. Holly also proposed to use different colored algae and in this framework, thus causing the glass skyscraper appear to be clad in contemporary stained glass (Figure 6).

Pedagogical Innovation

These two examples represent similar work done by all twenty-three students in the Biomimicry and Architecture class. The process was not only distinct from other studio classes, but also from typical biomimicry class currently being taught. It is becoming common for architecture students to look at natural organisms to apply to their design. This course looked deeper into the problem being defined and then explored principles of natural systems that applied to these detailed, defined problems. Each of the twenty-three architecture students spent most of the semester reworking how they approach the design training they had received thus far in their academic training. As described, the Biomimicry Spiral provided the overall framework to design a solution to the problem each student defined. To help with this innovative process required a series of detailed assignments to push the students to think differently.

It is typical to have a problem to solve in design studio. Here, however, the students had to ask: Why this was a problem? What were the elements of the problem? How are others trying to solve this problem?

Translating the problem was the most irregular, and therefore difficult, step for the students. One assignment had them breakdown the functions and context of the design question they posed. Not looking for answers yet, just posing questions. Following this, assignments had them think critically about the functions at the heart of the outcome their design question is trying to solve. Also, to consider including relevant opposites or tangential functions that may be worth exploring.

After this step, each were assigned to define relevant contextual factors and use biologically-relevant terms to describe the context in which their design must function. What terms do scientist use to describe the functions studied? Using these terms helped them look at the problem in a new language and see the biological strategies nature used to solve a problem. Taking this approach was another area that made this class unique from standard architecture and biomimicry courses.

When students went to Discover their natural models, the students researched the literature. To explore further, they had to list a variety of organisms and in addition to the literature, study research by scientists and look for patterns these natural systems had that addressed their problem. The class also had to write why they chose these particular organisms.

Students then rewrote the strategies previously defined using architectural terms but staying true to the science. Their assignment for this stated that the design strategy should clearly address the function they want to meet within the context it will be used. It was not to be a statement about the design or solution; it was a launching pad for brainstorming possible solutions. Repeating this step proved necessary since designers almost immediately begin making design statements.

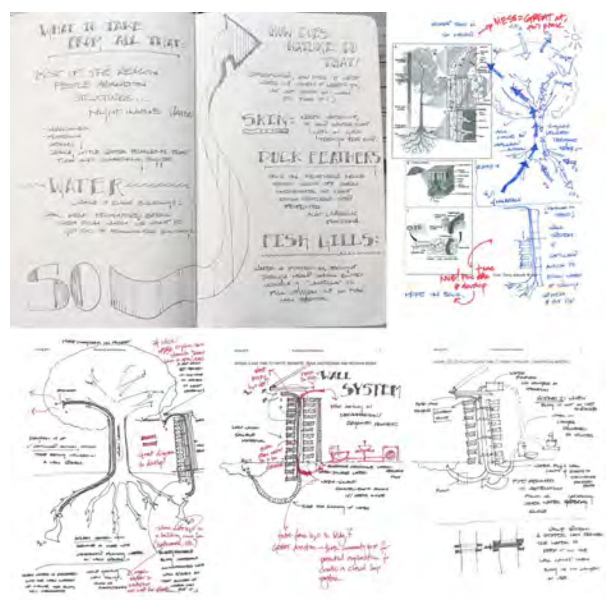

Fig. 7. Various in depth assignments

After much writing, the students created multiple diagrams based on these strategies while they began the Emulate Phase of the project. These drawings were to depict the design strategy based on their thorough research not simply a copy of the biological strategy. It was meant to focus on the functional elements in the natural system. A step to help with this was to have them imagine the strategy like a mechanical system or process diagram in order to draw it without depicting biological parts. Next, students reviewed and refined these diagrams to see if they gained any new insights or confirmed existing design approaches (Figure 7).

Conclusions

While this process proved beneficial, reflections on the class reveal steps to improve. Mainly to bring in scientists early in the process as collaborators. Architects already use the expertise of consultants in specific areas like structural and mechanical systems. Consulting with experts in scientific fields can benefit designers in the same manner. Their knowledge of the natural world and the applicable technology will continue to advance how architecture can create more energy efficient buildings. Doing so will require us to change our thinking and to not keep repeating the same approaches. Improving how our buildings work with nature will require a deeper understanding of how nature works.

The methodology for this class gave students a unique approach to create innovative design solutions. Applying nature's principles, clearly defining the problem at multiple levels, and exploring appropriate scientific research all made for an original course. Dealing with carbon dioxide, water, transportation, energy and structure can all be improved by emulating nature's time-tested strategies. It can lead to more environmentally efficient buildings but this process also provides an innovative design process since the students make a thorough investigation into the problem. Unexpected solutions were created by taking this innovative design approach which benefits the students in future design courses. It will help them to look beyond the construction industry, but more importantly to explore the essence of the problems they want to solve. Which will also create a heightened awareness of the world around them, architecturally and naturally.

Our understanding of this natural world and the problems like increased carbon dioxide levels is higher than it has ever been. How the architecture community, starting at the academic level, utilizes this knowledge is at a critical point. Looking at the problem they are trying to solve and using the current scientific knowledge available will cause the student to build on the shoulders of giants; DaVinci, Gaudi, Fuller and Otto for example, who took their inspiration from the natural world.

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CONFERENCE ABSTRACTS

Mbesese Build: An Experimental Experience

Kevin Dong
Thomas Fowler
Cal Poly – San Luis Obispo

Abstract

The Same' Polytechnic College is a proposed vocational training institution in the Kilimanjaro Region of the United Republic of Tanzania to provide supplemental and diversified tertiary educational opportunities which increase human capital and reduce the severe levels of poverty that are endemic in the region. The college is the pilot project for the Mbesese Initiative for Sustainable Design (MISD). MISD has partnered with design firms and Cal Poly-SLO to develop a framework for campus development. The Cal Poly team established overarching planning principles and design goals for buildings and related infrastructure required to support a projected enrollment of 1,200 students.

The project provided a platform for collaboration between faculty, students, and design professionals. The campus proposal encompasses architecture and planning, as well as, a variety of engineering disciplines such as mechanical, electrical, structural, water, and transportation. Students researched an array of topics that are requisite to building; energy usage and generation, water conservation and reclamation, natural ventilation and thermal comfort, natural day lighting and solar exposure, construction materials and structural systems, pedestrian and vehicular traffic patterns, as well as, site access and maintenance. Additionally, the masterplan recommendations are based on computational analysis and design, results from experiments conducted at Cal Poly, and valuable feedback from the design professionals. The students then developed building strategies for implementing the aforementioned concepts, while learning how those design issues are intertwined.

In 2018, students, faculty, and MISD volunteers constructed a micro structure in Tanzania based on the master plan recommendations. Results from block wall testing, wind tunnel/natural ventilation studies, and a thermal comfort study informed the design and construction methods used to build the structure. The building process allowed the team to better understand how cultural, environmental, and technological considerations influence design and building in developing areas. The linkage between experimental research, design, and construction is a hallmark for the project and has served as a selling point for instituting change in building practices in the rural town where the project will be constructed.

Keywords: Interdisciplinary, Materials and Construction, Structures, Energy and Systems, Design-Build, Computational Design

Acknowledgements

This project is not possible without the unwavering support of MISD, the design professionals who openly volunteer their time and expertise, and financial support from SSG Structural Engineers and the Student Support Fund at Cal Poly.

Material Design Integration

Roger Hubeli
Syracuse University

Abstract

The goal of an integrative building design studio is for students to develop and prove the capacity to integrate different technical and possibly legal and financial considerations into their architectural projects. In this context, it is most important for the students to learn how to maintain a clear conceptual strategy that can serve as a 'pièce de résistance' against the multitude of different pressures, providing a larger framework for design decisions. This presentation discusses a series of projects where this 'pièce de résistance' was based on the design potentials of advanced pre-cast concrete construction. Tectonic concerns, with a focus on structure, construction, and materiality were foregrounded in the studio. Meanwhile, other aspects such as program and building form were intentionally pushed to the background, offering a design methodology where the architectural form and expression emerges from working through the possibilities of the material and construction processes.

Throughout the 20th and 21st century concrete has been the main material used in construction.[1] Although the use of this material dates back to ancient Rome, it is also a material that has time and time again been adopted and transformed by new technological innovations. Over the last decades, there were extensive improvements in many aspects of concrete technology, such as new mixtures or improvements in reinforcement, which allow for concrete to be stronger, more durable, highly insulating, or even ductile. And the reduction of the cement content, through the use of reactive industrial by-products, such as fly ash or silica fume, provide sizable reduction of the embodied energy in concrete construction.[2] To create a framework that allows for material speculations in studio, the students were given very specific parameters for the typology of the building and a focused on prefabrication. Initial excises asked the students to carefully document construction processes in a series of case studies as well as design task to translate an existing joint, at the scale of furniture, into two cement cast pieces. The results of the exercise were then used by the students to develop a building strategy that is constructed 'from the inside out', contextualizing the program and the site through the constructive system and formal language that emerged from the translation of their initial studies into a more robust architectural project.

Keywords: Integrative-Buidling-Design-Studio, Concrete, Fabrication, Construction, Pedagogy

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Trans-Disciplinary Detail in Mass Timber

David G. Kennedy
Auburn University

Abstract

In Towards a New Architecture, Le Corbusier claims that the field of engineering, through its adherence to the noble fields of Economy and Mathematics, has surpassed the field of architecture in the pursuit of harmonious, meaningful structures. He does not suggest that architects partner with engineers; he only implores architects to cop-opt engineers' ethic to leverage their own field from its current state of "retrogression". Gaining expertise then obviates collaboration. Following this, Corbusier laments the glacial unfolding of architecture through incremental developments in structure and ornament, finding impetus for his cross-disciplinary foray in the previous five decades of material development, namely the "conquests" of steel and concrete. (9) This passage, titled 'Architecture or Revolution' finds resonance today when 'steel and concrete' are replaced by 'mass timber.'

Superficially anachronistic, this return to timber finds its depth not in the invention of the material, but in its reinvention as a medium under the purview of a variety of disciplines, from architecture and engineering to fabrication and materials science. This transdisciplinary thinking has defined mass timber types by their details, i.e., the ways in which they are assembled and joined with other materials. Mass timber is not borne of a fetishization of wood; it is most viable when its use capitalizes on the intrinsic strengths of steel, concrete, and other extant material systems. (Dangel 108) Unlike dimensional, heavy, or linear engineered wood products, mass timber's morphology operates as a function of its detail. This paper argues that, if mass timber is an assemblage of details and a fundamentally trans-disciplinary material, the details, or detail, itself is an acute source of trans-disciplinary interaction.

An emergent material, mass timber is only entering the adolescent stages of its development. Research and pedagogy surrounding mass timber are best focused on examinations of the intrinsic and extrinsic impacts of its detail. This detail manifests across scales; each scale corresponds to a set of disciplines. The cellular scale finds one in the realm of wood anatomy. Here, detail exists as designed by the growing tree, where the primary program is the express motivation to handle currents flowing through- and along them. (Bejan 130) An anisotropic, cellular solid, wood's structures and systems at the cellular scale exhibit analogies for mass timber and may provide insight as to how those systems are best assembled. This paper will examine this and a variety of other scales of detail through coursework and exploratory research. Ultimately, it posits methods by which a trans-scalar, trans-disciplinary examination of mass timber's detail might permit architectural practice, research, and pedagogy that better leverages its latent performance.

Keywords: Materials + Construction Techniques, Pedagogy, Mass Timber, Wood Anatomy

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Intuition Before Integers: Integrating Building Technology Into the Design Studio

James Leach and Kristin Nelson
University of Detroit Mercy

Abstract

The studio methodology, used almost universally to teach architectural design in the US, embraces speculative investigation and hands-on learning, offering unparalleled opportunities for integrated thinking and open-ended inquiry. Building technology courses, in contrast, tend to be taught in more constrained, and more passive modes - lecture classes, sometimes accompanied by a laboratory or including a project or two. As instructors of both design studios and building technology courses, we have found it difficult to generate the level of engagement and enthusiasm, or achieve the depth of inquiry, in the technology classroom that is common in the design studio. Moreover, we find that students fail to apply their developing technical knowledge to inform their studio design work. With a goal of greater comprehension and application as a guide, we developed an immersive making-based exercise in the design studio with an overt focus on building technology, elevating technical concerns to primary design drivers.

In this case, the development of a tectonic daylighting building skin was selected as an opportunity to incorporate building construction, structures, and performance, while exploring the potential of the envelope as moderator of the exterior environment and shaper of experience. The work was organized as a series of iterative feedback loops: make – learn – test – analyze – refine – make… This began with intuitive making – developing a series of material investigations in response to an initial prompt. Making was immediately followed by learning - the introduction of a specific building technology concepts and considerations. The previously-generated products then served as a subject for testing and analysis, applying the newly-learned technical concepts and tools. The feedback from testing and analysis directed refinement of the design. This pattern was repeated, with episodic technical workshops positioned throughout the project, presenting additional topics such as material selection, tectonics, and structures, for integration into the evolving design. This gradual exposure to new concepts and concerns incrementally built technical awareness and knowledge, spurring continued analysis and development. Additional design and performance criteria, aligned with the new technical topics, added complexity at a measured pace, allowing students to focus on a single concern at a time, without becoming overwhelmed.

By engaging with physical making and testing, and scaffolding technical concepts, students begin to perceive the opportunities to develop designs informed by a multitude of intentions – truly integrated design.

Energy Use Intensity as a Driver for Building-Envelope Design

Scott Murray
University of Illinois at Urbana-Champaign

Abstract

As the principal interface between interior and exterior environments, the building envelope plays a primary role in the success or failure of a building's response to its climate. The design and subsequent performance of building-envelope systems can have significant impacts on the overall energy performance of a building during its lifespan. Design decisions about window-to-wall ratios, the placement and orientation of glazing and shading devices, the components of opaque wall assemblies, and the selection of facade materials, products, and systems each contribute to a building envelope's performance. To design high-performance enclosures, architects must understand the relationship between these parameters and their relative influence on energy consumption. This paper presents an approach in which building-envelope designs are evaluated in terms of resultant Energy Use Intensity (EUI) utilizing energy-performance simulation to optimize the enclosure system. As a metric, EUI conveys a building's annual energy use per unit area (in kBTU/ft2/yr or kWh/m2/yr), thus allowing easy comparison of buildings despite differences in size, type, and location. When EUI is measured at each stage of building-envelope development, from the earliest conceptual studies to the final design, the designer is empowered to evaluate design decisions from an energy-use perspective, which can be integrated into a design process alongside other technical as well as aesthetic objectives. To provide historical context, this paper begins by presenting research about the evolution of building-envelope requirements contained in the International Energy Conservation Code (IECC) over the last two decades. Changes to code guidelines—such as maximum window-to-wall ratios, minimum R-values, and maximum U-values—are tracked to illustrate the evolution of performance criteria for building envelopes. A design/analysis exercise from the author's graduate-level seminar on building-envelope design is then presented to demonstrate a process that builds the designer's understanding of how the parameters of façade design affect EUI, in addition to more specific metrics for heating, cooling, and lighting loads. Using cloud-based Sefaira software, designers follow a series of steps that evaluate energy performance implications for a range of design decisions: the area, size, placement, and orientation of window openings, the insulation value of opaque components, and the thermal, solar, and visual properties of various glass products. Designers learn the relative importance of each decision based on given parameters of climate zone and building type. This process develops and understanding of not only the quantity of energy consumed, but also where and how this energy is used and how design revisions can impact this. This process engages digital simulation tools but also develops the designer's intuitive knowledge of the relative impacts of numerous building-envelope parameters on overall energy use; both types of knowledge contribute to better understanding of how to intelligently design the envelope to optimize its energy performance.

Keywords: Structures, Energy + Systems; Pedagogy; Facades; Envelope; Design

Maps, Videos, and Structures: Visualizing Structural Concepts through Media-Based Assignments

Marci Uihlein
University of Illinois at Urbana-Champaign

Abstract

Within building technology educators in architectural education, there is a frequent exploration of structural pedagogy. How best can the theory of structural design be taught? Are calculations necessary, for example? What participatory learning assignments can guide architectural students to haptic and intuitive understandings of structure? This paper adds to this discussion by presenting two exercises designed to capture the imagination of students whose environment is saturated with Snapchat, data visualization, and Instagram.

The first assignment is a digital "term paper" for graduate students that examines earthquake design through an analysis with GIS and presenting a "Story Map" of an historic seismic event. Learning objectives for the class included:

- to understand how a building structure behaves in a seismic event,
- to gain the ability to determine and apply seismic loads,
- and, to understand the role of the built environment and design in seismic events.

The visualization of a seismic event encourages spatial thinking and understanding of scale as well as the impact of the selection of construction type on the local communities after and earthquake.

The second project is a version of "teaching the teacher" with undergraduate students authoring two-minute videos explaining one of the primary loads on a building – live, dead, snow, wind, or seismic. Learning objectives for the assignment are:

- to understand the types of loads on a building,
- and to increase students' ability to visualize, problem-solve, and understand these demands.

Storyboarding, defining and redefining the load, filming, and editing allowed for students to use their creativity, narrative voice, and graphic skills in learning and conveying the subject material.

In both cases, students moved beyond the calculation, though did not leave the numbers completely behind. This presentation will share the assignment development, outline the support from campus units, show examples of student work, present lessons learned, and share reflections by students on the projects.

Keywords: Structures, Pedagogy, Participatory Learning, Visualization

Acknowledgements

Special thanks must be given to those who supported this work at the University of Illinois at Urbana-Champaign: James V. Whitacre, GIS Specialist, Library Commons and Robert Baird, Associate Director, Instructional Spaces & Technologies at the Center for Innovation in Teaching and Learning. Without their help, knowledge, and insights, none of this work could have happened.

CONFERENCE POSTERS

"Completing the Cycle" with Hardwood CLT: Innovation in material development and utilization

Edward Becker

Virginia Tech

Abstract

The New River Train Observation Tower design-build project utilizes custom-fabricated hardwood cross-laminated timber to construct an ADA accessible viewing tower in Radford, Virginia. The project showcases hardwood CLT research that positions the engineered biomaterial as a potential key asset for circular carbon economies and low-carbon construction. The study investigated the local sourcing, pressing, CNC fabrication, prefabrication, and exterior utilization of hardwood CLTs made with low-grade, locally-sourced Yellow Poplar. The project is the first example of prefabricated hardwood CLT construction in the United States and serves as an initial full-scale exterior test of fabrication and decay-prevention processes for the building product. Natural preservatives including a pine-tar-linseed-oil mix and wax were used to protect the CLT. BIM technologies such as Revit and Tekla were used to optimize the fabrication, shipment, and on-site assembly processes. The project illustrates that the upcycling and distributed manufacturing of locally-sourced, engineered biomaterials can provide novel architectural opportunities while enhancing local economies.

Keywords: Cross-laminated timber, Low-carbon construction, Design/Build, Materials + Construction Techniques

Acknowledgements

Virginia Tech administration and support staff, Henard Metal Fabricators, Walder Foundation Products, the City of Radford, Lowes, the Southern Virginia Higher Education Center, Truesdell Engineering, and other project partners.

"Completing the Cycle" with Hardwood CLT

Innovation in material development and utilization

Edward Becker
Virginia Tech

A primary benefit of cross-laminated timber (CLT) utilization occurs when low-value, sustainably-harvested timber can be upcycled into CLT – a high-value building product – benefiting rural economic growth while also lowering both construction time and carbon emissions from construction in urban areas. As construction costs in urban areas are lowered through rapid construction with CLT, more of the high-value product is purchased from nearby rural areas. When functioning optimally, this cyclical process of sourcing and utilization has demonstrated that CLT holds the potential to be catalytic to a wide array of associated entities, particularly when all entities are located in the same geographic region.

Considering that only softwood CLT is recognized by code but hardwood forests comprise a significant portion of the US forest stock, how can one 'complete the cycle' locally when code-compliant CLT made with softwoods must often be imported from great distances?

The Radford Train Observation Tower in Radford, Virginia demonstrates that such a "completion of the cycle" can be achieved in locations across the United States through the development of location-specific CLT. For this particular design-build project, locally sourced, locally tested, locally pressed, and locally utilized hardwood CLT panels that meet ANSI certification standards were developed for the project, the client a city attempting to transition their industrial image towards one of low-carbon, clean technologies. In coordination with specialists from wood science, structural engineering, building construction, and sustainable biomaterials, along with CLT pressing and fabrication expertise from the Southern Virginia Higher Education Center, the cross-disciplinary team designed a structure that not only showcases the use of a novel material, but also a structure that displays the first use of modular, prefabricated hardwood CLT construction in the United States, as well as the first use of hardwood CLT as a spatial enclosure system. The CLT was pressed on a custom-modified plywood press with Virginia Tech student's helping to cut the Yellow Poplar lamellae and apply the two-part structurally-rated glue themselves.

The ADA-accessible structure rests on helical pile foundations and is composed of a substructure of 'dancing' steel columns with two 10' x 15' modular, prefabricated hardwood CLT boxes above. The angular columns that appear to be dancing are intended to dematerialize the structure in its forest environment while the CLT boxes – lifted into place and set atop of the steel by crane – are perforated with CNC and hand-cut holes. Such perforations in the CLT allow the public of all ages and heights to playfully peer into the forest beyond. The dual perforation process of machine and hand-cut holes illustrated to the public that CLT is a durable yet malleable material. The structure extends over a steeply sloping site with the furthest horizontal point positioned 28' in the air. During an event in which the local community helped to clean the site, a civil-war era rail line was discovered that has been incorporated into the design as an access path, crushed stone being placed between the parallel rails. Community involvement, a multi-disciplinary project team, the development of a novel building material, and the deployment of unique prefabricated assembly processes comprise a successful attempt to "complete the cycle" in a hardwood-dominated context. The project is expected to be completed in Summer 2019 and has received an AIA design award for both design and material development and utilization.

Acknowledgements: Virginia Tech administration and support staff, Howard Metal Fabricators, Walder Foundation Products, the City of Radford, Lewes, the Southern Virginia Higher Education Center, Truesdell Engineering, and other project partners.

Truss-ting History

Chad Dennis and Joshua Friedman

Northeastern University

Abstract

Building performance in this case being evaluated by traditional means, such as energy use over time, in addition to qualitative questions of space, history, pedagogy etc. Another term explicit in this project is that of "future use" by which we build on typical modes of site analysis in addition to the growing body of research developed through building scientists, we ask how building systems can be used to accommodate a variety of program while simultaneously maintaining a strong connection to place. Through the use of a hybrid system of glulam trusses and CLT panels to repurpose an existing historic pumphouse on the UMass Boston campus, an annex is created in dialogue with said structure.

The use of long span trusses serves the long-term needs of the project, ensuring the building's resiliency into the future. In the short term, the raising of trusses from the ground plane enables a landscape program to be developed that deals with rainwater management and flooding. Sculpting of topography channels water beneath the structure, collecting it within a depression and eventually filtering it prior to discharge into nearby Boston Harbor.[1] In the long term, spaces have inherent programmatic flexibility; long spaces enabled by the trusses enable a large variety of programs to occupy the spaces. CLT floor panels might also be removed, the trusses serving as the main structural support members, allowing for sectional flexibility.

A final aspect of the project's adaptability is its programmatic functions. As designed in the current day, the structure is enmeshed in UMass Boston as a piece of critical infrastructure, serving much needed campus functions such as power generation, lab spaces, and rainwater management. The pump house in its current stage exists as a biomass power plant, serving increased power consumption needs stipulated in local master plans. The spans enabled by the structure, however, enable various types of machinery to be switched in and out, allowing conversions from one power source to another. The annex, as designed, serves laboratory functions. The overdesign, in terms of HVAC and a flexible raised floor system, enables expansion of this lab program or later conversion to other uses as classrooms, offices, etc.

In short, a model for adaptable design is offered, both in terms of program and in application. The system is applicable to both free standing and existing structures, as well as offering a multitude of spatial configurations as time progresses.

Keywords: Pedagogy, Material + Construction Techniques, Structure, Energy + Systems

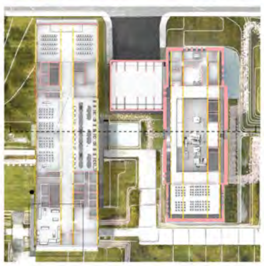
Acknowledgements

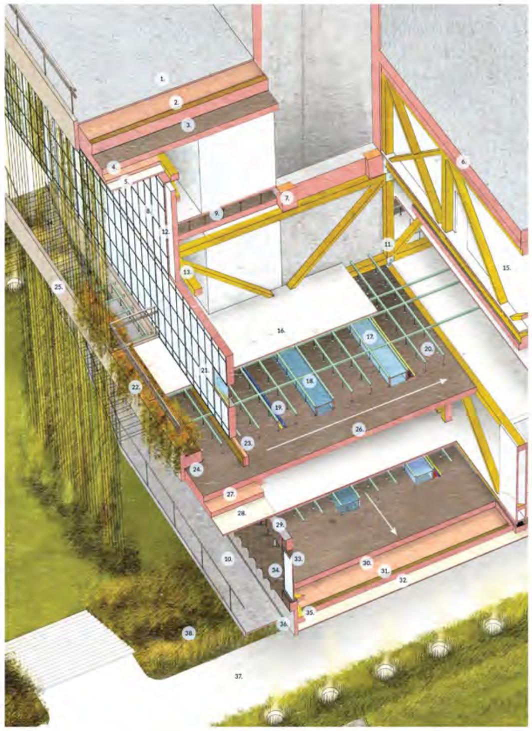
Project completed as an academic project for Associate Professor David Fannon's Comprehensive Design Studio to fulfill the requirements for Northeastern University's BS Architecture degree program

Notes or References:

1 "3D Data & Maps." Boston Planning & Development Agency. Accessed May 15, 2019. http://www.bostonplans.org/3d-data-maps/gis-maps/citywide-maps. (GIS Information for Site)

2 Several projects, including the Environmental Sciences Building at the University of British Columbia (Perkins and Will), the John W. Olver Design Building at UMass Amherst (Leers Weinzapfel), and the Wood Innovation Design Center in Prince George, BC (Michael Green Architecture) were analyzed as precedents and drawn on for inspiration in the design of this project

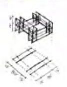




1. ROOF MEMBRANE AND INSULATION
2. ROOF BEAM
3. CLT COUCHED ON CORE
4. OVERHANG INSULATION
5. OVERHANG SHEATHING
6. ADDITIONAL SPACE FOR GREEN ROOF
7. TRUSS COUCHED TO CORE
8. HORIZONTAL AND VERTICAL PANEL SUBDIVISIONS
9. CLT RESTING ON TRUSS
10. EXTERIOR CATWALK STAIRWAY
11. TRUSS SADDLED TO TRUSS ABOVE AND BELOW
12. TRANSLUCENT PLASTIC WINDOW INSULATION
13. PANELS FIXED TO TOP TRUSS CHORD
14. VERTICAL TRELLIS WIRES ATTACHED TO WOOD PANELS
15. INTERIOR WALLS ATTACHED TO TRUSS
16. SUBFLOORING
17. SPACE FOR RETURN AIR
18. SPACE FOR SUPPLY AIR OR CHILLED BEAM
19. ACCOMMODATED CONDUITS AND PIPPING
20. RAISED FLOOR SYSTEM
21. INSULATED GLASS WALL PANELS WITH INSET WINDOWS
22. EXTERIOR HANDRAIL FIXED TO WOOD PANELS
23. INSULATION AND BLOCKING AT PANEL TO FLOOR CONNECTION
24. EXTERIOR PLANTER AND INSULATION IN RAISED FLOOR DEPTH
25. 3.75' x 6' EXTERIOR WOOD PANEL FIXED TO CLT
26. CLT RUNNING PERPENDICULAR TO BEAMS
27. CONTINUOUS INSULATION ALONG UNDERSIDE OF CLT
28. EXTERIOR SHEATHING ON UNDERSIDE OF CLT OVERHANG
29. CORK INSULATION BETWEEN UNITIZED PANELS
30. CORK INSULATION BETWEEN BEAMS
31. BEAM FIXED TO BOTTOM CHORD OF TRUSS TO HOLD CLT
32. EXTERIOR SHEATHING ALONG UNDERSIDE OF TRUSS
33. INSET PREFAB PANEL WINDOW
34. INSULATED PREFAB WOOD PANEL FIXED TO TRUSS
35. BOTTOM CHORD OF 15' TALL GLULAM TRUSS
36. 3.75' x 6' EXTERIOR WOOD PANEL FIXED TO TRUSS CHORDS
37. PERMEABLE PAVING.
38. PHYTOREMEDIATION AND WATER RETENTION STRATEGY
39. HYBRID WATER RETENTION AND PLAYSCAPE
40. LANDSCAPE/UNDER BUILDING LIGHTING

Alternating Truss Directions

By stacking 15' tall prefabricated wooden glulam trusses in alternating directions on a tartan grid, the primary structural system creates the possibility for long spans in perpendicular directions.



Cross Laminated Timber

The 15' x 30' tartan grid of the primary structural system of trusses allows for 45' CLT panels to span between truss chords giving rise to a number of opportunities for tertiary structural systems, and spatial variation

Raised Access Flooring

Saddling the trusses together at intersections along the tartan grid allows for flexibility in the distance from top to bottom chord. Using a RAF attached to the CLT panels allows for an easy and seamless distribution of mechanical systems, insulation, and planting strategies

Modular Facade System

Use of prefabricated structural elements lends itself naturally to prefabricated facade panels, especially when considering the buildings potential to change over time. A combination SIPS, insulated PVC, and typical glass curtain wall systems allow our highly adaptable structure to respond effectively to a variety of programmatic or climatic conditions.

Truss-ting History

Building Systems as a Temporal Dialogue

Chad Gregory Dennis
Northeastern University

Joshua Friedman
Northeastern University

with Associate Professor David Fannon
for Northeastern University's
Comprehensive Design Studio
ARCH 5120

Exploring the future use adaptability of wood construction techniques, our proposal utilizes a hybrid system of glulam trusses and CLT panels to repurpose an existing historic pumphouse on the UMass Boston campus and create an annex in dialogue with said structure. The radically different applications of the system, one as an internal frame to repurpose the pumphouse, the other as a free-standing laboratory, are a testament to the flexibility of prefabricated timber systems

A prefabricated structural system consists of long span glulam trusses, coupled with panelized CLT floors to span between trusses. The trusses offer their spanning capabilities to the building, allowing long span spaces within the design, uninterrupted by columns. At the same time, the CLT flooring system, due to CLT's inherent load-bearing capacities and spanning capabilities, offers uninterrupted spans perpendicular to trusses.

Trusses rotate 90 degrees to one another on every floor, allowing the system to "lock" around concrete cores, and thus gain lateral stability. This also allows the system to hang from cores to distribute loads to the ground. In the case of the historic pumphouse, this prevents further strain from being placed on already weather-worn walls, whilst in the new annex it allows for a completely free ground floor plan.

The use of long span trusses additionally serves long term needs functions in the project, ensuring the building's resiliency into the future. In the short term, the raising of trusses from the ground plane enables a landscape program to be developed that deals with rainwater management and flooding. Sculpting of topography channels water beneath the structure, collecting it within a depression and eventually filtering it prior to discharge into nearby Boston Harbor. In the long term, spaces have inherent programmatic flexibility; long spaces enabled by the trusses enable a large variety of programs to occupy the spaces. CLT floor panels might also be removed, the trusses serving as the main structural support members, allowing for sectional flexibility.

A final aspect of our project adaptability is its programmatic functions. As designed in the current day, the structure is enmeshed in UMass Boston as a piece of critical infrastructure, serving much needed campus functions such as power generation, lab spaces, and rainwater management. The pump house in its current stage exists as a biomass power plant, serving increased power consumption needs stipulated in local master plans. The spans enabled by the structure, however, enable various types of machinery to be switched in and out, allowing conversions from one power source to another. The annex, as designed, serves laboratory functions. The overdesign, in terms of HVAC and a flexible raised floor system, enables expansion of this lab program or later conversion to other uses as classrooms, offices, etc..

In short, by truss-ting history, we offer a model for adaptable design the consolidates, past present and future use. The system is applicable both free standing and as support for existing structures, as well as allowing a large array of programs to exist within its confines

Acknowledgements:
Project completed as an academic project for Associate Professor David Fannon's Comprehensive Design Studio to fulfill the requirements for Northeastern University's BS Architecture degree program.

Design/Lift: An Extra Concrete Beam in a Park

Federico Garcia Lammers
South Dakota State University, Department of Architecture (DoArch)

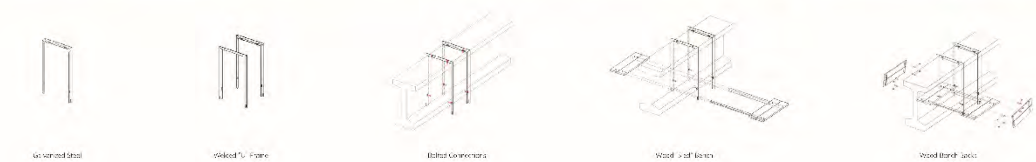
Abstract

According to the Department of Transportation, a commercial truck can drive at a maximum speed of sixty miles per-hour while carrying a sixty-foot-long precast concrete beam on a state highway. The beam in question is headed to a town of 1,800 people to be installed as part of a student-driven, faculty led Public Works project in Webster, South Dakota. Design/Lift focuses on the choreography of lifting and positioning a large piece of concrete on a public site. The beam sits in a yard, unapproved to span highway bridges, but potentially ready to engage the public in unexpected ways. The project in this poster is part of three-year long collaboration that connects architecture students at South Dakota State University with local communities and building industry leaders. During the third year of this project, two sets of fifteen undergraduate students worked on one-to-one mock ups, participated in city council meetings, and discussed design ideas at community gatherings. Through close collaboration with structural engineers and precast concrete manufacturers, students worked on the construction of a public space at the entry to a new athletic field. Students and faculty designed the installation of the beam by working with local laborers and engineers to understand the transportation and airborne movement of a 42,000-pound piece of concrete, which was expected to rest on two columns cantilevering at least 10 feet on both ends. After choreographing the beam's installation with certified 300-ton crane operators, students designed and fabricated a series of steel/wood "seating saddles" that connect the beam to a series of walking paths. The beam is a gallery wall, a long bench, a marker, and an unfinished monument. It appears to be a ruin that anticipates the construction of other things. It is in the process of becoming a mural for school children and the site of the annual chili cook-off. It is ready to bare any load that can balance on its slender profile. Design/Lift is part of the legacy of design/build pedagogy, presenting students and faculty with opportunities for on-going engagement with local expert labor.

Keywords: Design/Build, Pedagogy, Materials and Construction, Structures

Acknowledgements

Design/Lift was financially supported by a national grant from the Precast Concrete Institute in collaboration with Gage Brothers Concrete. Industry Collaborators: Clark Engineering, Pro-growth Construction, Northeast Excavation, B&B Contracting, and Soil Technologies. Community Collaborators: Webster School Board and Webster Area Development Corporation. Student Team: Ethan Millar (Graduate Teaching Assistant), John Angulu, Cody Blevins, Ji Cao, Guillermo Gonzalez Cebrian, Aspen Greene, Nicholas Kummer, Ted LaCoursiere, Megan Leebens, Jared Mulder, Cassie Pospishil, Jacob Ricke, Sharon Sanchez Ordonez, Kaitlyn Walker, and Megan Welbig.



Design/Lift

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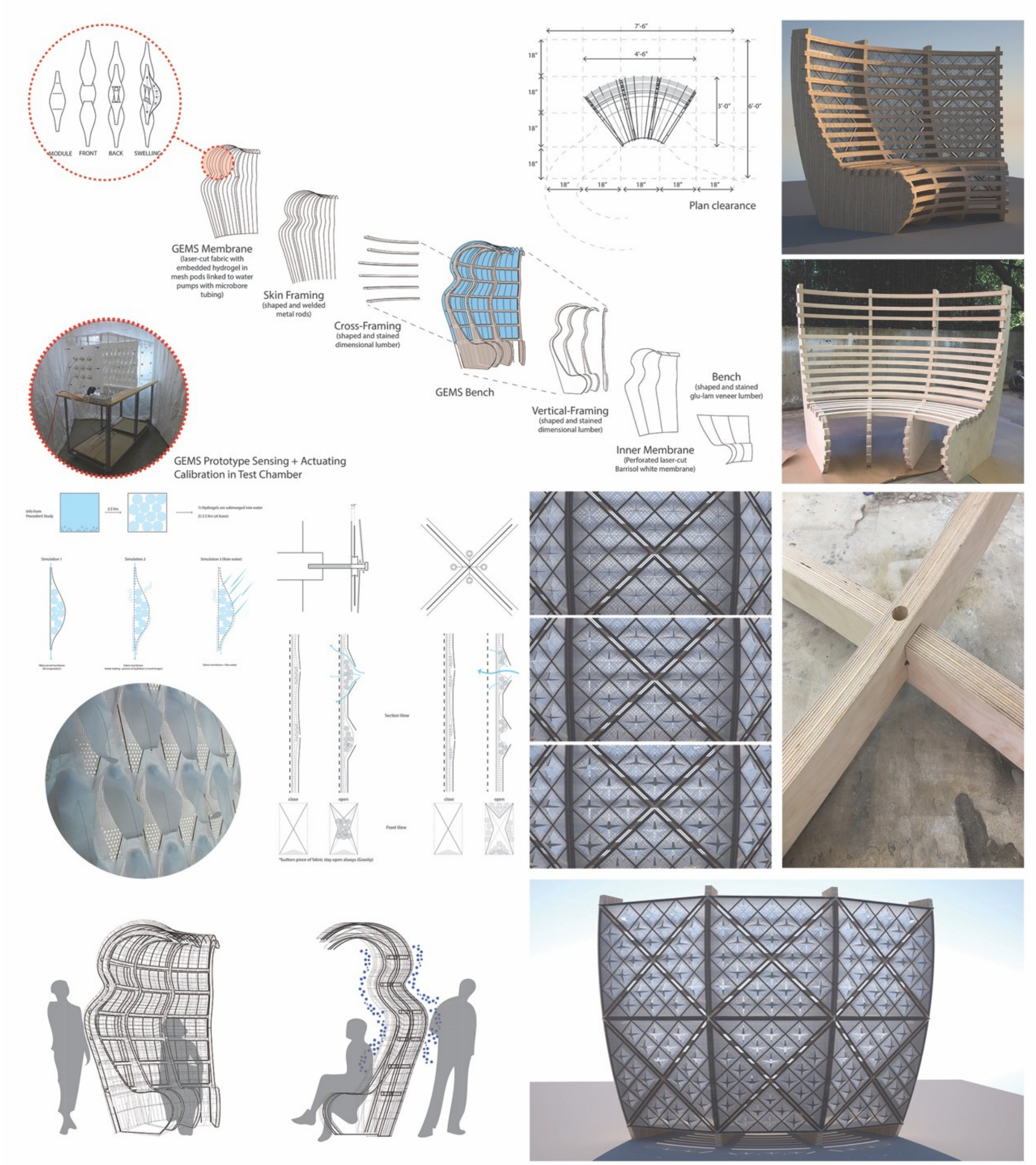
BENCH: Biorhythmic Evaporative-cooling Nano- TeCH

Aletheia Ida
University of Arizona, School of Architecture
Jialiang Ye
University of Arizona, School of Architecture Nick
Giambianco
University of Arizona, School of Architecture
Zechariah Fung
University of Arizona, School of Architecture

Abstract

The Biorhythmic Evaporative-cooling Nano-TeCH (BENCH) system is conceived as a novel building skin for architectural enclosures responsive to human interactions for thermal comfort in hot-arid climate conditions. The membrane system concurrently integrates natural ventilation cooling and modulations in daylighting transmission for inhabitant wellbeing and multi-sensory phenomena experience. The BENCH demonstration prototype combines CNC shaped and stained laminated plywood with all wood joinery for the structure of a small covered seating area with atmospheric effects. The soft skin membrane encloses the structure with embedded hydrogels that are actuated with water pumping into the mesh pod modules through clear microbore tubing. Each gel pod module expands during swelling, which induces the lift of an outer flap to allow for airflow through the skin. When air flows through the flaps, it carries humidity off of the gel pods and into the surrounding atmosphere for human thermal comfort cooling effects. There are three small water pumps located under each bench module on the floor. Humidity and temperature sensors are incorporated into the BENCH prototype and link to an automated hydro-pump actuator through Arduino servo motor control. The GEMS prototype is pre-tested with sensing and actuating functionality in an environmental test-chamber in a controlled lab setting. The demonstration prototype is currently being fabricated and will be installed for in-situ real-time testing beginning in May 2019. The project integrates the research and development of the author's work through collaborations with material science, electrical and computer engineering, and human health and wellbeing. Future work with the prototypes includes human wellbeing research in a living-lab setting with non-invasive biometric sensing for heart rate variability and sweat biomarkers in correlation to BENCH environmental fluctuations for temperature, humidity, and dynamic daylight conditions.

Keywords: Hydrogel Membranes, Bioresponsive Design, Evaporative Cooling, Machine Learning, CNC Wood Structure



BENCH

Biorhythmic Evaporative-cooling Nano-teCH

Aletheia Ida
University of Arizona
School of Architecture

Jiliang Ye
University of Arizona
School of Architecture

Nicholas Giambanco
University of Arizona
School of Architecture

Zechariah Feng
University of Arizona
School of Architecture

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Acknowledgements: University of Arizona Water, Energy and Environmental Systems (WEES) Interdisciplinary LINKS Funding (2017 - 2018); University of Arizona Office for Research Discovery and Innovation (ORDI) Accelerate for Success Grant (2018 - 2019)

Methods to Monitor and Simulate Existing Residences:

Analyzing and Improving Energy and Comfort for Native Hawaiian Homeowners

Wendy Meguro, University of Hawaii, School of Architecture, and Sea Grant College Program
Manfred Zapka, Sustainable Design and Consulting
Eileen Peppard, University of Hawaii, Sea Grant College Program

Abstract

To support the State of Hawaii's goals of improving energy performance of buildings and reducing dependence on fossil fuels, this study develops design recommendations that could improve the energy efficiency and thermal comfort of hundreds of existing and future homes for native Hawaiian families.

This poster shares the methods and learning objectives used by faculty, researchers, and a team of architecture, electrical and mechanical engineering, and computer science students to chart a path to net-zero site energy use in residences in sub-tropical climates by monitoring and simulating existing houses.

The faculty from Architecture and Sea Grant structured the research project into multiple phases over two years: 1) Monitor Existing Buildings; 2) Calibrate Simulated Whole Building Energy Models; 3) Simulate Potential Design for Future Energy Code; 4) Simulate Potential Energy Efficiency Improvements; 5) Estimate Potential Renewable Energy Production and; 6) Communicate Recommendations to Developers and Residents.

In this study, three existing house typologies are studied: naturally ventilated (no air conditioning); partially air-conditioned; and centrally air-conditioned.

Student and senior researcher teams monitor and manage data for temperature, humidity, and sub-metered for electricity in nine houses for one year. Air conditioning comprises a larger portion of the monitored houses' total energy use as compared to national hot-humid climate residential averages. The monitored data shows most occupants chose to use air conditioning year round despite the mild climate and high electricity rates. In addition, monitored data shows plug loads vary between houses by more than a factor of two.

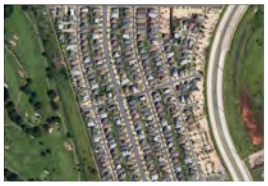
Student researchers using computational building performance simulation in NREL's BEopt with Energy Plus find that the most effective energy efficiency measures are 1) improving the air conditioning SEER rating and 2) increasing the thermostat cooling setpoint while using ceiling fans with occupancy sensors. The team graphically communicates recommendations and presents them to developers and homeowners for potential incorporation into the next hundreds of homes planned for construction.

Keywords: Energy Efficiency, Residential, Sub-tropical, Thermal Comfort, Energy Simulation

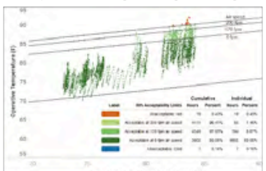
Acknowledgements

Thank you to Hawaii Natural Energy Institute as well as University of Hawaii Sea Grant College Program for funding to support staff, student researchers, and equipment.

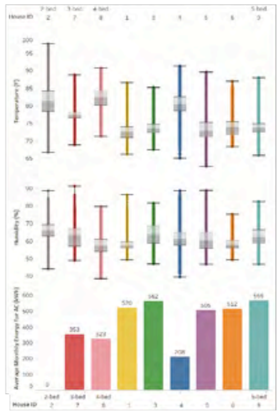
01 Monitor Existing Residences



The team worked with a major home developer for native Hawaiian families to improve energy conservation and thermal comfort in existing and hundreds of future homes. This helps meet the State's greenhouse gas reduction goals.



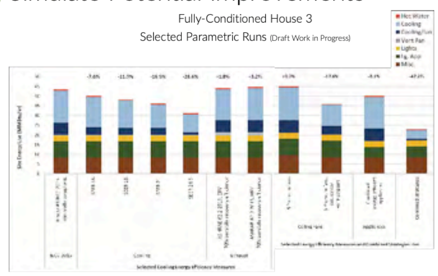
The computer science students learned about thermal comfort by developing a script to plot the monitored temperatures in an adaptive comfort graph for the naturally ventilated house. The graph also quantified the hours that could made comfortable by increasing air speeds.



After monitoring the temperature, humidity, and disaggregated energy use for about a year, we see significant cooling energy savings with natural ventilation (house 2) or mixed-mode ventilation (house 4).

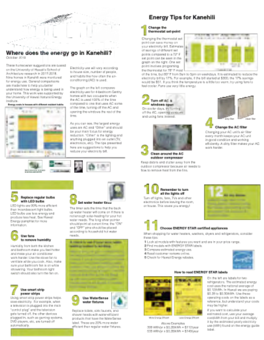
Architecture and mechanical engineering student researchers learned to create whole-building energy models using NREL's BEopt program with EnergyPlus. Students learned energy model calibration techniques, energy codes, and thermal comfort standards.

02 Simulate Potential Improvements



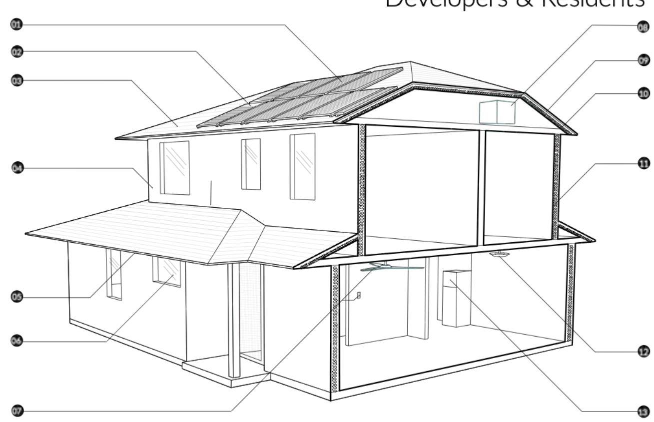
Students learned energy modeling steps including: 1) Calibrate; 2) IECC 2015 Base Case; 3) Parametric Options; 4) Combined Strategies Design Case. The most effective energy efficiency measures were improving the air conditioning SEER rating as well as increasing the cooling temperature setpoint while using premium efficiency ceiling fans with occupancy sensors.

03 Communicate Recommendations to Developers & Residents



Brochure for Residents

Based on the analysis, students and senior researchers presented energy conservation recommendations to homeowners using the brochure above.



After creating the simulated Design Case, and calculating the photovoltaic panels to achieve net-zero site energy, students created section perspective drawings to facilitate discussions with the developer and builders.

Potential Energy Efficiency Strategies

Fully Air-conditioned House

01 **Photovoltaic Panels**
02 **Solar Hot Water Panels**
03 **Light Colored Roof Material**
Reflectance: >0.70
04 **Light Colored Exterior Finish**
Absorptivity: <0.3
05 **3' Eaves**
06 **Window Type**
Clear, Air-Filled, Double Pane, SHGC: 0.25 U-value: 0.5
90% free area
07 **Ceiling Fan, Thermostat Offset**
Premium efficiency fans w/ occupancy sensors. Four degree Farenheit thermostat cooling set-point increase.
08 **Air Conditioning Unit**
SEER 24
09 **Radiant Barrier and Air Space**
10 **Roof Insulation**
R-19
11 **Wall Insulation**
R-13, Wood studs
12 **Lighting**
100% LED Fixtures
13 **Appliances**
Energy Star Refrigerator (with top freezer);
Energy Star Washer and Dryer;
Electric Stove - Premium

Methods to Monitor and Simulate Existing Residences

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To support the State of Hawaii's overarching goals of improving energy performance of buildings and reducing dependence on fossil fuels, this study develops design recommendations that could improve the energy efficiency and thermal comfort of hundreds of existing and future homes for native Hawaiian families living in developments by the Department of Hawaiian Homelands.

This poster shares the methods used by faculty and a team of architecture, electrical and mechanical engineering, and computer science students to chart a path to net-zero energy use in sub-tropical climates by monitoring and simulating existing residences.

The faculty from Architecture and Sea Grant structured the research project into multiple phases over two years: 1) Monitor Existing Buildings; 2) Calibrate Simulated Models; 3) Simulate Potential Designs for Future Energy Code; 4) Simulate Potential Energy Efficiency Improvements; 5) Estimate Potential Renewable Energy Production and; 6) Communicate Recommendations to Developers and Residents.

In this study, three existing home typologies are studied: naturally ventilated (no air conditioning); partially air-conditioned; and centrally air-conditioned.

Methods used and preliminary results for the monitoring portion of the project are as follows.

1 - After recruiting nine homeowner volunteers, the student and senior researcher team install sensors to measure temperature, humidity, and sub-meters for electricity for one year. Students learn to manage large quantities of data, create graphs for ASHRAE thermal comfort standards, and compare energy use intensity to similar residential developments.

2 - The monitored data allows the researchers to compare the houses to national averages and to each other in terms of energy use intensity and energy consumption by end use. In the monitored houses, air conditioning comprises a larger portion of the houses' total energy use as compared to national hot-humid climate residential averages.

3 - The monitored data gave insight into occupant behaviors that are not obvious from national averages. The monitored data shows most occupants chose to use air conditioning year round, even though mixed-mode ventilation yields significant cooling energy savings and similar indoor temperature and humidity. In addition, monitored data shows plug loads vary between houses by more than a factor of two.

Methods used and preliminary results for the simulation portion of the project are as follows.

1 - Student researchers learn to use computational building performance simulation to estimate existing and potential future reductions to house energy use and greenhouse gas emissions. Students researchers learn user-friendly software, NREL's BEopt with Energy Plus and Microsoft Excel.

2 - Students estimate on-site renewable energy production for net-zero site energy through hand calculations and PV Watts.

3 - The team develops recommendations and presented them to developers and homeowners. The team found that improving the air conditioning SEER rating and increasing the thermostat cooling setpoint while using ceiling fans were the most effective energy efficiency measures. We are hopeful that effective strategies will be incorporated into the next hundreds of homes built.

Acknowledgements: Thank you to our partners, DHHL and the builders. Thank you to Hawaii Natural Energy Institute as well as University of Hawaii Sea Grant College Program for funding to support staff, student researchers, and equipment. Thank you to student researchers including Riley Josephson, Shane Matsunaga, Dustin Chang, Carlos Paradis, Kathryn Paradis, and Benjamin Thrun.

WATeRVASE: Wind-catching Adaptive Technology for a Roof-integrated Ventilation Aperture System and Evaporative-cooling

Maryam Moradnejad
University of Arizona

Dorit Aviv
Princeton University

Aletheia Ida
University of Arizona

Forrest Meggers
Princeton University

Abstract

The WATeRVASE is a Wind-catching Adaptive Technology for a Roof-integrated Ventilation Aperture System and Evaporative-cooling. Prior research for the adaptive wind catcher technique demonstrates the effective multi-fin design composition for geometry shifting in response to wind directions and speeds (Aviv, Meggers 2018, 186-195; Aviv, Axel, 2017, 1123-1128). Other prior research demonstrates the effectiveness of superporous polyelectrolyte hydrogels for water sorption and diffusion (Smith, 2017, 2481-2488; Ida, 2018). Our team members have also developed a machine-learning platform for testing building technology prototypes for particular environmental conditions and building integration analyses (Smith, Lasch, 2016, 98-105). The new area of research combines the prior work of environmental systems, material science, and electrical and computer engineering for expanding the potential environmental variables that might be addressed simultaneously with the WATeRVASE. Human thermal comfort is one of the most significant challenges in hot-arid climate contexts due to energy-intensive building cooling needs, resulting in significant amounts of problematic carbon emissions. Existing experience has shown that passive cooling techniques with natural ventilation and evaporative-cooling provide excellent thermal comfort, together with very low energy consumption (Santamouris and Dionysia 2013, 74-79). The adaptive roof aperture is an advanced passive cooling system that responds to the external airflow thermodynamics by changing its membrane water sorption states to allow either downdraft airflow

(saturated top membrane) or nighttime radiation (open top with dry ventilation membrane). In this research, we are developing the adaptive roof aperture functions in the specific hot-arid climate location of Tucson, Arizona. The integration of the hydrogel membrane as an inner surface-lining of the wind-catcher will enable the control of moisture interface with airflow streams via hydro-pumps with sensors and actuation control, providing evaporative-cooling effects for the daytime downdraft system. Furthermore, the prototype incorporates a lyophilized hydrogel that provides for humidity sorption at the base of the cooling space for water recuperation. The hydrogel membrane may also provide daylighting and thermal conduction mitigation based on saturation states. The project will also explore the potential for rain-water harvesting with the roof-integrated aperture, which is especially necessary for drought-prone hot-arid contexts.

Keywords: Adaptive Windcatcher, Passive Cooling, Hydrogel Membranes, Machine-Learning, Natural Daylighting, Water Harvesting

Acknowledgements:

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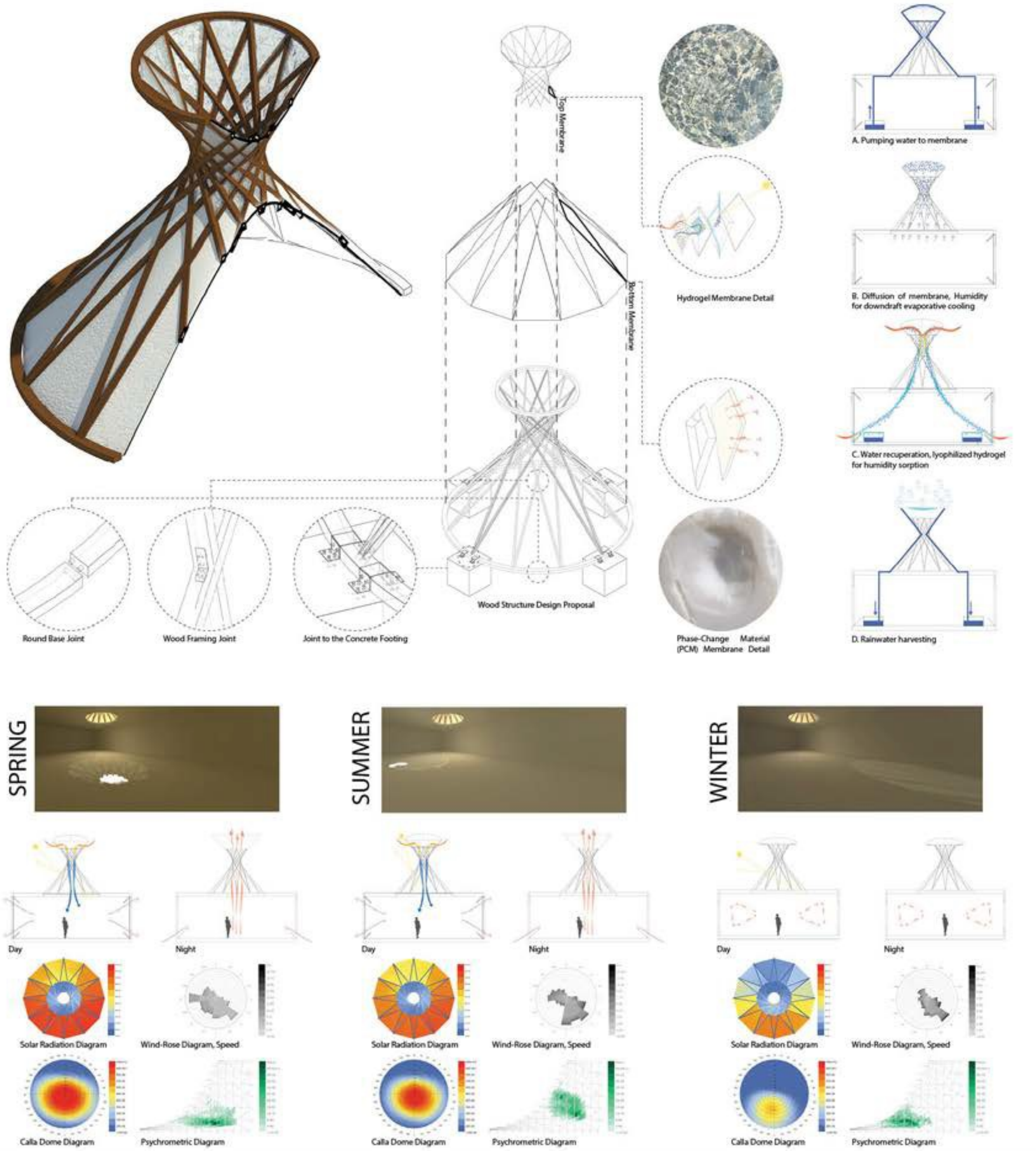
Smith, Shane Ida, and Chris Lasch. "Machine Learning Integration for Adaptive Building Envelopes." In 36th Annual Conference of the Association for Computer Aided Design in Architecture-Posthuman Frontiers: Data, Designers, and Cognitive Machines, ACADIA 2016, pp. 98-105. ACADIA, 2016.



WATeRVASE: Wind-catching **A**daptive **Te**chnology for a **R**oof-integrated **V**entilation **A**perture **S**ystem and **E**vaporative-cooling

Maryam Moradnejad
University of Arizona

Dorit Aviv
Princeton University

Aletheia Ida
University of Arizona

Forrest Meggers
Princeton University

The WATeRVASE is a Wind-catching Adaptive Technology for a Roof-integrated Ventilation Aperture System and Evaporative-cooling for hot-arid climate contexts. The example under study is being developed for the Sonoran Desert location of Tucson, Arizona. Prior research for the adaptive wind catcher technique developed by members of our research team demonstrates the effective multi-fin design composition for geometry shifting in response to wind directions and speeds (Aviv, Meggers 2018, 186-195; Aviv, Axel, 2017, 1123-1128). Other prior research by our team members demonstrates the effectiveness of super porous polyelectrolyte hydrogels for water sorption, diffusion, and daylighting control across large surface areas (Smith, 2017, 2481-2488; Ida, 2018). Both areas of prior work incorporate environmental sensing and actuation techniques for system responsiveness. Our team members have also developed a machine-learning platform for testing and developing building technology prototypes for particular environmental conditions and building integration analyses (Smith, Lasch, 2016, 98-105). The new area of research combines the prior work of environmental systems, material science, and electrical and computer engineering in a collaborative mode for expanding the potential environmental variables that might be addressed simultaneously with the WATeRVASE. Human thermal comfort is one of the most significant built environment design issues in extreme hot-arid climate contexts. Building energy consumption due to cooling loads in these climates is also contributing significant amounts of problematic carbon emissions to the environment, deeming passive cooling techniques a necessary approach in design. One of the oldest passive cooling systems that is still being used today is the wind-catcher (Jomehzadeh and et al., 2017).

Existing experience has shown that passive cooling through air-exchange dissipation techniques provides excellent thermal comfort and indoor air quality, together with very low energy consumption (Santamouris and Dionysia 2013, 74-79). The adaptive roof aperture is an advanced passive cooling system that responds to the external airflow thermodynamics by changing its geometry in order to maintain acceptable interior space temperatures. The passive cooling is accomplished through adjustments in the aperture fins to allow for either downdraft airflow (narrow top neck) or nighttime radiation (wide open top).

In this research project, we are developing the adaptive roof aperture functions with a specific hot-arid climate context so that multiple variables might be addressed. The integration of the hydrogel membrane as an inner surface-lining of the wind-catcher fins will enable the control of moisture interface with airflow streams, via hydro-pumps with sensors and actuation control providing evaporative-cooling effects for the daytime downdraft system. Furthermore, the prototype incorporates a lyophilized hydrogel that provides for humidity sorption at the base of the cooling space for water recuperation . When composited with glass or a translucent biopolymer fin substrate, the hydrogel membrane may also provide daylighting and thermal conduction mitigation based on saturation states. When the hydrogel membrane is saturated with water there is higher daylight transmission compared to the dry condition that condenses the polymer chains into a semi-opaque state. In both states, the hydrogel provides some amount of diffuse natural daylighting. The project will also explore the potential for rain-water harvesting with the roof-integrated aperture, which is especially necessary for drought-prone hot-arid contexts. The heavy monsoon rain season and winter rains provide opportunities for water harvesting with the large-scale adaptive aperture in an open position for gravity-feed collection.

The hydrogel membrane lining will enable large surface area exposure of a material condition that provides rapid saturation and retention of rainwater, helping to slow the rate of monsoon volume runoff during the water harvesting process. The work in-progress place-holders presented here will be further developed, including prototype development with the hydrogel and PCM materials, integration of sensing and actuation devices, the membrane sorption controls the relation to wind direction and temperature change. A full-scalemock-up with limited mechanical open-close aspects will be deployed for real-time in-situ testing for one month of Summer 2019.

The Corner: Tectonic Intersections of the Architectural Environment

Chad Schwartz, Kansas State University
Jaasiel Duarte-Terrazas, Kansas State University
Nataani Garnenez, Kansas State University

Abstract

Architectural corners serve as nodes of constructional shifting, of structural logistics, of environmental control emphasis, of spatial experience, and of aesthetic considerations and it is in these particular building intersections that our greatest architects have exceled. Despite the importance of the corner, most architectural software introduces generalizations into design work that all but assures improper understanding of a building's corners, especially for students and those novice to the profession. The transformations undertaken in the computer rarely reflect the strategies used to create physical, occupiable space. For instance, when working in building information modeling software, walls intersect via "butt" or "miter" techniques regardless of the materiality of the components. Any system can turn the corner with perfect resolution, without the need for additional components or finishes typically used to resolve aesthetic and performance issues. From this technical perspective, what is possible in the computer is often impossible in reality.

This presentation centers on a recently initiated, seminar-based research project through which a group of upper division and graduate architecture students are rigorously examining a set of precedents in an effort to better understand how significant architects of the 20th and 21st centuries treated or continue to treat, as the case may be, the architectural corner in their critically acclaimed works. The primary goals of this study are to absorb for configuring these junctures of construction, tectonics, and design potential and to create a framework of lessons, which students can use in the development of their own design work moving forward both in the academy and in the professional world.

Keywords: Materials + Construction Techniques; Architectural Tectonics; Architectural Detail

Acknowledgements

We would like to acknowledge the hard work of all of the students who participated in this course in the Spring and Fall semesters of 2018. Specifically, Professor Schwartz would like to comment Ashley Brunton (study of the works of Louis Kahn) and co-authors Jaasiel Duarte-Terrazas (study of the works of Peter Zumthor) and Nataani Garnenez (study of the works of Fay Jones) for their contributions to this line of inquiry.

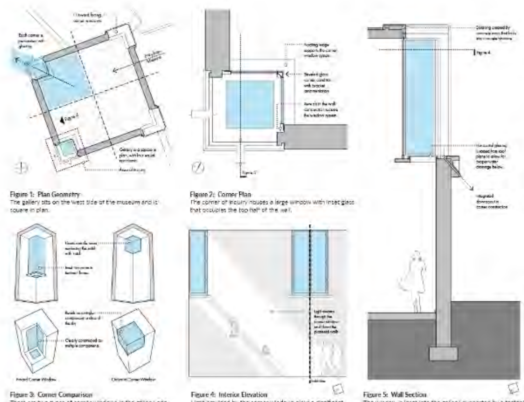


Figure 1: Plan Geometry
The gallery sits on the west side of the museum and is square in plan.

Figure 2: Corner Plan
The corner of inquiry houses a larger window with inset glass that occupies the top half of the wall.

Figure 3: Corner Comparison
There are two types of corner windows in the gallery; one inset and one outset.

Figure 4: Interior Elevation
Light provided by the corner windows plays a significant role in the quality of the gallery space.

Figure 5: Wall Section
The window is inset into the gallery, supported by a tectonic frame.

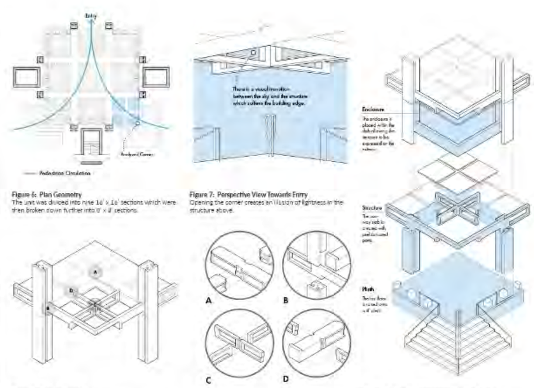


Figure 6: Plan Geometry
The unit was divided into nine 16' x 16' sections which were then broken down further into 8' x 8' sections.

Figure 7: Perspective View Towards Entry
Opening the corner creates an illusion of lightness in the structure above.

Figure 8: Corner Assembly
The prefabricated structure is assembled by four different connections.

Figure 9: Exploded Axonometric of the Corner
The enclosure is placed within the structure which is then offset from a plinth.

Addition to the Gipsoteca Canoviano

Carlo Scarpa | 1955 1957

In 1955, Carlo Scarpa was commissioned to design an extension to an existing 19th century gallery space housing a collection of work by late 18th century Italian sculptor Antonio Canova. The museum had outgrown its existing home and the collection required more display space. The newly conceived museum was "founded in the practical necessity of augmenting the permanent exhibition space of the existing galleries [while also] amplifying and rationalizing the display of this unrivaled surviving collection" of Canova's sculpture.[1]

The corner under investigation here is located in the taller, square gallery, which is raised a single step from the entry gallery and is twice the height of that previously occupied space. The proportions of this room are derived from those of Canova's studio space, turning the master's workspace on end, but maintaining the dimensions of the space.[2] Here, "the form and position of the openings were derived directly from an attempt to 'cut out the blue of the sky.'"[3] The glass corners of the room are of two types, those that replace the wall and ceiling surfaces with glazing and those that are incised into the room. Scarpa imagined these two typologies as blocks of light, providing natural illuminance from above for the sculpture within. "Positioned at each of the upper corners of the cube, [these] rectangles in two matching pairs allow the sky with its moving clouds to illuminate the gleaming white volume of the gallery."[4] Our study focuses on the taller pair of windows, those incised into the gallery. The frames of the windows are iron and the windows are supported by a thin plaster shelf which bestows on the space "a greater architectonic feeling than apparent in their counterparts."[5]

Notes

1 Judith Carmel-Arthur and Stefan Buzas, "Canova and Scarpa in Possagno," in Four Museums, ed. Axel Menges and trans. by Michael Robinson (London: Edition Axel Menges, 2004), 6.
2 Robert McCarter, Carlo Scarpa (New York: Phaidon Press, 2013), 110.
3 Guido Beltramini and Italo Zannier, eds., Carlo Scarpa: Architecture and Design (New York: Rizzoli International Publications, Inc., 2007), 114.
4 Carmel-Arthur and Buzas, "Canova and Scarpa in Possagno," 14.
5 ibid.

Richard's Medical Research Laboratory

Louis Kahn | 1957 1961

Richard's Medical Research Laboratory is located in Philadelphia, Pennsylvania and was completed in 1961. This building was intended to house biology laboratories for the University of Pennsylvania. It was one of Kahn's first projects, which permitted him to put his set of architectural ideas to work. To create an efficient building for laboratories, Kahn imagined a structure that would be appropriate for this type of a facility and allow the laboratories to be open, flexible, and free of structural intrusions.

To solve this problem, Kahn introduced thick floor plates that provided ample space for systems and advancing technologies. Mechanical units and service spaces were then placed in brick towers as to not disturb the open floor plan. Kahn wrote, "The nature of space is further characterized by the minor spaces that serve it. Storage rooms, service rooms and cubicles must be given their own structure."[1] Though the brick towers may appear to be supporting the floor plates, this is a mind game intentionally facilitated by Kahn in the design of the facility. The two columns flanking the brick tower are the actual structure for the floors. The actual structure looks so small in comparison to the large brick towers that it creates an illusion of lightness.[2]

The entry sequence of Richard's Medical Research Laboratory is unique. Kahn intended for users to enter on the corner, luring users between the brick towers. People then walk up the stairs, onto a plinth, and are invited in by the articulation of the structure at the corner. Kahn chose a prefabricated concrete structure which is comprised of four different units. This strategy allowed the building to be built efficiently. To support this idea of lightness in the composition, Kahn opened the corners, creating a cantilevered structure. The floor plates themselves get smaller at the corners to reduce visual loads.

Notes

1 Kahn, "Architecture is the Thoughtful Making of Spaces," Perspecta, no. 4 (1957) 2.
2 Joseph Rosa, Louis I. Kahn: 1901-1974 Enlightened Space (TASCHEN, 2006), 37.

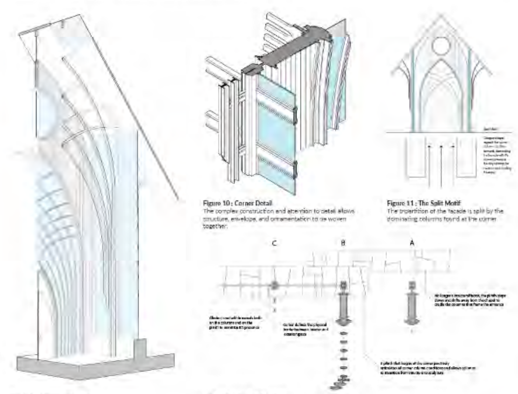


Figure 10: Corner Detail
The complex construction and attention to detail allows structure, envelope, and ornamentation to be woven together.

Figure 11: The Split Motif
The transition of the facade is split by the protruding columns found at the corner.

Figure 12: Corner Perspectives
View of corner from interior of nave.

Figure 13: Plan Relationships
Details of the corner's plan geometry and the engagement of its tectonic components.

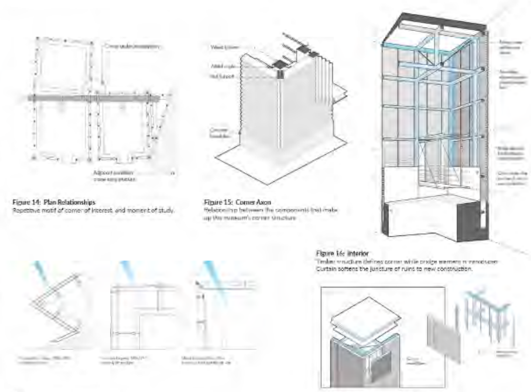


Figure 14: Plan Relationships
Repetitive motif of corner of interest and moment of study.

Figure 15: Corner Axon
Relationship between the components that make up the museum's corner structure.

Figure 16: Interior
Timber structure defines corner while bridge element in steel... Curtain softens the juncture of ruins to new construction.

Figure 17: Comparative Corners
Comparing the corner configuration and transparency of three of Zumthor's projects.

Figure 18: Peel Back Reveals Anatomy
Revealing Figure affords an understanding of the layered transparency and lightness.

Mildred B. Cooper Memorial Chapel

Fay Jones | 1986 1987

As two Mozart sonatas may share a three part musical framework yet vary in key and ultimately in kind, the Mildred B. Cooper Memorial Chapel explores, expands, and transposes the Gothic theme introduced at Thorncrown Chapel. Cooper Chapel, commissioned by the children of Mr. and Mrs. John Cooper, Sr. in honor of the late Mrs. Cooper, is set in a dense grove on a hill above the 7,000-person community of Bella Vista, Arkansas.[1] Often called the little sister of Thorncrown, the Mildred B. Cooper Chapel utilizes strong repetitive elements in the structure of the design. Jones composed, again in harmony with the natural surroundings, a wood and steel structure exploring a unique perspective on the design theme of Gothic architecture. The entrance to the chapel rises from a stone floor and organically frames the entrance with a Gothic arch. Above floats an oculus giving visitors a glimpse of the chapel's signature steel work. To the sides of the chapel the columns splay out to support the roof, reminiscent of the flying buttress of Gothic cathedrals.

Although heavier in facade composition, Cooper Chapel recreates the light and delicate feel of Thorncrown within the walls of the nave. Built steel members, painted a soft brown hue, grip each other like the interlocked fingers of two hands.[2] Steel columns, encapsulated in wood cladding, reach out through reveals to anchor the structure to the ground. This move is reflected on the exterior as well, where it supports the delicate roof structure.

The chapel, sitting gracefully in its natural environment, creates a cradle at its entry with a door that is recessed underneath the archway. This configuration provides a smooth transition between exterior and interior. Jones uses three different sets of column types, referred to as A, B, and C in the diagram above, which are organized differently in the chapel's entrance, nave, and altar. The corner under investigation is a B-column type that features elements from both A and C-column types. Occurring at this corner is a transition from a heavy facade, anchored to the ground, to a light and airy glazing system that allows the natural environment to have a strong presence within the chapel walls.

Notes

1 Ivy, Robert Adams., and Fay Jones. Fay Jones: The Architecture of E. Fay Jones, FAIA. New York: McGraw-Hill, 2001.
2 ibid

Shelter For Roman Ruins

Peter Zumthor | 1986

There was an almost unquestionable desire to preserve all that was left of two Roman Masonry structures in the town of Chur, Switzerland, two ruins which had, for quite some time, gone untouched and were on the brink of being lost. Zumthor's intervention, conceived as a sort of abstract reconstruction of what had been, is described as "a lightweight framework of walls, made of timber lamella which admit light and air, exactly follow[ing] the roman outer walls."[1]

The newly defined confines of the interior, therefore, allude to those of the Roman ruins. Once more, the location is given a visible form upon which light, air, and the sound of the town can permeate. At night, the ruins are given a new life, as the structures transform and become a lantern in the city.

One enters atop a modern steel foot bridge, not from the perceived archaic remains of the Roman entrance, which instead act as windows into and out of the protected space. The entry leads to an elevated observation level, one of many simple gestures aiming to preserve the ruins and not disturb them. This walkway allows one to walk along "a path through dark connecting tunnels from one spatial unit to another."[2] A literal piercing of the newly erected wooden wall sets the segmented and articulated procession in motion with points of release through the use of stairs that lower and meet the ruins to provide moments to engage with the ruins as they were. The area of inquiry is located at one of these piercings along the main walk, where the foot bridge engages with the corner of one of the wooden shells.

In this place, one can sense the city and experience life as it was before simultaneously. "You are steeped in history and you hear the city of the present."[3]

Notes

1 Peter Zumthor, "Protective Housing for Roman Archeological Excavations, Chur, Graubunden 1985-86" Peter Zumthor Works: Buildings and Projects 1979-1997 (Lars Muller Publishers, 1998), 20.
2 ibid.
3 Peter Zumthor "Peter Zumthor 1985-2013, Vol. 1" (Verlag Scheidegger and Spiess, 2012) 28.

The Corner

Tectonic Intersections of the Architectural Environment

Chad Schwartz
Kansas State University

Jaasiel Duarte-Terrazas
Kansas State University

Nataani Garnenez
Kansas State University

"...corners and walls are mutually dependent on each other for the definition of a space. It is the corners which make the space a figure; it is the corners which tell us where we are."[1]

In order to create enclosure, and architectural space in general, the primary systems of a building must turn, they must wrap, and eventually they must return to where they began. This fundamental precept of building is essential to the creation of space, but the moments of change, of intersection, of shifting that we define as corners are often overlooked – especially in academia – as critical to the functional performance, aesthetic appearance, and conceptual understanding of the built environment. When a wall, or any other construction system, turns and a corner is formed and a complex (sometimes significantly complex) situation is created. Corners serve as nodes of constructional shifting, of structural logistics, of environmental control emphasis, of spatial experience, and of aesthetic considerations and it is in these particular building intersections that our greatest architects have excelled.

The catalyst for this examination of the architectural corner is found embedded in the contemporary design process of the vast majority of those in the architectural profession. Utilized both in academia and in the professional world, most architectural software introduces generalizations into design work that all but assures improper understanding of a building's corners, especially for students and those novice to the profession. Although encompassing a larger range of issues, in the generation of architectural schemes, we utilize modeling programs that require us to shift from point, to line, to plane, and to volume, but the transformations undertaken in the computer rarely reflect the strategies used to create physical, occupiable space. When working in building information modeling software, walls intersect via "butt" or "miter" techniques regardless of the materiality of the components. Layers of walls can be "wrapped" at the ends, again regardless of material or structural makeup. Any system can turn the corner with perfect resolution, without the need for additional components or finishes typically used to resolve aesthetic and performance issues. From this technical perspective, what is possible in the computer is often impossible in reality, potentially leading the novice student or architect to improperly consider a building's corners, satisfied with the level of resolution provided by the computer.

This presentation centers on a recently initiated, seminar-based research project through which a group of upper division and graduate architecture students are rigorously examining a set of precedents in an effort to better understand how significant architects of the 20th and 21st centuries treated or continue to treat, as the case may be, the architectural corner in their critically acclaimed works. Each student participating in the seminar selected an architect to spend the semester examining and, from this particular architect, three corners from three different buildings to be the focus of the study. The semester was then spent creating an analysis of each of these three corners. From this analysis, the students produced a series of diagrams and other drawings that demonstrate how the corners of the buildings work with respect to structural, construction, assembly, enclosure, performance, aesthetic, spatial, and conceptual considerations. A model of one corner was created as a final course submission. Components of four of these corner analyses are presented above.

The primary goals of this study are to dissect these junctures of construction, tectonics, and design potential and to create a framework of lessons, which students can use in the development of their own design work moving forward both in the academy and in the professional world.

1 Thomas Thiis-Evensen, *Archetypes in Architecture* (Oslo, Norway: Scandinavian University Press, 1997), 121.

Acknowledgements: We would like to acknowledge the hard work of all of the students who participated in this course in the Spring and Fall semesters of 2018. Specifically, Professor Schwartz would like to commend Ashley Brunton (study of the works of Louis Kahn) and co-authors Jaasiel Duarte-Terrazas (study of the works of Peter Zumthor) and Nataani Garnenez (study of the works of Fay Jones) for their contributions to this line of inquiry.

Phenomenology and Performance: Technology | Architecture + Design Through Music

Jerry Stivers, AIA, LEED AP
Associate Professor, Oklahoma State University

Abstract

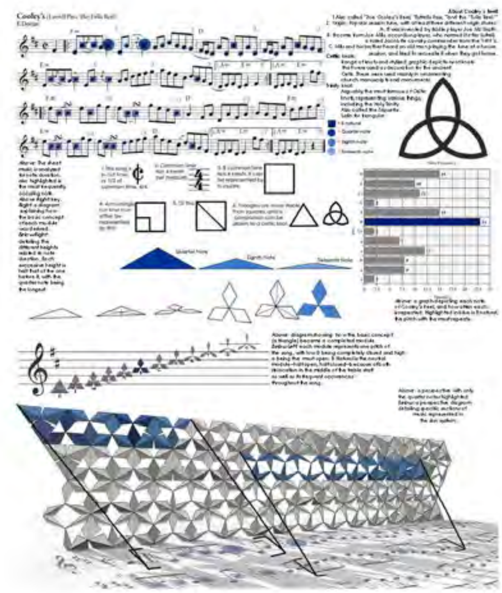
“Phenomenology” is a design philosophy that was first used to criticize the modern movement and as an urge to return to “place-based” architecture. Juhani Pallasmaa further expanded the ideas by introducing the phenomenological aspects of kinesthetic and multi-sensory perception of the human body into this architecture theory.

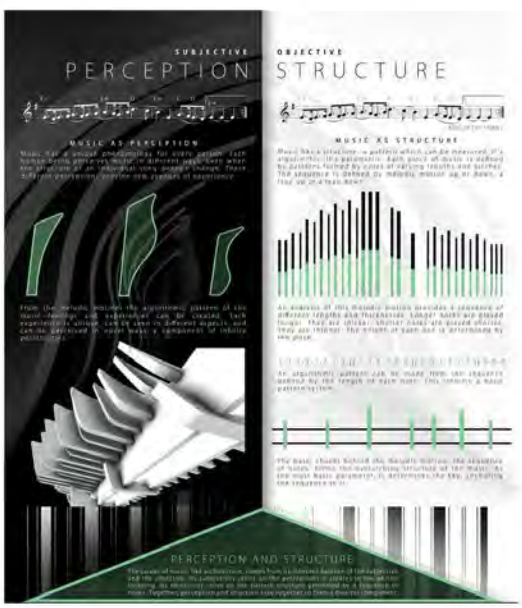
“Performance Based” design, with the help of computational tools, is a design paradigm within architecture that has emerged in the 21st Century by using building performance as a guiding design principle for the design of cities and buildings. Current interest in building performance as a design paradigm is largely due to the emergence of sustainability as a defining socio-economic issue and the recent developments in technology and cultural theory. “Phenomenology” and “Performance Based Design, students were asked to develop an interpretive building component (structure, skin, space) inspired by the relationships found between music and architecture. Music has distinct phenomenological qualities that can be thought of in conjunction with the spatial experiences of architecture. Music also has distinct computational or technical qualities that can be thought of in conjunction with building performance and the tectonics of architecture.

Music and architecture have many things in common and have many divergent means for creation. Rhythm is the underlying pattern and found in the beats / repetition of music as well as the structural elements of architecture. Texture is heard in layering different instrument voices and seen in the composition of building materials. Harmony is achieved through note combinations within a musical work or in architecture through the successful relationship of individual spaces becoming one cohesive space. Dynamics in music and architecture deal with quality and emphasis both needing hierarchy and identity as well as feeling. Musicians experience music in very deep ways, e.g. subtle moments in songs / tunes that some people might not notice. Architects similarly feel and experience space in deeper ways than most non-architects. When architects move through space, it becomes a phenomenological journey of tectonic discovery.

The ideas and artifacts were presented in conjunction with the playing of the music initially chosen. As with many art forms, their subjective appreciation and evaluation was quite varied depending on the listener and observer and their personal sensitivities and biases. As a design critic and musician who plays Celtic music, final evaluation was prefaced by the design conversation that led up to the final submission as well as my own phenomenological and performative understanding of the music. Because of these mutual behaviors, music and architecture share a relationship generated by subtle experiences (phenomenology) and underlying computational codes (performance). In that shared relationship lie the creative potential for mutual understanding and discovery.

Keywords: structures, energy + systems, computational design + analysis, pedagogy, open





Phenomenology and Performance

Technology | Architecture + Design Through Music

Jerry L. Stivers, AIA, LEED AP
Oklahoma State University

"Phenomenology" is a design philosophy that was first used to criticize the modern movement and as an urge to return to "place-based" architecture. Juhani Pallasmaa further expanded the ideas by introducing the phenomenological aspects of kinesthetic and multi-sensory perception of the human body into this architecture theory. He argues that hand drawing is a vital spatial and hap-tic exercise in facilitating architectural design. Through this process, "architecture emerges as the very 'material' existence of human embodied 'immaterial' emotion, feelings and wisdom."

"Performance Based" design, with the help of computational tools, is a design paradigm within architecture that has emerged in the 21st Century by using building performance as a guiding design principle for the design of cities and buildings. Current interest in building performance as a design paradigm is largely due to the emergence of sustainability as a defining socio-economic issue and the recent developments in technology and cultural theory.

While considering two divergent design philosophies, "Phenomenology" and "Performance Based Design, students were asked to develop an interpretive building component (structure, skin, space) inspired by the relationships found between music and architecture. Music has distinct phenomenological qualities that can be thought of in conjunction with the spatial experiences of architecture. Music also has distinct computational or technical qualities that can be thought of in conjunction with building performance and the tectonics of architecture.

Music and architecture have many things in common and have many divergent means for creation. Some of those commonalities include rhythm, texture, harmony, and dynamics. Rhythm is the underlying pattern and found in the beats / repetition of music as well as the structural elements of architecture. Texture is heard in the layering of different instrument voices and seen in the composition of building materials. Harmony is achieved through note combinations within a musical work or in architecture through the successful relationship of individual spaces becoming one cohesive space. Dynamics in music and architecture deal with quality and emphasis both needing hierarchy and identity as well as feeling.

Musicians experience music in very deep ways, e.g. subtle moments in songs / tunes that some people might not notice. Architects similarly feel and experience space in deeper ways than most non-architects. When architects move through space, it becomes a phenomenological journey of tectonic discovery.

The ideas and artifacts were presented in conjunction with the playing of the music initially chosen. As with many art forms, their subjective appreciation and evaluation was quite varied depending on the listener and observer and their personal sensitivities and biases. As a design critic and musician who plays Celtic music, final evaluation was prefaced by the design conversation that led up to the final submission as well as my own phenomenological and performative understanding of the music. Because of these mutual behaviors, music and architecture share a relationship generated by subtle experiences (phenomenology) and underlying computational codes (performance). In that shared relationship lie the creative potential for mutual understanding and discovery.

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BTES SPECIAL FOCUS SESSION AT ACSA 2018

Architecture + Structures: Ethics and Responsibilities in Academic Design/Build Studios

Ahmed K. Ali, Ph.D.
Texas A&M University

Introduction

In a recent interview with Fred Bernstein for *Architectural Record*, published on February 2014, Rafael Viñoly, one of the most prolific architects of the modern age, made the following remark: *"It's a crisis for the profession. In the last twenty years, people have come into the field without knowing what construction is. In architecture, construction is the medium."* Viñoly later admitted that he recently "*made a lot of mistakes*" with his buildings in London, Vegas, and Manhattan and consequently criticized the current status of architectural education in falling behind the inquiry of constructive knowledge. Viñoly recalled that as a young architect he did rebar drawings. A notion that Chad Schwartz, in his book, citing Marco Frascari and Juhani Pallasmaa, pointed out to the disappearance of construction site apprenticeship in today's' architectural education which possibly resulted in the current crisis (Schwartz and Ford 2017). A year later, Piet Hein Eek, a famous Dutch designer, in an interview with Emma Tucker during the *Dutch Design Week* published in Dezeen on October 2015, said: *"Most architects are "not interested" in construction, most buildings are drawings filled in by engineers."* Eek added; "*many architects do little more than produce drawings and leave others to work out how to build them*."

Viñoly and Eek's recent remarks are a reminder to similar discourse, almost fifty years ago, that established a foundation for modern architectural education in the realm of construction. In 1964 Aris Konstantinidis said, *"Good architecture always starts with construction. Without construction, there is no architecture. Construction embodies materials and its use according to its properties, that is to say, stone imposes a different method of construction from iron or concrete."* One year later, in 1965, Edward Sekler, a renowned Austrian architectural historian, published his foundational essay entitled: *Structure, Construction, Tectonics* where he stated that "*through tectonics the architect may make visible, in a strong statement, that intensified kind of experience of reality which is the artist's domain – in our case the experience of forces related to forms in a building. Thus 'structure,' the intangible concept is realized through construction and given visual expression through tectonic."* Konstantinidis affirmed the impossible existence of architecture without constructive knowledge, while Sekler emphasized the role of the structure as the intangible concept in architecture where expressions become a product of understanding the relationship between forms and forces.

The Disconnect Between Structure, Construction, and the Design Studio

If Viñoly's remarks are true, and probably they are, a set of questions should be asked; what causes that disconnect between durable knowledge of construction and the design studio? How design educators overcome the reluctance and hesitation that still exists in students regarding constructive knowledge? Where does the question of constructive inquiry fall within performance-based architecture? With the ever-increasing specialization in performative demands, how do educators address construction as the art of building within today's design studio? And finally, does academic design/build studios address such disconnect?

To begin addressing those inquiries, it is necessary to return again to Eduard Sekler, who in 1965 distinguished between three critical terms that are still somewhat misplaced today; structure, construction, and tectonics. In his foundational article, Sekler elaborated on the relationship between the three terms as they referred to ultimately reaching an expressive "truth" in the making of architecture. A truth that demonstrates the architect's ethical imperative and is equally concerned with the relationship between forces, forms, and materials (Sekler 1965). The relationship between structure, construction and tectonics are indeed critical to achieving true expressive and timeless work of architecture. The relationship between architecture and structure in particular was noted by Don Watson, who stated that Louis Kahn would often refer to his colleague, the structural engineer, August Komendant, as an "equal partner" (Watson 1997). Theirs was an exemplary relationship that began in 1956 and lasted nearly two decades, Komendant at that time was known for his outstanding pre-stressed concrete work, which Kahn found a good fit for his architectural forms and ideas. Collaboration between architects and engineers resulting in masterpieces of architecture in the twentieth century dates back at least to the 1950s, In his book, *18 Years with Architect Louis I. Kahn*, Komendant reproduced a letter that Kahn wrote to the American Institute of Architects in 1973, recommending that Komendant be honored with the AIA's Allied Professions Medal for "*inspiring and influencing the architectural profession*" (letter from Louis Kahn to Eero Saarinen, March 23, 1959) (Komendant 1975). That relationship is one example of how closely architects and engineers should work, and how the design process can be inspired by both disciplines.

More recently, Catherine Wetzel reiterated that when architecture schools integrate design and structures in their curriculums, they increase the working vocabulary and expertise of students, as well as the potential for innovative collaborations in the academy and the profession (Wetzel 2012). Bruce Wrightsman also emphasized the importance of integrating structural knowledge in design/build studio by referring to it as "durable knowledge" which students gain by departing from the traditional pen and paper structural education curriculum (Wrightsman 2014). As design/build education began to take a critical part in architectural education, the role of structural knowledge integration, simulation, and testing to academic design/build are of vital importance in order to address two fundamental outcomes; the first is balancing the deliverables between the physical product (project) and the academic learning objectives (process), the second is related to assurance in safety, liabilities, and responsibilities. Students, faculty, university administrators, and beneficiary community members demand a form of safety and risk mitigation that no matter how elaborate and expressive a design/build project is, no one (student) will get hurt. It only takes one accident in a design/build studio to shut down the entire initiative, thereby resulting in the loss of a tremendous educational opportunity for an architecture school.

In light of Sekler's work and under the shadow of Kahn and Komendant's relationship, the presented design/build case studies have attempted to investigate the relationship between structure, construction, and tectonics. That is through two projects in design/build studios within the academic context which focused extensively on collaborating with structural engineers. In the following section, a critical description of the experiments in the two design/build studios, which were conceived at non-NAAB, accredited undergraduate four-year programs in architecture in two different countries (Turkey and the United States respectively) is presented. The first is an academic-based collaboration and the second is a practice-based collaboration. Both studios engaged students in designing and building projects from conception to realization, working with real clients, city officials and industry consultants.

Fig. 1: Physical Models and computer simulation were used in the coordination sessions with structural engineers

'Academic-based' Structural Knowledge Integration

The first design/build studio led by the author at one of the top-ranked Turkish universities was conceived as an experimental study that implemented careful observation and recording, followed by a qualitative opinion solicitation from the project participants to document their lived experiences. The physical product (The Kilim Project) and the process were compared to both historical and modern precedents. The project followed a traditional design process, starting with schematic design, refinement, and modification, and finally construction. Emphasis on collaborating with structural engineers was implemented throughout the process, and a faculty member from the structural engineering department collaborated with the studio from the beginning (figure1). Moreover, the project site happened to be in a seismic zone and therefore required a close consideration of issues related to stability and lateral forces. Literature suggests that the role of structural design integration in architectural education, specifically in seismically active regions such as Central Turkey is crucial (Ünay and Özmen 2006).

The setting of the design/build studio was conceived as a hybrid environment that was constructed from a building technology laboratory, an indoor fabricating facility (wood shop), and an outdoor assembly/testing yard. Although the workload was divided among students' groups, team leaders, and project managers, everyone was involved in every aspect of the project at some point. Since the project started with nearly no funding, students were asked to seek sponsorships and to raise funds and in-kind donations of discarded materials from vendors. Wooden shipping pallets were among the only materials donated, and a strategy for disassembling and sourcing structural members was developed. However, after consulting with the academic structural engineer, it became apparent that continuous framing members were essential to the structural stability and integrity of the project. At this point, the university provided a small amount of funding to purchase the appropriate structural framing members. After the completion of the project, a reflection phase consisted of two stages was performed. First, the students visited the Finnish pavilion at the Venice Biennale in 2014, which to their surprise shared similar aspects of their project. Second, a post-project questionnaire was administered to collect and record their lived experience.

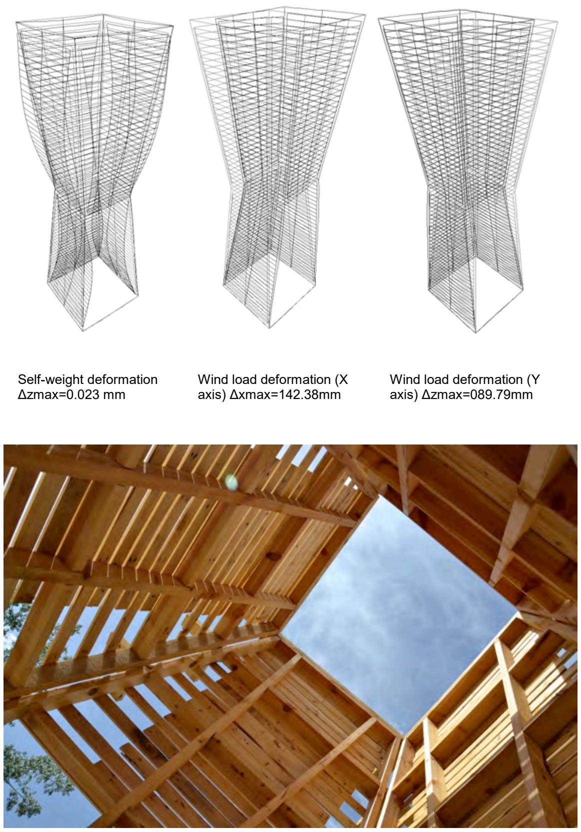

Fig. 2: Displacement Analysis for the Kilim project and a view from inside one of the two observation towers

Since the design/build studio was the first of its kind to be established at the Turkish university, concerns regarding students' safety were raised by the university administrators, who required a detailed assessment of the project's structural integrity. Demands were made clear that the studio must test the proposed design before the actual construction began. Computer simulated structural analyses were performed at the design development phase of the project to determine the stability of the proposed structure and to understand its performance under its weight, seismic, and wind loads. While the proposed framing and skin systems were initially found to be acceptable, the connections between the upper and lower modules and the whole structure to the ground were critical (figure 2). A permanent foundation was not suitable, since the two observation towers of twenty-five feet high each needed to be dismantled and relocated to different locations. A temporary foundation base larger than each tower's footprint was required to overcome the overturning effect of the structure. The exterior wooden skin attached to the structural frame could only carry its weight. The wooden frame, therefore, was subject to deformation, and steel connectors were needed to ensure stability. Also, a cross-bracing steel wire was determined to be sufficient for establishing rigidity, and only the sides of the structure subject to torsion needed additional bracing. Knee-bracing for the modules were recommended for providing rigid connections but couldn't be justified to the historical precedents that inspired the project. Continuous framing members were required, but the use of spliced short members salvaged from the shipping pallets was not suitable. In addition to scaled physical models, computer simulations of the towers' behavior were conducted. The structural analysis of the "Kilim Towers" was performed using SAP2000 software that considered the closest real dimensions and material characteristics. There were two load conditions: the self-weight of the frame and wind forces (considered according to Turkish Structural Analysis Codes). As revealed by the initial results, no critical conditions were found. Two overlapping timber members (50x100mm) were suitable for the main framework, but they had to be held firmly by steel connectors. The simulation models revealed deformation of the shape of the frame due to gravity and wind forces, respectively, as seen in (Figure 3). Additional details about the inaugural design/build studio were elaborated in details in a previous publication (Ali 2016).

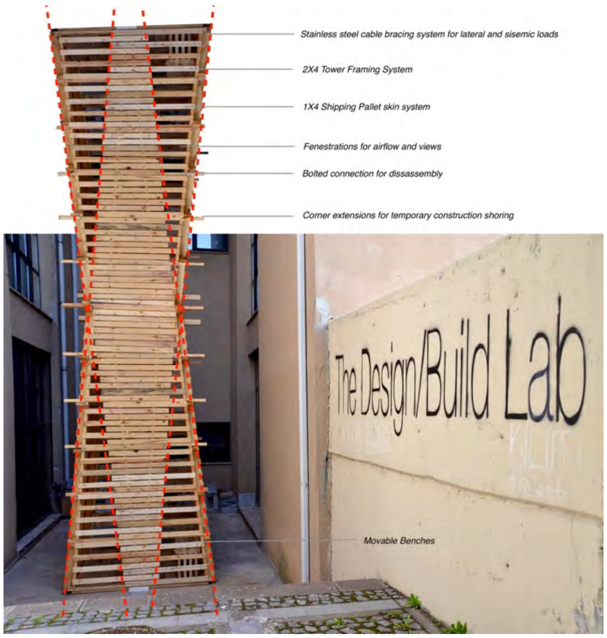

Fig. 3. The Design/Build Lab Assembly Yard with the steel Bracing Diagram

'Practice-based' **Structural Knowledge Integration**

The second design/build studio also led by the author was conceived at a large state university in the United States and was part of a high-impact interdisciplinary service-learning initiative that focused on community projects. The interdisciplinary studio involved faculty and students from architecture, landscape architecture, and construction science who collaboratively developed projects from conception to realization, demonstrating the impact of design on their immediate local community. Students were immersed in an in-depth, hands-on, learning experience that was based on active participation from students and the peer-learning principals of funding, design, engineering, management, fabrication, production planning and construction. The overarching goal was for the students to be able to understand the value that other disciplines bring to the teamwork and learn to think as collaborators. The selected site which was located in the neighboring city of the University which included several properties that remained underdeveloped or in need of rehabilitation. The reclamation of these properties could potentially bring additional economic activities to the community as well as provide ecological and social benefits. The selected project site remained undeveloped for fourteen years except for some public parking, which was used by nearby churches. Development on this site needed to consider the site's history, culture, and its impact on the community. The design/build studio proposed developing a permanent farmers' market structure on the site to replace a temporary weekend farmer's market, which was held every Saturday in a parking lot. Temporary tables and tents made up the farmers' market, which is why a permanent, functional, and an aesthetically appealing structure was proposed. It was agreed that both the sellers from the current farmers' market and new vendors would move to the new location if an appropriate, functional, and attractive structure were built. Also, a visitor's center for the city was proposed for the eastern side of the site (Dvorak and Ali 2016).

The site for the design/build project was gifted by a private foundation to the city in 2001 under the condition, that it must be developed for the benefit of the public. The site included two of the oldest and historical buildings in the city, a house originally built in 1872 and a separate carriage house. The project was selected for funding by the University's College of Architecture's real projects initiative and achieved three major goals: First, a student design competition was offered to design a visitor center; second, a masterplan for the entire historic site was developed by the students; and third, a modular farmers' market was designed and built for the city's Farmers Association. During the Fall 2015 semester, the first two phases of the project were launched: a student's design competition for a visitor's center was announced and funded by the private foundation who gifted the site to the city. Next, graduate-level landscape architecture students conducted research and data collection through numerous meetings with the city and the private foundation members. During Spring 2016, and while the masterplan document was refined by the landscape architecture students, the design/build studio launched the design and construction of the modular farmers' market. The spring semester was divided into six weeks of design and six weeks of building. Architecture and construction students worked together in collaboration with the landscape architecture students in designing, scheduling, budgeting, and constructing the modular market at the University's fabrication facility. Input from landscape architecture students, faculty, city officials, and a local engineering firm was coordinated throughout the twelve weeks. Construction documents were approved by the city, and a building permit was filed and obtained. The modular farmers' market was named "The Tree," which was described as an autonomous shading structure with a multilayered roof that stemmed from a cluster of four columns. It is the prototype for a proposed series of identical sections that, when placed side by side, create a row of farmers' market stalls. Each section, or "tree," provides approximately one hundred square foot of shaded stall (8x12 feet of vendor space) supported by four 6x6 inch posts (Figure 4).

Figure 2: Farmers Market Structural Framing Plan, and a view after the prototype completion

Since the design/build studio acted as the 'project architect,' the city required a licensed engineer to approve and stamp the drawings to move forward with the plan's approval and the building permit process. Through the efforts of the author, a local engineering firm agreed to provide sealed structural drawings and consultation as 'pro-bono' service. The studio's students collaborated with the structural engineering firm from the beginning, and several charettes were conducted to inform their design decisions (figure 5). Contrary to the Turkish design/build experiment, no computer simulations were performed to determine the appropriate sizing and connection methods of the structure. Instead, simple calculations and practical experience of the structural engineers informed the design of the pavilion units' structural members. As a result, a slightly higher factor of safety was apparent in the sizing of the structural members. For example, each cluster of columns contained 4 members that were specified as 6”x6” instead of 4”x4”. The students, however, redesigned the ultimate height of the market roof and the layering logic of the roofing elements, so that the overall proportions remained elegant and harmonized the transition from column to roof despite the relative bulkiness of materials.

Fig. 3: Students in Collaborative Session with the practicing structural Engineer

The Design/Build Studio and the University

The two models presented in this paper offer two distinct perspectives on balancing both the product and the process deliverables. Also, issues related to risk and legal responsibilities that exist in the majority of design/build studios today drastically influence the mode of collaboration between architecture students and engineers. In the ‘*academic-based’* case, a safety protocol was established with the University based on computer modeling and simulations, which were performed in collaboration with a faculty member in structural engineering, while safety training was delivered to students both before and during construction. The ‘*practice-based’* case, however, relied on the knowledge and the practical experience of a licensed structural engineer. For example, the foundation and members connections were determined and drawn according to the engineer’s experience as seen in (figure 6). Safety training was performed according to the required University standards before using the fabrication facilities. In the latter case, students were insured as long as the work proceeded on the University’s property, but once the assembly of the project started off-campus, additional insurance was required.

In the two experiments, both the structural engineering collaborators had a Professional Engineers license (P.E.s). Although all licensed Structural Engineers (S.E.s) are also licensed Professional Engineers, all Professional Engineers are not licensed Structural Engineers. In fact, only a small fraction of Professional Engineers passes the state requirements that allow Professional Engineers to be licensed Structural Engineers. Both experiments were effective regarding learning and goals achieved, and it’s difficult to suggest one model over to the other. However, exposing students to real-world coordination with consultants to produce a set of construction documents and obtaining a building permit was daunting, but nevertheless provided an unmatched learning opportunity. Both projects offered an added-value to the typical design/build studios by allowing architecture students to move from ‘*engineers will figure out how the project will stand for us’* to ‘*the dialogue with engineers enhanced our design decisio*ns.' As stated by Ted Cavanagh, the transformation of design/build pedagogy from learning by doing to learning by experimenting increases the research agenda, and therefore closes the gap between abstract and reality (Cavanagh 2012). In addition, the understanding of the relationship between structure, construction, and tectonics is expressed through making. Wither collaborating with an academic or professional consultant, a raised level of responsibility is instilled in the students of architecture. From the presented models, structural integration professionally enhanced the experimenting process and added an ethical dimension to the design process.

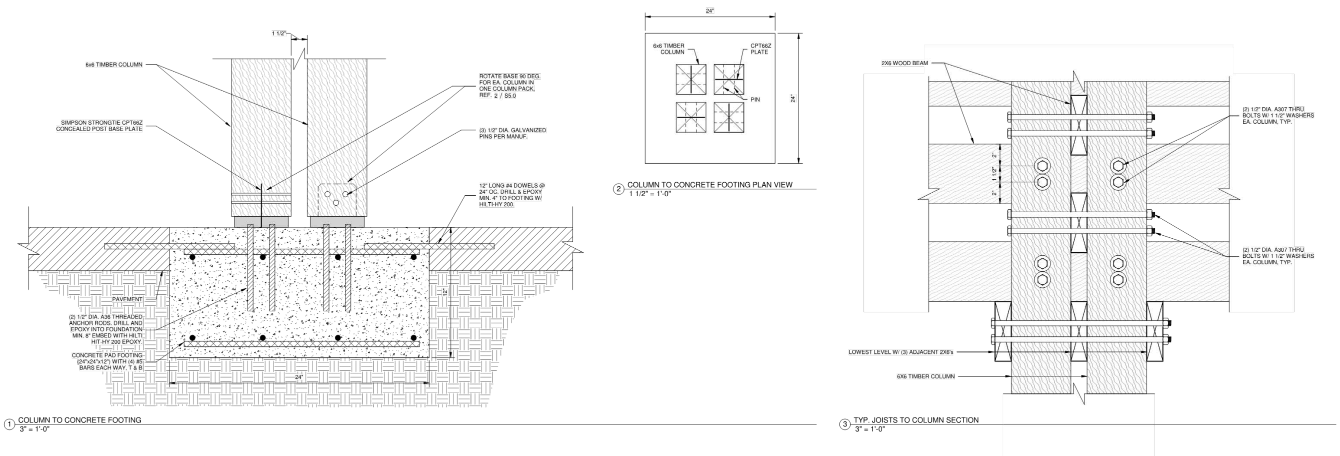

Fig. 4: The Modular Farmers Market Structural Framing Connection and Details

Conclusion

There exist a complex renegotiation of constructive relationships surrounding structure, enclosure, and performance that are reshaping the role that construction plays in the making of architecture. It could be argued that the structural and formal expression that articulated the regulating lines and tectonic expression of a work of architecture has steadily given way to performance-driven demands emerging from evolving codes and regulations. Balancing the need for delivering a completed design/build project and the forms of learning exploration within the academic design/build process requires orchestration and careful coordination between the different project stakeholders. Based on the two-presented experiments, the balance is highly achievable when paying careful attention to the fundamental relationship between structure and architecture. In both models, the integration of either the academic or the practicing engineer assured the clients regarding issues of risk, safety, and responsibility. Although that assurance may seem to be prioritized over the learning objectives, the reality is that it also allowed the students to gain substantial knowledge in coordination, refining and constructing with a focus on tectonic expressions.

The collaborative experiments with both academic-based and practice-based structural engineers challenged issues of liability, shared risk, and accountability in real projects built by unlicensed and inexperienced college students. However, the value of collaborating with structural engineers at the early stages of both projects differs from academic to practice settings. While the academic collaborative case allowed a substantial room for unconventional discoveries and further design exploration, the practice-based collaborative case involved real-world problems and liability requirements associated with licensure. Structural simulations were utilized within the academic setting, and design decisions mostly were based on computer programs and physical modeling. In the practice-based settings, intuition coupled with experience mainly influenced the major architectural and structural design decisions. The impacts of the two different collaborative models confronted both students and educators with the critical knowledge needed to further their efficiency and effectiveness in the practice. While the interdisciplinary nature of collaboration with structural engineers enhanced both models, challenges in addressing the relationship between structure and construction were expressed differently through the final built work. Here the question of tectonic expressions was distinctly explored through each model.

Acknowledgements

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The Kind of Problem Technology Is: A Case for Integrated Models of Architectural Technologies Education

Robert Arens
Professor and Associate Department Head, California Polytechnic State University, San Luis Obispo

Brian Osborn
Assistant Professor, California Polytechnic State University, San Luis Obispo

Carmen Trudell
Associate Professor, California Polytechnic State University, San Luis Obispo

Organized Complexity

In *The Death and Life of Great American Cities*, Jane Jacobs writes "the theorists of conventional modern city planning have consistently mistaken cities as problems of simplicity and of disorganized complexity". In the final chapter, "The kind of problem a city Is" she follows with, "why have cities not been identified, understood and treated as problems of organized complexity?"[1] Inspired by Jacobs' call, the authors of this paper, seeking to reinvent technology courses for undergraduate architecture students, ask "why has architectural technology not been identified, understood, and treated as a problem of organized complexity?"

The guiding principle for a redesign of second-year technology courses derives from the definition of organized complexity as understood by Jacobs. Distinct from problems of *simplicity*, which are characterized by having two variables with clear relationships to each other, and from problems of *disorganized complexity*, which might include millions of variables whose behavior is best determined probabilistically through the use of statistical analysis, problems of *organized complexity* require the coordination of a sizable number of variables that are interrelated into an organic whole.[2] In other words, to discuss daylighting strategies, for instance, independent of an understanding of available solar resources; the qualities of glass through which the light passes; the wood on which the light falls; the reradiated energy that must be mechanically removed; and the environmental impact of this machinery, is to segregate and oversimplify an issue that is best understood within the context of interrelated *contextual*, *material*, and *energy* systems.

Acknowledging the inherent complexity of architectural technologies and the interrelated nature of the distinct knowledge areas included within them, the authors have worked to integrate instruction in materials, methods of construction, and environmental controls by distributing multiple short modules of each topic across a 30-week academic-year (*Fig. 1*). Additionally, new course content focused on methods of site analyses has been added to the existing curriculum; acting to contextualize architectural technologies within large-scale environmental systems. The authors have worked together to deliver modules pertaining to their individual areas of expertise. This reinforces the importance of collaboration as modules and instructors loop—supporting one another and building sophistication and specificity over the course of the year.

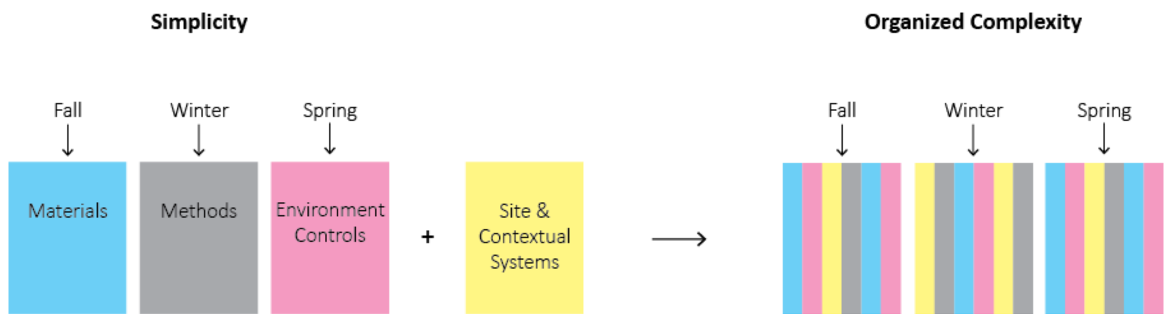

Fig. 1. Integrated Technologies Course Organization. On the left shows the previous model where topics were separated by quarter, and site systems was not formally covered. On the right is the new curricular model of integrated topics taught each quarter.

Provoked by a perennial responsibility to align architectural education with evolving contemporary practice, this paper works to establish a theoretical basis for the consideration of architectural technology as a problem of organized complexity. It expands on teaching methodologies developed by the authors and provides a critical reflection on experiences from a 2-year pilot of these courses.

Aligning Course Organization with Contemporary Architectural Practice and Student Development

Shifts toward models of *organized complexity* have begun to appear within the mainstream disciplinary activities of practicing architects. Notably, in November 2016, the National Council of Architectural Registration Boards (NCARB) launched a restructured version of the Architect Registration Examination (ARE) featuring an integrated model of organizing test subject areas (*Fig. 2*). Since the beginning of its national standardized testing in 1965, the NCARB has performed periodic monitoring of the discipline in order to assure the maintained relevance of the ARE to the daily practice of architecture.[3] Beginning with the *Task Analysis and Validation Study* in 1979, and more recently through the *Practice Analyses* published in 2001, 2007, and 2012, the NCARB has regularly adjusted its testing format, introduced relevant workflow technologies such as Computer-aided Drafting, and updated the content covered in the ARE.[4] Given its analytical bases, it could be argued that the ARE offers a representation, albeit conservative, of trending disciplinary concerns over time; in which the most recent iteration signifies a formal acknowledgement of the complex and interrelated nature of the various knowledge areas required of the Architect. Compared to previous iterations of the exam, which, up to now have been organized "vertically" around discrete content areas, i.e., *Structural Systems*, *Building Systems,* etc., ARE 5.0 includes 6 divisions arranged "horizontally" around the progression of a typical architectural project, i.e., *Project Planning and Design*, *Programming and Analysis*, etc.[5] This flattened model distributes individual subjects across multiple tests and results in two critical distinctions from previous exams. First, organizing tests by project phase rather than subject encourages the integration of multiple knowledge areas within each exam allowing subjects to be paired in relevant combinations. For instance, the *Programming and Analysis* exam might require candidates to assess the probable bearing capacity of soil substrates, determine the allowable floor-area, and identify suitable construction types for a given site and program. This combination melds considerations of material properties with those of building assemblies and zoning regulations in a way that is relevant to the early phases of building design. This organization also allows that levels of sophistication and specificity in each

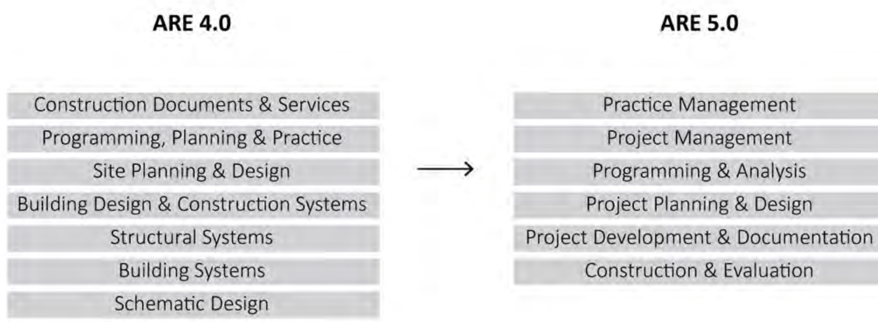

Fig. 2. Architect Registration Exam 5.0 Restructuring, 2016.

knowledge area, as well as in the relationships between them, graduate over the 6 exam divisions, as they are likely to do through the various phases of design development for an architectural project.

Similarly, and returning to pedagogy, integrating architectural technologies education allows content in each subject area to increase in sophistication and specificity across the curriculum and as student knowledge and skill levels mature. A common problem associated with traditional technology course organizations has been determining *when* to introduce any given subject. Given a range of preferences and curricular determinants, it might be ideal to introduce concepts of materials and methods of construction, for instance, early on in a design education. However, this would inevitably come at the expense of withholding instruction on solar geometry and or principles of passive thermal control until later in the curriculum. Subsequently, the depth to which any subject can be explored has inevitably been linked directly to the term in which it is taught—limiting discussions about materials, for example, to the maturity of a first-term second-year student. Alternatively, returning to topics in shorter modules that are distributed throughout an academic year allows those discussions to deepen along-side student development. An intended outcome of the integrated technologies organization is the decoupling of knowledge areas from specific student maturity levels and the making available of a wider range of technologies to students as potential drivers for design decisions in all of their work.

Curricular Development

The Architectural Technology curriculum at California Polytechnic State University, San Luis Obispo has historically included six courses under the titles of *Practic*e and *Environmental Control Systems* and have been taught in the second and third years of the undergraduate architecture program. Within each of the six courses, topics are introduced within (2) 50-minute *Lecture* experiences, serving 120-180 students, while (2) 110-minute *Activity* sections, serving 16-20 students and taught by additional faculty, allow the application of those topics, often to projects underway in co-requisite design studios. Historically, instructors of each *Activity* section have been responsible for developing class exercises and assessment tactics on an individual basis for their respective sections. While this structure has afforded the *Activity* instructors a great deal of flexibility to integrate technology topics within the applied design studio project, it has also resulted in difficulties linking the learning experiences between Lecture and Activity modes and in establishing and meeting a shared set of course learning objectives for the technology curriculum. In response to the ideas introduced above, the authors have initiated a fundamental shift in how Architectural Technology is taught. Each year now has a bench of three instructors who work collaboratively toward a common syllabus, outline, learning objectives, and assessment tactics. From the student's perspective, instead of six distinct class experiences beginning anew every 10 weeks, they now have a 2nd year technology set of classes spanning three quarters with a great deal of consistency in content delivery and assessment methods, and a similar 3rd year experience. The new courses have been rebranded as Architectural Technology Fundamentals in 2nd year, and Building Systems Integration in 3rd year, as can be seen in the Bachelor of Architecture Flowchart diagram below (*Fig 3*).

The past model of teaching Architectural Technology siloed content areas by quarter, such that material systems and assemblies were only minimally discussed in the context of environmental control systems (ECS) and vice versa. In the redesigned courses, topics that would have previously fallen under the umbrella of "materials" or "ECS" have been broken down into smaller modules of content. We have also added new course content that was not previously taught in our curriculum in the area of site and contextual systems. We initially blended the three content areas fully into an uncategorized flow of topics. After the first term of integrated teaching, student surveys revealed that students found it very confusing to keep the three instructors and the interwoven subjects clear. Therefore, we moved to a modular course structure where each instructor teaches for approximately 3 consecutive weeks, and students complete a corelated laboratory exercise and an exam before moving on to the next subject area. Following surveys indicated an improvement in student satisfaction with this early correction to our delivery strategy.

Further detail on each of the course content areas is provided in the following paragraphs. The sequencing of the modules emerged from collaboration with the co-requisite design studio learning objectives. For example, in fall quarter, all design studios work with a small urban infill site in a local city that students can visit multiple times. The subject matter covered in the Technology course is curated to support the studio investigations at some points in time, while at other times the Technology courses lead the students toward possible design drivers.

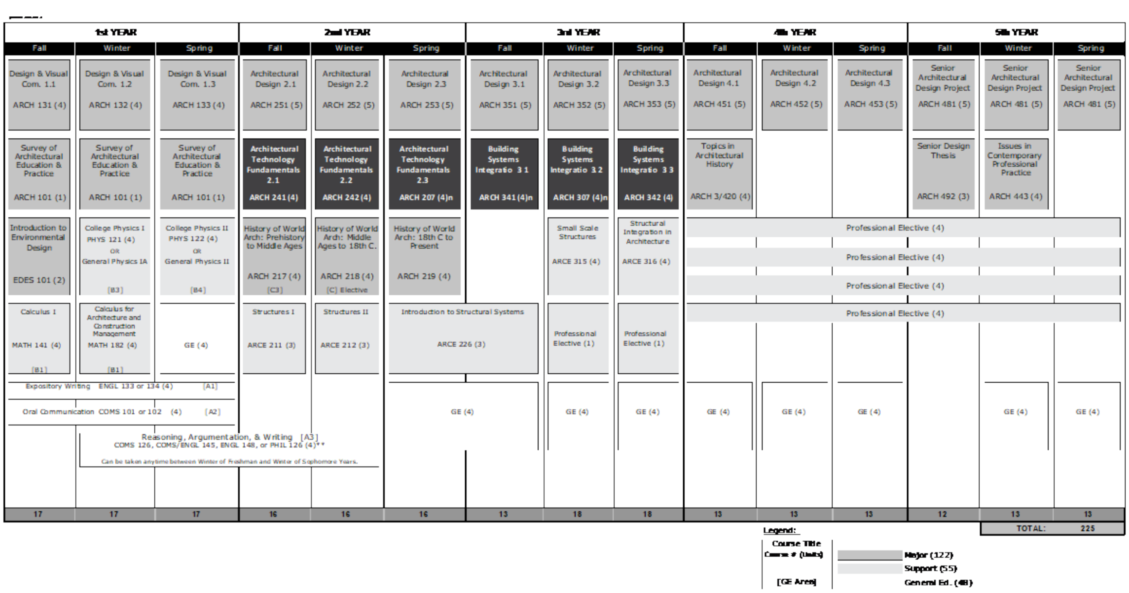

Fig. 3: Bachelor of Architecture Flowchart diagram with six Architectural Technology courses highlighted. The six courses must be taken in order, and are co-requisite with the Architectural Design studios, shown directly above the highlighted courses.

Site & Contextual Systems

The Site and Contextual Systems modules introduce methods of reading and responding to a variety of situational typologies from densely bound urban contexts to more open rural sites with varied landform. The fall module is based around an urban context and introduces the physical and legal determinants of city form, including those regulated by local city zoning regulations. The fall term offers frameworks for developing a meaningful architectural interface between the building and public rights-of-way; understanding architectural form as a component of the larger urban fabric and the value of contemporary public space. The winter term module engages a rural, or sub-urban, site including a sloped topography and offers an introduction to land form, morphology, and hydrology. Class discussions provide a framework for considering the physical connection between building and ground. Class exercises introduce students to techniques of grading and drainage and present concepts of accessibility and site circulation. The spring term module focuses on methods of constructing landscape assemblies such as paving and walls as well as offering a framework for considering planted-form in architectural contexts.

Energy & Environmental Systems

The Energy and Environmental Systems modules focus on passive, climate appropriate, strategies for human thermal comfort and health. The fall module introduces students to climate, bioclimatic resources, and takes a deep look at the solar energy. The focus is on daylighting for health and energy efficiency and assignments promote students as informed designers of daylight. Physical daylighting models are used to experiment with, and light effects are captured quantitatively with light meters and qualitatively with photography. In the winter, the psychrometric chart is employed as a guide for passive heating and cooling design strategies. Over several weeks, each region of the psychrometric chart is unpacked with vernacular and contemporary examples of how buildings can both overcome and benefit from outdoor temperatures, humidity, and winds. A case-study project is carefully drawn by students in order to document the project's climate and formal and material responses. In the spring term, a closer examination of the building envelope reveals ways in which designers have been inventive with the layers of material commonly utilized to separate interior from exterior environments. By systematically working from thin envelopes to thick envelopes, students see how layers can be separated to create partially thermally controlled occupiable spaces, and how these spaces enrich the experience and aesthetics of buildings and cities. Students are asked to propose an envelope system for their design studio project as the culmination of their learning over the year.

Material & Building Systems

The Material and Building Systems modules introduce students to the properties of materials and the principles of assemblies while connecting these considerations to issues of site systems and energy systems. In the fall quarter, assembly systems are introduced to students as building elements such as foundations, walls, frames, roofs and envelopes. By discussing assembly systems as building elements students are introduced to contemporary systems thinking, but also to 18th century theories regarding conception and construction established by Semper and others. Students are also introduced to other important factors that influence material and assembly decisions such as life safety requirements and building codes. In the following two quarters, the phenomenal as well as the performative aspects of materials are discussed in terms of properties and composition. To underscore the importance of resource conservation and environmental responsibility, the courses present the origin and manufacture of materials so that life-cycle implications may be understood. Taken together, these discussions on material and assembly systems strive to help students consider beautiful, ethical and responsible ways to approach their own design work in second year while providing a scaffold for more in-depth study of material and tectonic issues in subsequent courses. Case study projects, which link together concepts from Site and Environmental Systems, are completed each quarter, beginning with simple diagramming in the fall, then moving into more detailed building sections, plans, and 3D representations in the subsequent quarters.

Assessing Success through Laboratory Exercises and Exams

How can we know if we have been successful? While we feel a responsibility to align the architectural education with innovations in contemporary practice; namely an increased capacity to consider complex technologies relative to rather than in isolation from each other, we struggle with the most appropriate methods of assessing the success of our curricular changes. Likely, the best indication of success will be available after our students enter the discipline, and have had a chance to understand how their education has prepared them for practice. At best, we might see results after a year or two, when our past students can be assessed by faculty in later years of our curriculum. We hope that our paper presentation can incite a dialogue about assessment tactics with colleagues outside of our own university. However, in the short term, we currently assess our own through a review of student laboratory exercises and exam results. Following is a sample of each.

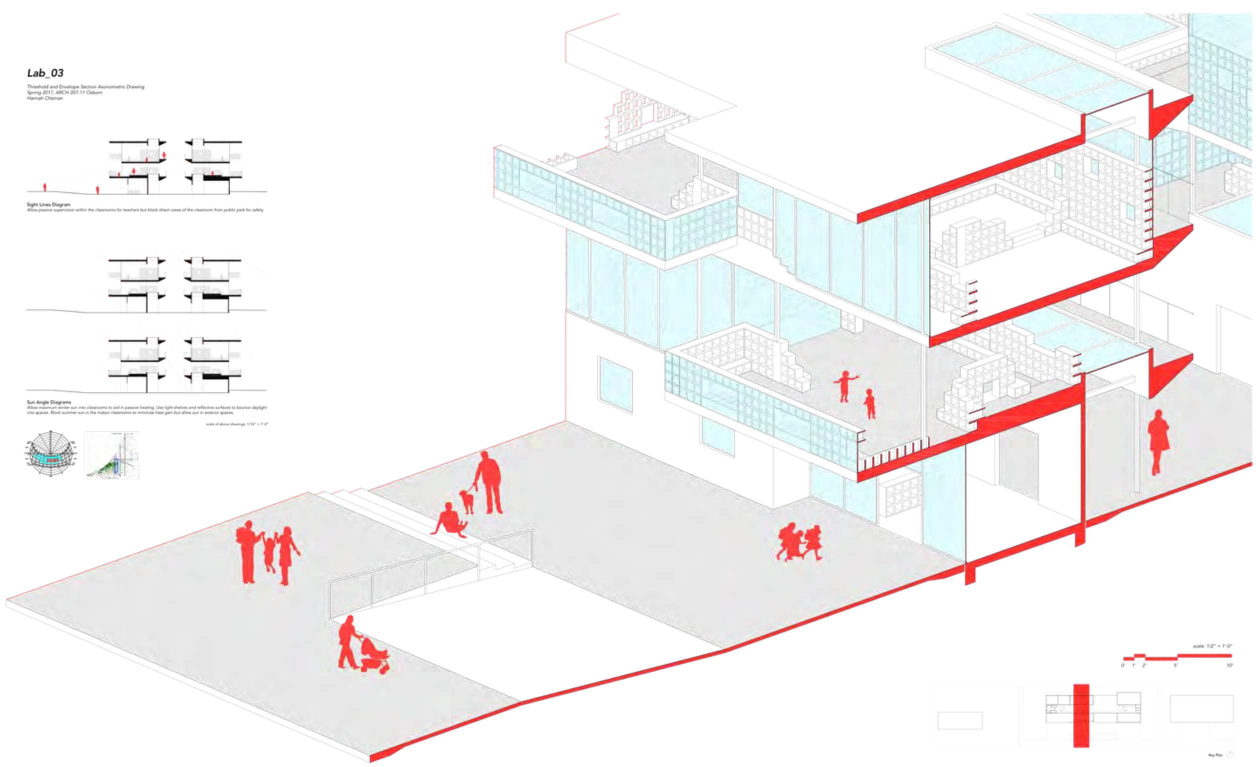

Fig. 4: Sample laboratory assignment asking students to develop an enclosure system and entry threshold. Work by 2nd year student Hannah Oitzman

As mentioned previously, students are asked to propose an envelope system for their spring-term design studio project as the culmination of their learning in the second-year technology courses (*Fig. 4*). Architectural envelopes negotiate complex sets of considerations—forming a physical boundary between outside climate and interior comfort, negotiating material selection and building assembly methods, and accommodating both physical and experiential access to the site and surrounding context. Through a schematic building envelope design, students are asked to develop an entry threshold that delineates a sequence of space—from exterior to interior and from public to private, and to articulate a physical boundary between interior and exterior that negotiates both separation (exterior climate vs interior comfort, natural environment vs tempered environment, sunlight vs daylight, etc.) and continuation (passive heating and cooling, ventilation, natural light, views, etc). Articulated through a building section-axonometric, the sample of student work shown below is successful in delineating interior from exterior space using the convention of poché. Basic material differences, such as glazing versus a potentially insulated wall or floor assembly, are identified through thickness. Strategies for passively accommodating human thermal comfort, namely solar shading in this case, are explored through a series of diagrams and are further evident in the long horizontal overhangs designed for the south façade of the proposed building. Finally, the interior programmatic spaces are drawn relative to the city beyond, and a sequence of movement from outside to inside is implied. While a successful level of understanding for a second-year student can be represented by a building section, the expectation is that this student is able to work intelligently at the level of detail requisite of a wall section by the end of third year study.

Multiple-choice exams have been used in the Architectural Technology courses at Cal Poly for decades. In the second iteration of the piloted new Architectural Technology courses, the instructors of the integrated large lectures decided to make a change in the testing strategy. The tests needed to be more meaningful to students. Instead of short-term memorization of a lot of concepts, the tests should be more like real life, and incidentally more like the updated ARE. We decided to make the transition from multiple-choice midterm exams of 30-40 questions, to vignette and essay questions with 3 to 5 questions. The final comprehensive exam changed from 70+ questions, to just 6 questions. Ironically, the time to complete the exams increased. While there are now fewer questions, students must work harder and use a variety of digital and analog resources to facilitate proposed solutions to problems. Instead of selecting from a menu of possible choices, some of them rather minor points, students were now asked to utilize codes, texts, notes, and previous assignments to work through complex parameters and provide technically sound design proposals. The new exams challenge students to think as critically as architects, which is a shift from the previous exams which asked students to perform as test takers.

The fall quarter is now taught with three modules: Urban Sites, Solar Geometry & Daylighting, and Building Elements. The final exam asks students to bring these concepts together, by asking a series of questions that are all linked together. In the first question a site and program are given and students are asked to use the City Zoning Code (which they must find and navigate themselves) in order to determine the allowable building envelope. They sketch the envelope in axonometric in the exam, providing their calculations for lot coverage and allowable area. In the next question, they determine the allowable construction types using the Building Code (which again they must find and navigate). Then they are asked to calculate the live loads, dead loads, and do a preliminary foundation size in order to determine if a shallow foundation system is viable for the given program and site. In the final questions, they are asked to re-evaluate their building massing given additional information and a requested change from the hypothetical client. For the last questions, they must read the polar sun path chart, calculate shadow lengths, sketch the shadows on a site plan, and redraw the massing in order to best position the building and the outdoor space in response to solar availability. Four sample pages from the exam are shown below (*Fig. 5*).

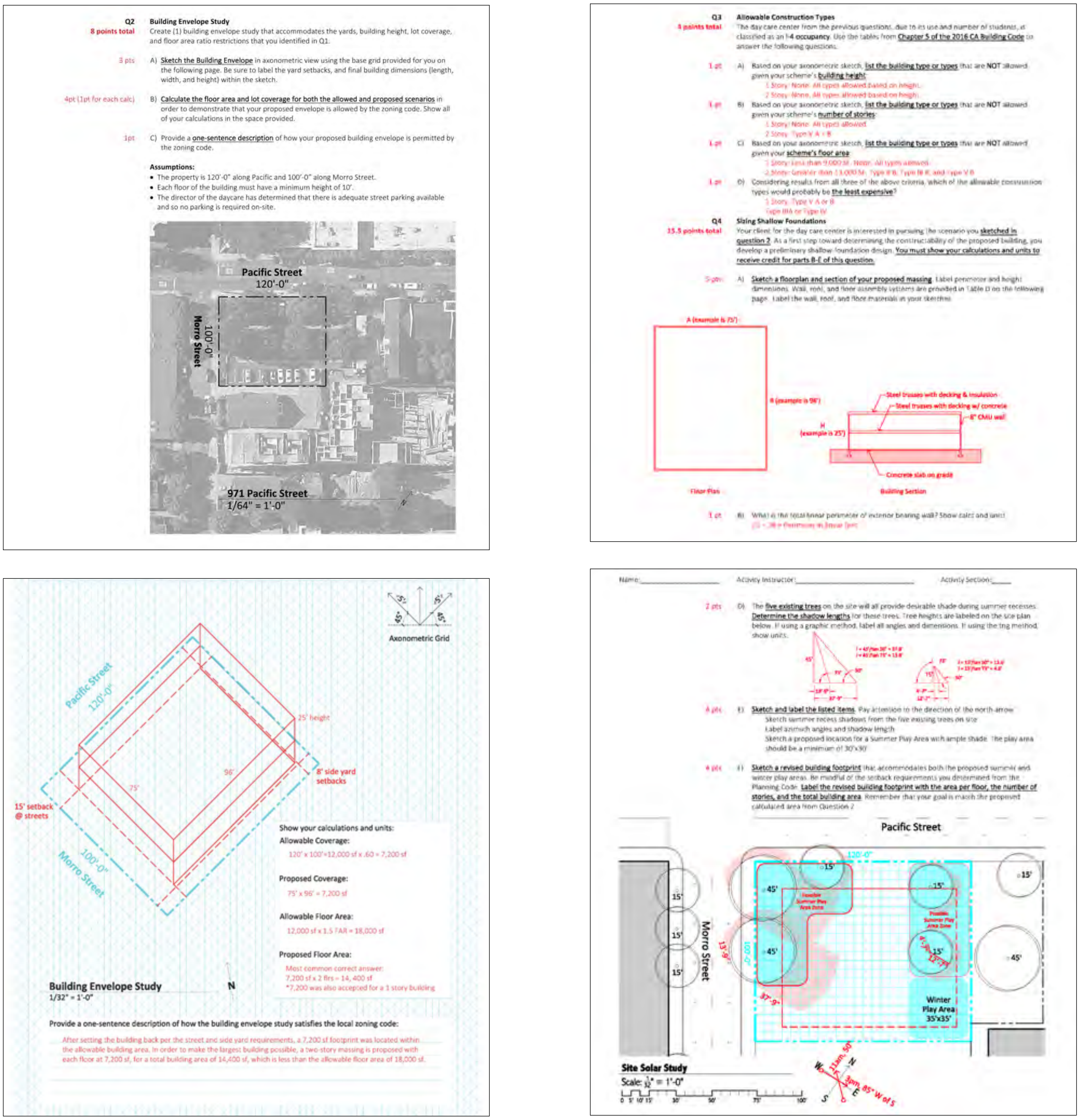

Fig. 5: Sample pages from the Fall Quarter 2017 final examination showing integration of course topics. Red text shows correct answers that would not have been provided to the student taking the exam.

Notes or References:

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1 Warren Weaver, author of “Science and Complexity” (*American Scientist*, 36: 536, 1948), was quoted extensively by Jacobs in “The kind of problem a city is”. In his essay Weaver defines three types of problems that faced physical scientists since the 17th century: problems of simplicity, problems of disorganized complexity and problems of organized complexity.

2 Weaver defined problems of organized complexity as those “problems which involve dealing simultaneously with a sizable number of factors that are interrelated into an organic whole.”

3 https://www.ncarb.org/about/history-ncarb/history-are

4 Ibid.

5 Jared Zurn, AIA, and director of examination at NCARB refers to the difference between the vertical and horizontal organization in Steve Cimino’s, “A New Era of Exams”. *Architect Magazine*. November 2016. http://www.architectmagazine.com/aia-architect/aiaknowledge/a-new-era-of-exams_o

From Informational Barrier to Ethical Obligation: Evolving Perceptions of Teaching Energy in Architecture

Christopher Cosper
Ferris State University

A brief history of energy modeling in architectural education

Dreaming of Energy Modeling

Energy has been a part of architecture since the beginning. The Western world's oldest extant architectural text, Vitruvius's *The Ten Books on Architecture*, includes numerous passages dedicated to energy.[1] For the purposes of the paper, however, history begins in 1973, with the OPAEC oil embargo. On October 6, 1973, a group of Arab countries led by Egypt and Syria attacked Israel on the Jewish holy day of Yom Kippur. Israel suffered some initial military setbacks, inspiring the United States to quickly resupply its ally with military equipment. Israel prevailed, and the war ended on October 25.

In response to the United States and other industrialized nations support of Israel, the members of the Organization of Arab Petroleum Exporting Countries (OAPEC, often confused with OPEC) embargoed oil exports to the United States and other specific Western countries. The embargo lasted until March 1974, but the market disruption reverberated into the mid-1980s. In the United States, the oil embargo resulted in long lines at gas stations and skyrocketing energy costs. On an unadjusted basis, a gallon of gasoline cost on average $0.36 in 1972. In 1973, the cost rose to $0.39, in 1974 it became $0.53, in 1975 it became $0.57, and it peaked in 1981 at $1.31. On an adjusted basis, gasoline spiked in 1974 and did not return to pre-oil embargo levels until 1986.[2]

The end of cheap energy was not only problematic for the transportation sector but also for the built environment. Modernist architecture often showed little regard for solar orientation or climate-appropriate design. In the era of cheap energy, heating, cooling, and lighting problems could simply be solved by engineered systems, including electric, natural gas, or fuel-oil heating systems; air conditioning systems; and fluorescent lighting.

Slowly, architects began to address the issue of energy in contemporary architecture. Like a lonely voice crying out in the wilderness, Jeffrey Cook opened his 1978 article "Thinking about Energy Education" by asking, "Must architects know anything substantial about energy?"[3] More opinion piece than traditional journal article, "Thinking about Energy Education" outlined Cook's vision of incorporating energy education into an architecture curriculum. Answering his own question, Cook argued that architects are the right professionals to manage the energy usage of buildings:

> If energy is simply a matter of hardware, perhaps the profession does need a new set of hardware specialists. But if the piece of hardware is of building size, maybe the architect must become an energy specialist. Particularly in the highly industrialized countries of the West, the adaptation of present living standards to a future of scarce energy resources may be a primary social goal.[4]

The increasing prominence of LEED, the Living Building Challenge, the (Architecture) 2030 Challenge, and the International Green Construction Code, suggests that Cook's statement about energy design becoming a "primary social goal" is prescient. Writing in 1978, Cook not only understood the potential of energy-based design but also the challenge of such a design strategy, asking, "Can architects trained by past methods operate in such a likely future context?"[5] Cook understood that the problem involved both faculty and students. Concerning professors, Cook wrote, "For energy there are few champions in faculties. An architecture school with more than one energy champion is regarded as having a particular strength in that area."[6] The lack of faculty interest in energy education is a recurring theme in articles that discuss energy modeling from Cook forward. Concerning students, Cook noted, "Energy understanding does not come easily or quickly."[7] He argued that design based on solar orientation may be an entry point for energy consciousness in the design studio.[8] Although Cook is writing as an educator and for educators, his conclusion on the ability to teach energy in school is less than sanguine. In the end, he seemed to advocate for experience over school, writing, "Thus, the perception, visualization and projection of energy as an objective quantity and quality of the human experience seems best practiced by those professionals with the longest experience."[9]

Finding barriers to energy modeling

The 1970s ended. Jimmy Carter was out, Ronald Reagan was in, Disco was dead, New Wave dominated the airwaves, and gas (and other energy) prices began to return to "normal." Responding to the OPAEC oil embargo—in 1984, a mere 11 years after the embargo occurred—the ACSA published *Architecture, Energy & Education.* In that work, authors Robert G. Shibley and Laura Poltroneri identified four barriers to teaching and energy in architecture school:

- Methodological barriers: the idea that energy concerns are somehow separate from design concerns
- Structural barriers: the age-old division between studio courses and technical or support courses
- Attitudinal barriers: students and faculty who believe "that energy concerns are unimportant, too complex or difficult to address, [and/or] too limiting to the designer"
- Informational barriers: lack of understanding of what energy efficiency means[10]

In 1984—or today, for that matter—there was/is no excuse for falling victim to the first three barriers. Shibley and Poltroneri's methodological, structural, and attitudinal barriers can all be corrected if educators and students decide to correct them. Methodological and structural barriers are largely the responsibility of architecture faculty, while the attitudinal barrier is shared equally by faculty and students, with the faculty having the responsibility to set a good example. Regardless of the actors, methodological, structural, and attitudinal barriers can be overcome if there is a desire to do so.

However, the informational barrier was formidable in 1984 and actually quite difficult to overcome with the computers commonly available at that time. Since the informational barrier is the barrier most relevant to this paper, it is worth quoting Shibley and Poltroneri directly: "**Informational Barriers** deal with the lack of knowledge or appropriate access to knowledge about what constitutes energy-efficiency in buildings."[11] A major component of the informational barrier was the lack of training of professors in energy-related issues. To that point, Shibley and Poltroneri wrote

> A number of schools simply state that another barrier to the integration [of energy conscious design] is faculty ignorance about energy. A particular concern was expressed by faculty of more advanced studios, that they are ill-equipped to evaluate estimated building performance of more complex solutions.[12]

How is this lack of knowledge manifested in pedagogical issues? Take, for example, a "solar cube" project. Even when a student designs and constructs a solar cube that performs well, how is that knowledge applied in design studio? Shibley and Poltroneri argued that a "missing link" existed between projects like solar cubes and studio work.[13]

One major issue in the 1980s was the difficulty of visualizing energy flows. It may be a stereotype, but it holds a kernel of truth: architects are more comfortable with images than numbers. This is true of architecture students, also. Shibley and Poltroneri observed that "[t]he schools [participating in the study] articulate a number of emerging tactics intended to deal with the question of the 'visualization' of energy" (Shibley, Robert G.; Poltroneri, Laura; 1984, 36). Some schools had made progress on the issue. Shibley and Poltroneri noted that the research team at the University of Minnesota discovered that projects which led to a visualization of energy early in the design process were the most successful.[14]

The ACSA's response to the OPAEC oil embargo was slow in coming; so slow, in fact, that the clear mandate of the 70s had faded during the Reagan era. Writing in the preface to an issue of the *Journal of Architectural Education* dedicated to energy, one of the co-authors of *Architecture, Energy & Education*, Robert Shibley, argued, "[I]t is popular these days to dismiss energy as a fad which has passed. There is a perception that…there is nothing of importance left to do."[15] If the 1980s represent a step backward, then the 1990s represent the dawning of the modern era of sustainability, and thus, a renewed interest in teaching energy-related design. Awareness, however, did not lead quickly to application, resulting in frustration for many faculty interested in energy-related design.

Writing in 1996, Mark DeKay expressed dismay with the lack of progress. After establishing the link between the built environment and overall environmental degradation, DeKay wrote, "Architects, educators, and students recognize these issues, but *architectural education has repeatedly failed* to graduate students who can design buildings that reduce these environmental impacts."[16] DeKay specifically mentioned the four barriers identified in *Architecture, Energy & Education*, but he did not address them individually. Instead, he noted the different ways that design and technical issues are taught:

> [I]n many schools, visual and formal principles (harmony, balance, contrast, color theory, etc.) are taught as the fundamental introduction to design. This formality and visuality ignores ecology by limiting perception to small system boundaries: what is important is what can be seen, drawn, and frozen in time.[17]

The issue is compounded when the lessons in "support" classes are not validated in studio courses. DeKay wrote, "When technical, energy, and environmental issues are **not** deliberately brought into the studio course by faculty, the student's model of a dualistic world of architecture is further reinforced."[18] DeKay's proposed solution to these challenges, an "evolutionary model" of curriculum design, is intriguing, but beyond the scope of this paper.

Also published in 1996 was Ernest L. Boyer and Lee Mitgang's *Building Community: A New Future for Architecture Education and Practice*, a report commonly referred to as "The Boyer Report." Although it is now more than 20 years old, *Building Community* is the most recent, comprehensive, third-party examination of architectural education.[19] Reinforcing DeKay's concerns above, Boyer and Mitgang found that 55 percent of faculty believed their schools were not doing enough to integrate sustainability into design studios.[20]

Making energy modeling happen

The early 1990s represent the beginning of the "digital turn" in architecture.[21] Supporting that assertion, discussions of energy modeling in architectural education became less theoretical and more specific, often focusing on specific modeling software. Writing in 1998, University of Michigan professor Ali M. Malkawi noted that energy modeling software had been historically difficult to use and, thus, required specialists. Designers who did not have access to energy modeling specialists because of time constraints, budget limitations, or a lack of physical access, had to "rely on intuitive methods, guidelines, or prescriptive methods" to design energy efficient buildings[22], a set of design tools with obvious limitations. Malkawi discussed his research designed to make energy simulation more accessible, particularly during "the first stages of design where the designer must make critical decisions."[23] Professor Malkawi's program used a "Graphical User Interface" and a "Building Envelope database."[24] Moreover, a project could be developed with CAD software and imported into Malkawi's program.[25] Using "Artificial Intelligence" techniques, Malkawi's program could provide "critique and advice" on potential energy saving changes to the design.[26] Malkawi's once cutting-edge features are now common features in energy modeling software, and his graphical user interfaces appear primitive compared to contemporary software. Looking back today, however, one should remember that 20 years is eons in terms of computer software development.

Building on his theoretical 1996 article, Mark DeKay returned in 1999 with a pragmatic class built around a web-based program called "Energy Scheming," which DeKay described as "a very graphical, user-friendly energy simulation tool with minimal numerical inputs."[27] Because "Energy Scheming" was created to be fast and easy to use, a designer could receive input early in the design process, which DeKay believed had important pedagogical benefits. He wrote:

> Therefore, computer simulation, which models behavior in compressed time, offers a seductive potential. Taking energy issues as a beginning point, the educational hypothesis is that students who learn using whole-building simulation will gain a good understanding of complex, higher order building/energy relationships.[28]

By inputting data early in the design process, students could make changes when they would be most impactful. Looking at the available simulation technology, DeKay developed his class with the following learning objectives in mind:

- To gain experience with a design tool that can help architects to verify the quantitative thermal implications of non-thermal design decisions, and to explore the non-thermal design potentials latent in passive design.
- To understand the complex relationships between architectural form and its energy and lighting performance.
- To experience a process of cyclic architectural design that incorporates issues to energy and lighting, and to begin to develop this process on an individual basis.[29]

Energy Scheming provided an evaluation of a student design versus a "code minimum building."[30] Today, in comparison, the goal would be net zero or regenerative design. DeKay was upbeat about the potential of Energy Scheming to address difficult problems. He wrote, "Seeing the complexity of the particular within the context of these general patterns is the essence of the recognition of the complex interdependence between structure and function, form and flow."[31] Also writing in 1999, a team of University of Oregon faculty (Brown et al.) discussed their success using Energy Scheming to power an "automated" web-based support course. Repeating concerns noted in Malkawi and DeKay, Brown et al. noted that "[f]aculty and students alike hesitate to use software that is difficult or cumbersome."[32] In contrast, the students in Brown et al.'s small test group appeared to like the simplicity and accessibility of Energy Scheming. One of the students wrote:

> The World-Wide Web interface and the exercises were helpful in learning how to use

> Energy Scheming; however inputting my own studio design was **much** more helpful. This is because of the knowledge you already have concerning your design, your site, and the materials your building is made from. It is also more interesting because you have a stake in what you are analyzing and improving—it helps your studio design.[33]

The Oregon course included eight exercises, each with in a "warmup, exercise, and cooldown" format (Brown, et al. 1999, 137). The warmup component delivered content, substituting for a lecture in a traditional course. The exercise component was the problem itself, while the cooldown provided answers. In addition to the automated support course, Brown et al. discussed their plans for an upcoming studio course. To overcome the barrier of faculty not teaching energy issues in design studio because of a lack of confidence, knowledge, and/or interest, technical faculty were paired with design faculty.[34] Interestingly—and perhaps counterintuitively—the design studio exercise included three weeks of preliminary design before Energy Scheming was introduced.[35]

The shift in tone between DeKay's 1996 article and his and Brown et al.'s 1999 articles is remarkable. What is the difference? The digital turn in architecture had provided a tool that eviscerated the informational barriers to energy design. As Brown et al. note, "By speeding up the energy calculations, Energy Scheming allows students to spend more time trying out their design idea."[36] Writing in 2012, approximately 20 years after the digital turn in architecture and 35 years after Cook's article, Shen et al. are in a position to probe the effectiveness of various pieces of software to teach sustainability. Echoing Cook's seminal article on studying energy, Shen et al. wrote, "One of the technical challenges in teaching sustainable building design is enabling students to quantitatively understand how different building designs affect a building's energy performance."[37] Looking beyond digital tools, Shen et al. noted that, as of 2012, not much had been published concerning the integration of sustainability into curricula.[38] This suggests that the tools existed, but faculty and students were still not applying them to the degree they should.

Energy modeling today

When this author first taught an environmental systems support course in 2007, he continued using Energy-10, which the previous instructor had used. A DOS-based program, Energy-10 compensated for its limited abilities by being extremely buggy. Starting in 2013, this author required students to use the OpenStudio plugin for SketchUp. OpenStudio combines the powerful EnergyPlus simulation engine with SketchUp, which is visual and easy to use.[39] After hours of troubleshooting the combined software package, the author was able to help students use the software. However, the very next academic year, the university upgraded to the newest version of SketchUp, which was not compatible with the then current version of OpenStudio.

Looking for a stable energy simulation software, this author moved to Autodesk products. Autodesk has an arrangement with Ferris State University which provides free student versions of Autodesk products. To date, the combination of Revit and Green Building Studio has provided a reasonable introduction to the power of energy modeling. In the next phase, this author plans to encourage the adoption of energy modeling in subsequent design studios. However, it is important to remember that having the software does not necessarily mean that student projects are accurate in real-world scenarios. In 2009, construction management faculty looked at three pieces of building performance software—Autodesk's Ecotect, Autodesk's Green Building Studio, and Integrated Environmental Solutions' Virtual Environment—and found that students typically *overestimated* energy consumption by 30-50 percent.[40] Echoing this sentiment, Cendon wrote

> An important caveat for those in the energy modeling and building science community is that energy models do not predict actual building performance. Instead, building energy models are more analogous to the miles-per-gallon sticker prominently featured on every new car. A car's estimated fuel economy….isn't an exact measurement of how much gas it will use per mile driven [which] will vary depending on speed, air-conditioner use, and whether the car is driven in the city or on the highway, but the number is useful for car-shoppers because it allows for comparisons between models.[41]

Obviously, introducing energy modeling into an architecture curriculum will be an ongoing process.

The ethical obligation to teach energy modeling

An architect not using energy modeling today is akin to a mid-19th century doctor not using anesthesia. When a technology is developed that clearly improves the human condition, an ethical obligation is imposed on the practitioner to use that technology. Just as it is hard for 21st century people to believe that 19th century people resisted the use of anesthesia, future people will likely hold our views of energy design with disdain.

With today's powerful desktop computers and user-friendly software interfaces, Shibley and Poltroneri's "informational barrier" to energy design has been removed. That barrier may have been an acceptable excuse in 1984, but it is certainly not today because programs such as Revit and Green Building Studio put powerful tools in the hands of faculty and students. *Why should architectural educators care?* Increasingly, the built environment is being designed by specialists, with the architect's role often diminished to little more than a project manager (or perhaps ringmaster). But as Cook pointed out, high design is only part of an architect's skill set, since "[a]rchitects have developed skills otherwise useful to society."[42] One of these useful skills is energy design. As noted earlier in this paper, Cook argued "if the piece of hardware is of building size, maybe the architect must become an energy specialist."[43] The idea of broadening the architect's range is echoed by Boyer and Mitgang, who argued that schools of architecture should "expand their knowledge" of energy, among other factors.[44]

Buildings are complicated, multivariate problems. During the design process, ideas are winnowed from the set of all possibilities to the singular thing the building becomes. Thus, Crawley et al. note in their review of EnergyPlus that "Designers need tools that provide answers to very specific questions during design."[45] This is becoming even more relevant, as the needs to provide both comfort and sustainability collide. Cendon noted, "As the green building movement evolves, it's becoming more and more clear that the road between sustainable design intent and actual design performance is paved with data."[46]

We know that architecture is both an art and a science. In making his case for the science of architecture, Cook quoted Book 6, Chapter 2 of Alberti's treatise on architecture, which said that "All arts were begot by Chance and Observation and nursed by Use and Experience and improved and perfected by Reason and Study."[47] Writing for a modern audience, Stephen Kieran argued that "[t]o move the art of architecture forward….we need to supplement intuition with science."[48]

The digital turn in architecture is an important point milestone for the profession. Cendon argued that energy modeling is part of a "conceptual shift as dramatic as Modernism's break with traditional architectural forms."[49] In which classes will students address this conceptual shift? In support classes, certainly, but the lessons must be repeated and augmented in studio. Cook argued that "the design studio is where energy must be taught if it is to become an integral part of the architect's vocabulary."[50] Otherwise, students lose interest in energy and other building systems and they become simply "the domain of engineering consultants."[51] This often happens, according to DeKay, because

> [T]echnology is usually approached scientifically and analytically, rather than aesthetically or integratively. Present curricula often treat energy and environmental issues as a rationally based physical science, while design students think more associatively and relationally, life artists, poets, entrepreneurs, or social activists.[52]

A successful energy curriculum will introduce the science of energy, but also the art of energy, with support classes and design studios working together.

Conclusion

Energy modeling was made both effective and accessible during the digital turn in architecture, removing the informational barrier to energy design. Those of us teaching tomorrow's practitioners are obligated to introduce this powerful technology to our students as a critical component of our students' technical and design education. And this is the lesson as technology—specifically energy modeling software—continues to evolve: in the field of architecture, continuous technological improvements lead to and ever-shifting set of ethical obligations.

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[1] See Book VI, Chapter I, for example.

[2] Office of Energy Efficiency & Renewable Energy. 2016. "Fact #915: March 7, 2016 Average Historical Annual Gasoline Pump Price, 1929-2015." energy.gov. March 7. Accessed October 1, 2017. https://energy.gov/eere/vehicles/fact-915-march-7-2016-average-historical-annual-gasoline-pump-price-1929-2015.

[3] Cook, Jeffrey. 1978. "Thinking about Energy Education." *Journal of Architectural Education* 8-10: p. 8.

[4] Ibid., p. 8. Spelling error corrected.

[5] Ibid., p. 8.

[6] Ibid., p. 8.

[7] Ibid., p. 10.

[8] Ibid., p. 9.

[9] Ibid., p. 10.

[10] Shibley, Robert G.; Poltroneri, Laura. 1984. Architecture, Energy & Education: Case Studies in the Evaluation of the Teaching Passive Design in Architecture Workbook Series. Washington, D.C.: Association of Collegiate Schools of Architecture: p. 35.

[11] Ibid., p. 35.

[12] Ibid., p. 42.

[13] Ibid., p. 36.

[14] Ibid., p. 37.

[15] Shibley, Robert G. 1984. "Preface." *Journal of Architectural Education* 37 (3-4): 3.

[16] DeKay, Mark. 1996. "Possible Evolution of Technology Education in Architecture: The Case of Energy and Environmental Issues." *Constructions for Tectonics for the Postindustrial World.* Washington, D.C.: Association of Collegiate Schools of Architecture. 172-175. Emphasis in the original.

[17] Ibid., p. 172.

[18] Ibid., p. 172. Emphasis added.

[19] Long, Paul W., and Christopher L. Cosper. 2017. "105th ACSA Annual Meeting: Brooklyn says, 'Move to Detroit'." *At the Vital Center: The Small Town Studio at Ferris State University.* Washington D.C.: Association of Collegiate Schools of Architecture. 401-406.

[20] Boyer, Ernest L., and Lee D. Mitgang. 1996. *Building Community: A New Future for Architecture Education and Practice.* Princeton, NJ: The Carnegie Foundation: p. 87.

[21] Carpo, Mario. 2012. "Introduction: Twenty Years of Digital Design." In *The Digital Turn in Architecture 1992-2012*, edited by Mario Carpo, 8-14. Chichester, England: Wiley.

[22] Malkawi, Ali M. 1998. "Computer-Based Evaluation and Criticism for the Design of Energy-Efficient Buildings."

Constructing New Worlds. Washington, D.C.: Association of Collegiate Schools of Architecture. 300-305: p. 300.

[23] Ibid., p. 300.

[24] Ibid., p. 300.

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The Role of Retrofits in Architecture Education

Mohsenin Mahsan
Florida A&M University

Introduction

"The 2012 AIA firm survey shows that architecture firms received 42% of their billings from renovation projects. For small firms, renovation projects made up the majority of billings."[1] Retrofits aim to utilize already-established buildings and upgrade them to operate more efficiently. Our Architecture students need to know how to think critically about using resources economically, as ethical professionals of the future. This paper seeks to establish the soundness of retrofits as an ethical architectural practice and, therefore, should hold a more prominent place in the Architecture curriculum. The following points enumerate reasons to include retrofits in architecture curriculum:

- Engaging the present students with past buildings, for the future (educating present students to view older buildings positively and with an eye toward future use);
- Engaging lesson plan exploring the one or two famous structures, why a retrofit was appropriate, and how it turned out, then practice on a campus building;
- Improving efficiency and performance of in-use buildings for the future, thereby extending lifespan of buildings;
- Decreasing environmental impact/moving toward "net zero.

Outcome-based design is mentioned as the future of high-performance buildings, based on American Institute of Architects (AIA). Outcome-based design calls for more case studies and expert building performance simulations. Although building performance outcomes will vary based on the design and location, the study of retrofit solutions could be applied in similar climate conditions. Finding the effective retrofits requires the study of different economically possible solutions and optimization of results. Ardente et al. summarized the results of retrofit actions in six case studies within the European Union projects "Bringing Retrofit Innovation to Application in Public Buildings."[2] This study highlights the importance of life cycle to optimize retrofits. Asadi et al. studied the optimization process to combine retrofit actions;[3] Although, the scientific literature reviewed emphasized that there is a lack of knowledge in retrofit evaluations, using Building Energy Modeling (BEM). US Department of Energy defines BEM as a multipurpose tool for building energy efficiency, which includes retrofit design. This study provides BEM-based retrofit data for a campus building in a hot-humid climate to expand the literature for architects and designers.

Existing buildings are being upgraded at a very low rate, even though the cost of upgrading is most often lower than demolishing and constructing a new building, depending on the condition of the building. Itrad and Klunder compared renovation with new construction possibilities in Dutch urban renewal cases and found that renovation is more environmentally efficient than demolition.[4] Rocky Mountain Institute (RMI) introduces deep (whole building) retrofit steps by identifying opportunities and analyzing options.[5] Opportunities include engaging stakeholders, defining technical potential such as reducing loads (windows, radiant barriers, tenant load), installing efficient systems (chiller, AHU retrofits), and ongoing monitoring of energy systems.[6] After identifying opportunities, the retrofit team analyzes options based on energy modeling and cost analysis tools. Case study examples such as the Empire State Building, Byron Rogers Federal (Denver), and Indianapolis City-County Building could be found on RMI reports for an in-depth retrofit analysis.[7] There are different resources for financial analysis, including the Energy Star financing guide and building cost analysis programs.

Ma et al. categorized building retrofit technologies into Demand and Supply management, and Energy consumption patterns.[8] "*Demand side management* includes heating and cooling demand reduction, and energy-efficient equipment, whereas *Supply side management* focuses on renewable energy, and *Energy consumption patterns* deals with human factors."[9] Ma et al. provided a valuable summary of the findings from previous retrofit studies, indicating the significance of insulation, glazing measures, PV panels, lighting load reduction, and heating system retrofits.[10] Retrofits could be selected based on the economical possibilities and that indicates the significance of energy modeling to evaluate the energy savings and compare them with their cost to optimize retrofit actions.

Conservation is the most common topic, underlying the idea of repair in historical buildings. Aside from theories of Le Duc and Ruskin, this research focuses more on the consumer versus repair mentality in students through the subject of retrofits. The topic of retrofits is included in conservation, and urban planning education, but it is missing from architecture.

Research Methodology

The first part of this research explores retrofit actions on a campus building in hot and humid climate, using simulation method. The next part focuses on the feasibility of this research for graduate master's students in architecture and discusses the lack of retrofit studies in the architecture curriculum.

The Empire State building is an excellent cold climate example for a successful retrofit based on large capital investments. This retrofit upgraded windows, lighting fixtures, radiator insulation, and ventilation controls. Comparing this example with a retrofit in a hot and dry climate of Arizona State University Health Services shows that the hot dry one benefited from envelope sealing and HVAC replacement. Both of these examples used envelope strategies. About half of the old clinic is renovated and the rest added as new construction.[11] This project also engages the historic palm walk and water conservation as a campus-wide decision. This research provides energy settings used to test retrofits on a campus building in hot and humid climate of florida and lessons learned from applying it in architecture research. Palau de la Música in Barcelona, Catalonia, Spain is a great example for an extension to a historical building, using retrofits and restoration of the old building. The interior of the old building is kept, while framing the facade, using glass.

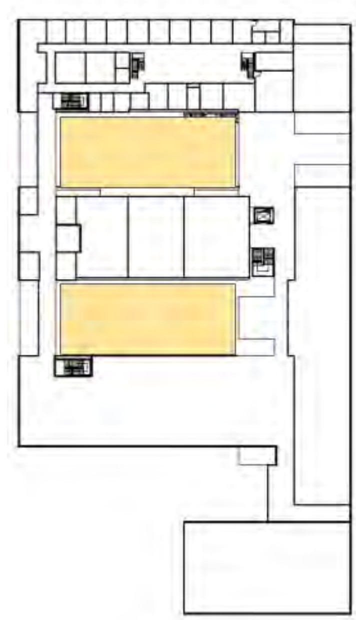


Fig. 1: Building configuration, illustrating the atria, earth berms

In this research, a campus building is modeled in Autodesk Revit with details of building material assemblies and analyzed using Autodesk Green Building Studio.[12] The building envelope is one of the main factors in evaluating the energy performance of an existing building and effective retrofit actions. The simulation in this study is tested, using building material based on the wall sections and architectural detail drawings. The modeling applied details of electricity and HVAC schedules to match the existing conditions. The selected building covers a variety of design features such as different envelope features, earth berming, and atrium (Figure 1). Each atrium measures approx. at 90 ft. (27 m) by 40 ft. (12 m), which is partially covered with a skylight. The following information summarizes the data used for the energy model located in Tallahassee, FL.

- Building type: Educational, Year built: 1985-86, remodeled 2001, with floor area: Approx. 38,000 ft^2 (3,500 m^2)
- Material properties: Bottom-half wall type with U-value: 0.0238 BTU/(h.ft^2.F) = 0.1351 W/m^2.K consists of brick finish (3 ⅝"), and top-half wall type with U-value: 0.0228 Btu/(h.ft^2.F) = 0.1295 W/m^2.K consists of Metal deck finish (3"), Roof U-value: 0.04 BTU/(h.ft^2.F) = 0.227 W/m^2.K, Window typologies and characteristic: Double-glazed U-value: 0.35 BTU/(h.ft^2.F) = 1.987 W/m^2.K.
- Average lighting power: 0.99 W/ft^2 = 10.65 W/m^2 and HVAC system/size: Central VAV, HW Heat, Chiller 5.96 COP, Boilers 84.5 eff.

This paper provides a systematic approach to proper selection and identification of the best retrofit options for a campus building pilot study. Retrofit actions studied include insulation, windows, renewable energy, and efficient lighting. The energy savings are then compared with their cost to provide the most cost-efficient option.

Preliminary Results

The base case results indicate 332,939 kWh electric, 6,912 Therms energy, and 56 EUI. In this case, identifying technical opportunities such as reducing loads, installing efficient systems, and ongoing monitoring of energy systems are studied. The current insulation and window to wall ratio has been studied and resulted in reasonable energy usage, with no need for energy changes. To reduce loads, this research considered renewable energy and lighting efficiency plugs. Since chillers in this case are upgraded by Siemens, there is no need to retrofit efficient systems, although one of the most energy saving retrofit options is high efficiency HVAC. Roof mounted PV system (with medium efficiency 10%) could save 27,000 kwh/yr energy, with an approximate cost of $120,000 to cover 2,000 sq. ft (185 m^2) of a gable roof facing north and south. The next retrofit action focuses on the use of lighting efficiency to 0.3 W/sf (3.2 W/m^2), which results in EUI equals to 49.

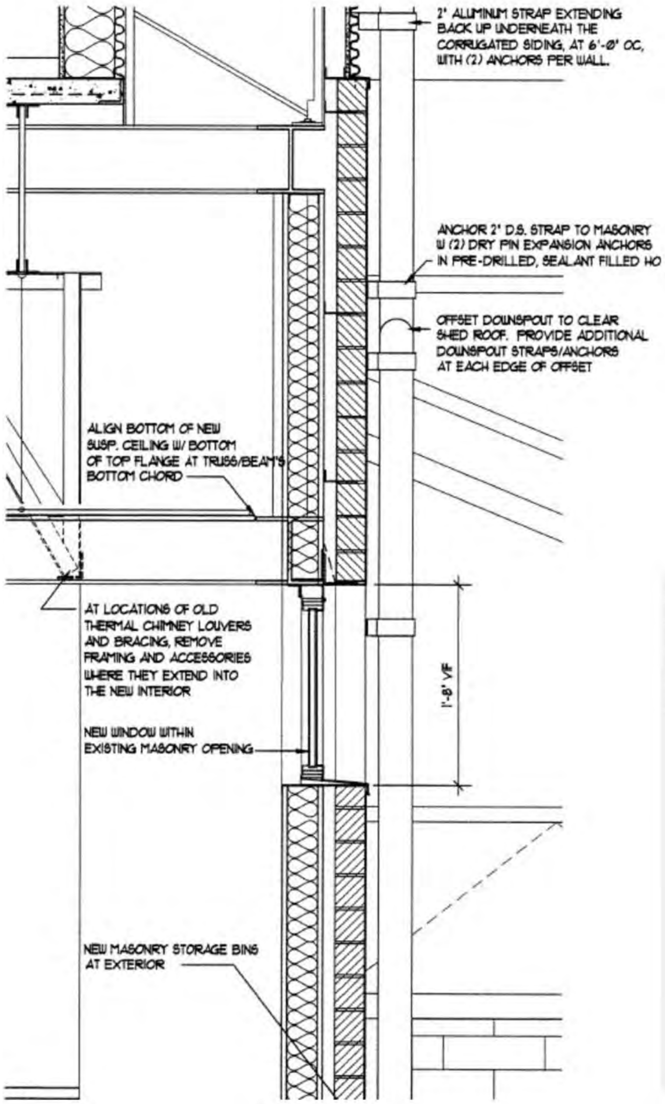
Energy Use Intensity (EUI) is the total energy use (electricity bill) per square foot in a year. Site EUI focuses on the energy usage of the building, whereas source EUI considers the energy generated or transported to the building. U.S. Environmental Protection Agency data state median site EUI for educational buildings as 58.0 kBtu/sq.ft./year (182.967 kW/m^2), with decreased targets using Energy Star portfolio manager.[13] The base case EUI, in this study, represents 56, which could be reduced to meet the target EUI through using renewable energy or combination of retrofit actions. Retrofit actions are different based on climate conditions; for example, PV panels or geothermal might work in a climate and do not have reasonable results in another climate.

One of the constraints in retrofit implementation is the cost and payback evidence for investors. Based on RMI research, in a retrofit retail pilot in Florida (43,000 GSF) that $11/GSF total capital cost and $7/GSF marginal cost could result in 72% annual utility cost savings in 2012.[14] A similar cost basis analysis could be applied to this project in a hot and humid climate. The marginal cost adjusts calculations based on future maintenance needs of not taking actions versus applying retrofits. To make cost-efficient decisions based on budgets, the team should consider the energy saving and life cycle cost for combinations of retrofit action. In this case, for instance, there is a need to compare cost and life cycle payback of including renewable energy, efficient plugs and Air Handling Units and find the right time to retrofit.

Retrofits in Pedagogy

The idea of providing architecture students with a "repair" vision defines the underlying didactics of this graduate research project. There are a few schools of architecture across the U.S. that offer Facilities Management as their business side of architecture as a graduate level degree. Facilities Management programs provide a clear vision about the future career path for students; however, joint-degree programs such as M.Arch/ MBA are quite broad as a graduate program, since most graduate students have already decided about the future career path. Most of the students in this Master of Science degree programs (such as Facilities Management) have architecture backgrounds, while undergraduate architecture students usually do not take Facilities Management or preservation courses. Examples of curricula that include retrofitting as preservation include Master of Science in Preservation Studies offered at University of Notre Dame, University of Oregon, Columbia University, Clemson University, and University of Minnesota. Historic Preservation courses at University of Oregon offer promising course material, such as Experimental Course: Principles of Adaptive Reuse and Building Pathology: Masonry and wood. While it's important to provide the opportunity for undergraduate architecture students to take some elective courses in preservation, Historic Preservation programs are offered mostly as graduate level programs. As a result, there is a need to have the subject of "repair" added to current design studio and technology courses in undergraduate architecture courses.

National Architectural Accrediting Board (NAAB) covers financial issues in one of the accreditation criterion, which can be met through professional practice lecture course in addition to upper level design studios. Finances and contract management is one of the important aspects that an architecture firm expects students to know, entering the firm. Schools of Architecture play a significant role in conveying this knowledge, in addition to the Architectural Experience Program. Including retrofits started with a graduate Research Assistant modeling and analyzing an existing campus building in Revit. The students used the energy analysis results to understand the building performance and find out appropriate retrofit actions. The analysis of cost and combinations were then added by the Principal Investigator. One of the examples for integration of different courses such as material and methods with student's research is when students translated construction assemblies to Revit for the energy model (Figure 2).



Family: Basic Wall
Type: BOTTOM HALF
Total thickness: 1' 0 1/2"
Resistance (R): 42.1033 (h·ft²·°F)/BTU
Thermal Mass: 7.2126 BTU/°F

Layers

EXTERIOR SIDE

	Function	Material	Thickness
1	**Core Boundary**	**Layers Above Wrap**	**0' 0"**
2	Finish 1 [4]	Brick, Common	0' 3 5/8"
3	Thermal/Air Layer [3]	<By Category>	0' 0 3/4"
4	Membrane Layer	Vapor Retarder	0' 0"
5	Substrate [2]	Gypsum Wall Board	0' 0 1/2"
6	Structure [1]	Metal Stud Layer	0' 6"
7	Thermal/Air Layer [3]	EIFS, Exterior Insulation	0' 1"
8	Finish 2 [5]	Gypsum Wall Board	0' 0 5/8"
9	**Core Boundary**	**Layers Below Wrap**	**0' 0"**

Fig. 2. Student's interpretation of wall section into the envelope assembly for simulation.

This experience brings up the question of the extent to what educators focus on retrofits in architecture education. It is an issue of ethics in technology to consider providing students with retrofit solutions and adaptive reuse, as case studies to convey the sustainable design techniques. Budget is one of the controversial parts of design studios, which is covered in lecture courses. However, there seems to be a need to combine every aspect of design for graduate students as a holistic action to have more efficient design deliveries. This research was a unique opportunity based on graduate researchers, while case studies of adaptive reuse could be combined in Introduction to Technology courses, to make students familiar with the concept. If other majors such as Facilities Management take the course, this will provide them with an opportunity to learn solutions that can be applied later in their career as facility managers. This research has also considered and tested including retrofit case studies and energy modeling as part of Environmental Systems course. The students were given an exercise to revisit one of their design studios with an energy efficient vision and improve its performance. Students used Autodesk energy simulation and evaluated their base case, then applied and tested changes to improve their building in a workshop. The results of this exercise showed that students learned about possible passive design strategies and how to integrate the strategies either at the beginning stages of design or as retrofits. The other benefit of this exercise was to make students familiar with the concepts used in energy modeling and parameters that affect the efficiency of a building. To summarize, including retrofits in architecture education provided the students with better understanding of building cost and design, more efficient retrofit solutions, integration of energy modeling in design, and solutions to improve the building performance.

Campuses are excellent places to practice retrofits, because the buildings are generally long lasting and need periodic retrofitting. As a result, including topics about retrofits in architecture technology courses and explaining case studies is necessary to prepare students for their careers. The present study provided an applied example for retrofit actions in architecture on a campus building in hot and humid climate, the results are applicable in similar conditions. The methodology to use energy modeling to recognize optimal retrofit actions makes it easier to include retrofits in architecture education.

This research was an attempt to include avenues of improvement for teaching building performance in existing buildings in architecture education. The comparison of benefits and costs helps students with more logical design decisions based on the factors that are taken into consideration. Facility managers play an important role in decisions regarding retrofit actions on campus buildings. As a result, there is a need for educators in schools of architecture to provide students with more practical life cycle cost analysis studies. Life Cycle Cost Analysis (LCCA) is a method to assess building cost, which takes into account construction, maintenance, and personnel salaries. There are codes and formulas to calculate LCCA, such as the Building Life-Cycle Cost (BLCC) Program, which is a tool developed by the National Institute of Standards and Technology for the U.S. Department of Energy. The understanding of LCCA in studio teaching would make students think about the life cycle of a building and give them an in-depth view of the scale and materiality of their design. To conclude, the goal of focusing on energy analysis and understanding the LCCA in design education is to have students critique and revise their decisions in the early stages of design. This should lead students to be more cognizant of their design options as professional architects, and, ultimately, more efficient and ethical building construction in the future.

This research concludes with the fact that Energy Modeling and Life Cycle Cost Analysis should play a significant role in architecture undergraduate education. On the one hand, practical aspects of the profession could be more emphasized throughout design studios, by inviting architects for jury sessions to comment more on financial aspects of the projects. On the other hand, retrofit examples could be explained to undergraduate students as case studies in courses such as Introduction to Technology in Architecture. The retrofit subject is a touch on the more critical issue of replacing the mindset of consumerism with “repair” by increasing the collaboration between architecture schools and practice.

Retrofitting could be discussed through a broader lens than energy and life cycle analysis, such as bringing back the meaning of preservation into architecture studios or urban design projects. Usually students in architecture are only focused on designing a new building that sometimes they forget the role of their architecture to the urban context and to what extent their design could maintain the existing fabric. As an example, in a fourth-year design studio, students were given a project to redesign an urban courtyard in Lisbon, Portugal. The results that faculty received from students work were impressive in the sense that students initially struggled to find ways to preserve and couple the new intervention with the urban fabric. Simon Burton and Hyde in Sustainable Retrofitting of Commercial Buildings values the idea european perspective and the idea of resilience [15,16]. One of the successful points in applying this idea in a design studio was to have the students think cautiously about the occupants, space planning, and the use of space in the context.

Sustainability rating systems are the next approach in retrofit discussion in architecture education. LEED has adopted certain criteria and credits for material reuse and space adaptations, while european rating systems take the lead on more advanced measurement methods and solutions. For instance, LEED Building Design and Construction provides credits for protecting and restoring sites, storage of recyclables, and demolition waste management. The familiarity of students with these ideas in design and technology courses will play a positive role in their future designs. There are various approaches to integrate retrofitting in architecture education, including design studios, technology courses, design competitions, sustainability rating systems, etc. This paper reviewed examples to apply retrofit education in technology, sustainability discussions and studio classes, with a focused research study approach towards energy modeling. Interaction with students during this process and research demonstrated the need to make student's knowledge of material and methods more practical and integrated with the holistic vision of their design.

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